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INITIAL POST NEUTRON MEASUREMENTS IN THE ORR

C. D. Cagle
R. A. Costner, Jr.

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OPERATIONS DIVISION

INITIAL POST NEUTRON MEASUREMENTS IN THE ORR

C. D. Cagle
R. A. Costner, Jr.

DATE ISSUED

MAY 28 1959

OAK RIDGE NATIONAL LABORATORY
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INITIAL POST NEUTRON MEASUREMENTS IN THE ORR

C. D. Cagle R. A. Costner, Jr.

ABSTRACT

The first approach to criticality of the ORR (ORNL Research Reactor) was completed at 6:06 PM, March 21, 1958. Following the initial instruments and controls performance checks using a small core, full-size cores were assembled for the post neutron measurements. The measurements included core and rod reactivity calibrations, the temperature coefficient, the reactivity effects of voids, the reactivity effects of experiments, the reactivity effects of fuel additions, and the spatial distribution of the thermal neutron flux. The results of the measurements are given together with discussions of the methods.

INTRODUCTION

The post neutron, low-power tests and measurements in the ORR were planned to supply only the most necessary information in the shortest time. For this reason the core and rod calibrations were combined into a single procedure per core, and the neutron measurements were confined to thermal neutrons. The number of core arrangements to be investigated was reduced from an original seven to two. The first core was a 4 × 7 array for checking the design criteria, and the second was the arrangement which benefited the greatest number of experiment facilities.

During these measurements, personnel from other reactor sites were present to be trained in this type of work and to assist in making the measurements. The organizations represented were Wright Air Development Center, Union Carbide Nuclear Company, National Advisory Committee for Aeronautics, Westinghouse Electric Corporation, and the University of Puerto Rico.

This fairly detailed account of the procedures and results is for the benefit of these observers as well as others who may wish to use this report as a guide to making some of the startup measurements in other reactors. Some of the step-by-step procedures followed by the operators are also included in the Appendix to illustrate the types of procedures desirable for this kind of operation.

APPROACHES TO CRITICALITY AND ATTAINING FULL-SIZE CORES

Since the low-power, post neutron tests and measurements would require manual handling of fuel elements between measurements, it was undesirable to operate the reactor at any power level above a few watts. It was, however, advisable to thoroughly check the behavior of the reactor instrumentation and control system before proceeding with the low-power tests. The fuel elements on hand for the startup tests were:

Eight	70-g elements
Twenty-eight	140-g elements
Twenty-eight	168-g elements
Twenty-three	200-g elements
Eight	131-g shim-safety rods

Calculations (*1*) indicated that the full-size initial test cores would have to be made up of a mixture of the 140- and 70-g elements in order to have a low enough excess reactivity for safety. Because of the small supply of 140-g elements, it was decided to make up the first performance-check core of 168-g elements and to reserve the 140-g elements for the low-power runs. This required that two approaches to criticality be made.

Two-group calculations indicated that the critical mass for a 4 × 7 core having an infinite beryllium reflector on the four sides and water on the top and bottom would be 2310 g of U^{235}. The minimum mass of a 4 × 7 core that could be assembled with the fuel elements on hand would be 3324 g. The excess reactivity for that mass was calculated to be 12.7%. Since the core would not quite have an effectively infinite reflector, the excess reactivity could be expected to be possibly less

than 12.7% or could be made greater by "clumping" heavier elements into the central part of the core. The geometrical inefficiency of the core configuration chosen to accommodate the experiments, and designated as the "operating core," could be expected to accept the mass of two additional 140-g elements with very little gain in excess reactivity.

Initial Preparations

The hydraulic performance tests had been completed, and it was known that the coolant system was performing properly. The instruments and controls had been checked out as thoroughly as possible by using neutron sources and simulated signals from the reactor. Since, for the approach-to-critical runs, the high-intensity instruments would not be functioning, it was deemed necessary for safety to increase the sensitivity of some of the permanent neutron-detecting instruments and to install additional temporary low-power instruments. The changes and additions were as follows:

1. The Log N sensitivity was increased by a factor of 100 by the calibration adjustments.
2. The sensitivity of the safety channels was increased by a factor of about 1000 by changing the input resistors.
3. Two additional fission chambers and associated instrumentation were installed. One of the chambers was inserted vertically into an aluminum tube in the reactor lattice and the other was inserted into one of the horizontal beam holes, HB-4.

Neutron Source

The neutron source for the approaches to criticality and the low-power runs was made to be removable so that criticality could be checked at the lowest possible instrument readings in order to keep the neutron flux low. This was necessary in order to keep the radioactivity of the fuel elements low to permit handling soon after shutdown. The source was a 60-curie Sb-Be photoneutron source activated in the LITR. It was attached to a cable and inserted into a guide tube located in a hollow beryllium reflector piece in the reactor lattice; this allowed the source to be pulled out of or lowered into the reflector region manually. A stop on the cable ensured that the source would be kept under at least 5 ft of water.

Procedures and Records

Before making the approach-to-critical runs, detailed procedures and check lists were prepared to ensure that the runs would be made in a careful and methodical manner (see Appendix). The check lists assured that proper equipment was on hand and that the reactor instruments were functioning. They also provided a basis for ascertaining that all personnel were completely aware of their responsibilities and knew how to handle them. The procedures listed each step of the work in sequence to guarantee that no confusion would result from the excitement which normally attends the first startup of a reactor.

Records consisted of a log book and graphs. The use of long, tedious record forms was avoided because only two approaches to criticality would be made. The use of a log book made entries of a commentary type possible, and it was felt that this would be more appropriate and more useful for future reference. The graphs were plots of the reciprocal of the counting rates of the fission-chamber channels plotted against fuel mass in the core. These graphs were useful in predicting the final core size as the loading progressed.

In order to have a readily available visual guide to the reactor core size at all times, a layout board had been prepared and mounted on a wall in the control room (Fig. 1). The bare lattice configuration was painted on the board, and hooks were provided for markers representing fuel and reflector pieces. As each fuel addition was made, a marker showing the fuel weight was hung on the layout board. This proved to be a great aid to operations personnel and to visitors who were observing the startup.

First Approach to Criticality

The first approach to criticality began with the reflector pattern and shim rod placement shown in Fig. 2. The fuel content of the shim rods was 525.03 g. With this arrangement the counting rates of the fission chambers were:

Fission Chamber Number	Counts/Sec	Location
1	0.74	Permanent channel
2	2.62	In reactor tank
3	2.27	In HB-4

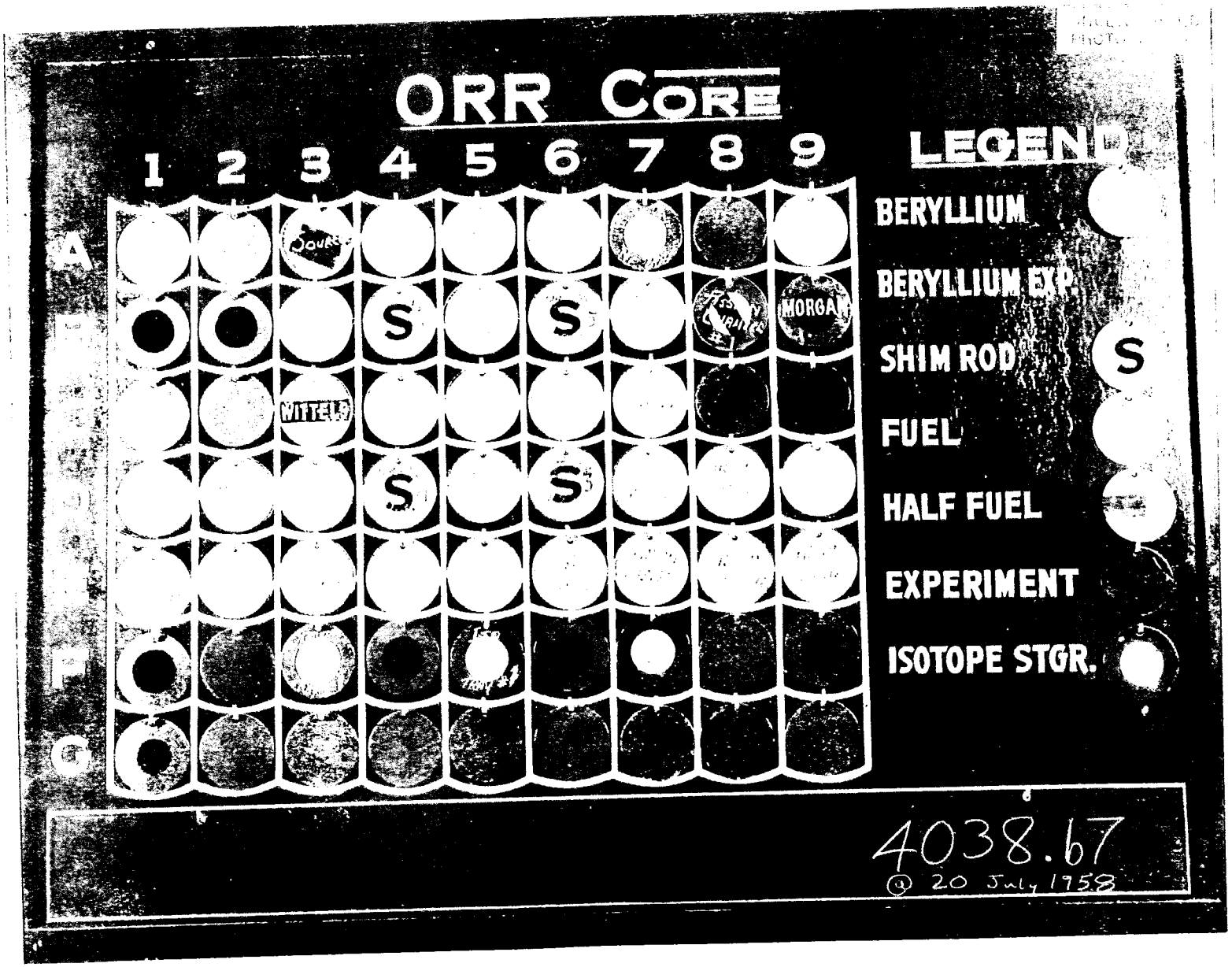


Fig. 1. ORR Core-Layout Board.

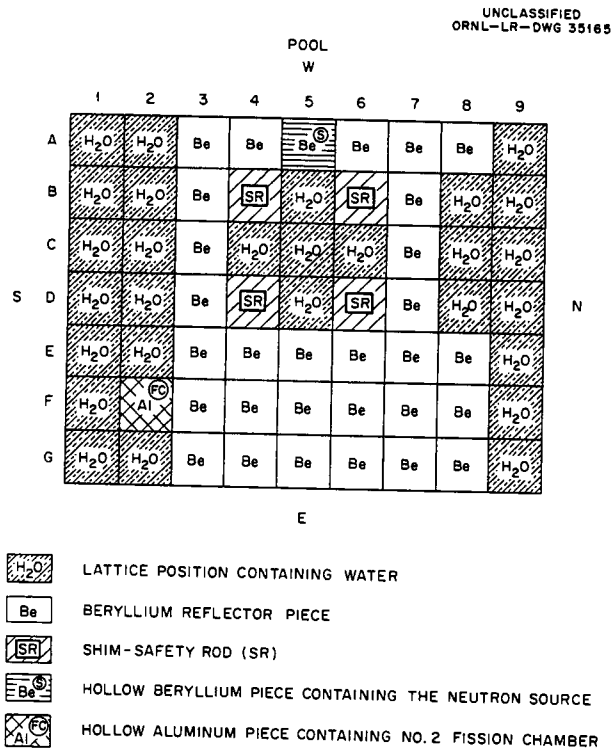


Fig. 2. Core Condition at Start of Approach to Criticality. The permanent fission chamber (No. 1) was directly below position B-8. The No. 3 fission chamber was located in HB-4 and was just east of position G-5.

The first fuel loading began at 4:00 PM, March 21, 1958, and consisted in elements being put into positions B-5, C-5, and D-5 to bring the core total to 1029.49 g. Following the rod withdrawal the counting rates were:

Fission Chamber Number	Counts/Sec
1	11.33
2	53.55
3	29.75

The next fuel addition was in position C-4 to give a total of 1197.93 g. During this loading, the No. 2 fission counter developed trouble and its use was discontinued. This left the minimum instrumentation which had been agreed upon before the startup was begun. The counting rates were:

Fission Chamber Number	Counts/Sec
1	28.83
3	102.42

The third fuel addition was in position C-6, to bring the total fuel in the core to 1366.16 g. When the rods were withdrawn 85% of their full travel, the reactor was critical. This occurred at 6:06 PM, March 21.

A plot of the reciprocal of the counting ($1/CR$) rate vs fuel mass in the core is shown in Fig. 3, and the core is shown in Fig. 4. Because of the large amount of fuel added per loading, the curve is not very useful for establishing the exact critical mass.

The excess reactivity was reduced by substituting a 140-g element for the 168-g element in position C-6, giving a total mass of 1309.70 g. Criticality was thereby achieved with the rods withdrawn 92% of their full travel. Substitution of a 70-g element in position C-6 made the reactor subcritical with the rods fully withdrawn. It is estimated that the critical mass was between 1280 to 1300 g. The calculated critical mass for

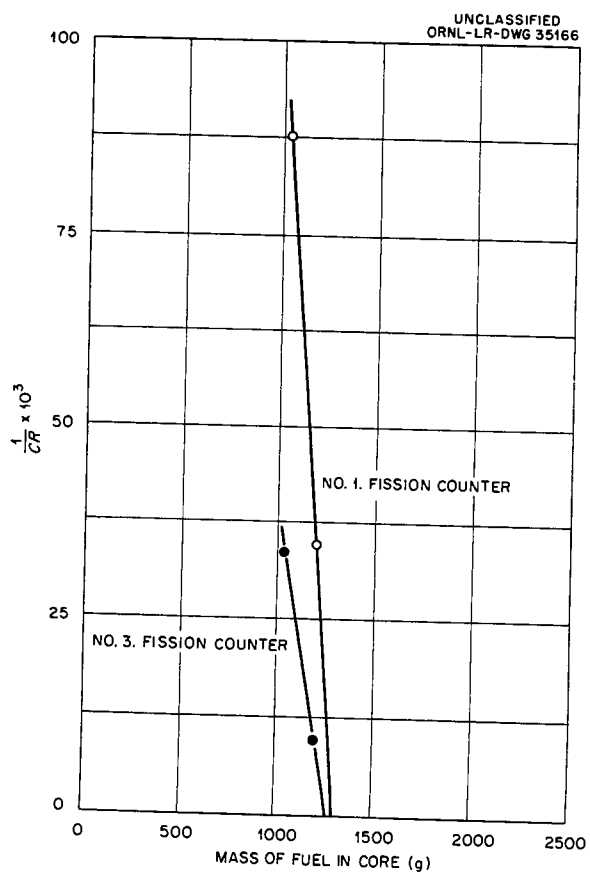
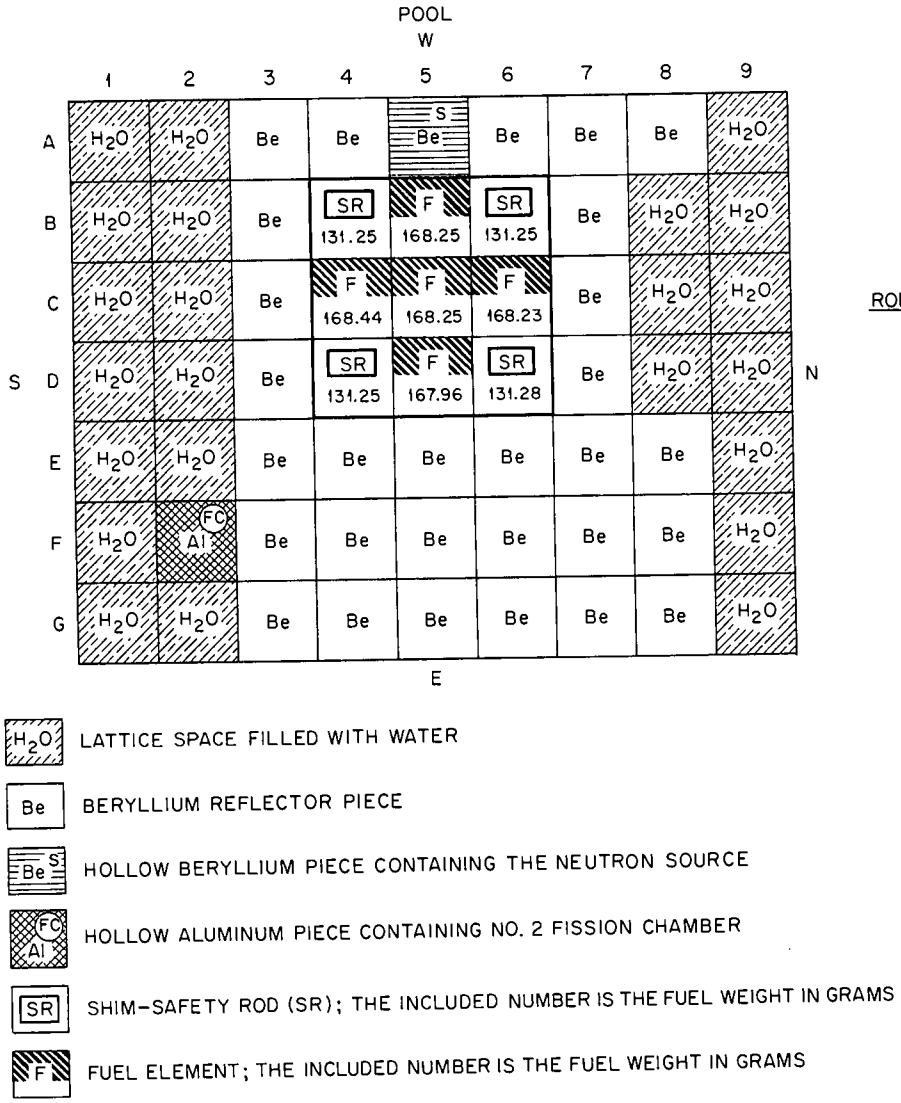


Fig. 3. First Approach to Criticality.



ROD POSITIONS AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	25.0
4	D-4	25.0
5	B-6	24.5
6	B-4	24.5

Fig. 4. First Critical Core. Total mass, 1366.16 g; core temperature, 26.5°C.

a 3 × 3 core assembly having an infinite beryllium reflector on four sides and water on the ends was 1150 g.

Instruments and Controls Checks with First Core

In the checkout of the instruments and controls, no major difficulties were encountered. With the exception of the permanent fission counter, the instruments behaved as expected. The need of some changes in the control circuits was found to be desirable, but no unsafe conditions were encountered.

The permanent fission chamber is housed in a thimble which enters the reactor tank from the bottom; therefore, it is below the core. When the reactor is scrammed or the rods are driven in, as by a reverse, the counting rate increases rather than decreases because of the freshly irradiated fuel section of the rods falling or being driven closer to the fission chamber. (The freshly irradiated fuel still emits delayed neutrons, and the gamma radiation produces photoneutrons in the water.) The increased counting rate drops rapidly; still, it is annoying to have any neutron

instrument whose reading goes upscale following a scram.

In order to obtain a rough power calibration for the instruments, a bare and a cadmium-covered gold foil were exposed in the center of the core, and the thermal neutron flux was determined at that point. The power level was estimated from the maximum-to-average flux ratio, which had been calculated earlier.

Second Approach to Criticality and Attaining Full-Sized Cores

The instruments and controls checkout with the first critical assembly was completed on March 28, and the second approach to criticality was made on March 31. The procedure for fuel additions was the same as that for the first approach to criticality, except that each of the elements contained a nominal 140 g of U^{235}. Criticality was reached at 3:30 PM with 1365.46 g of fuel in the core, three of the rods withdrawn all the way, and the other rod 90% withdrawn. The plot of the reciprocal of the counting rate vs fuel mass is shown in Fig. 5 and the critical core in Fig. 6.

Immediately following attainment of criticality, the core size was extended to the full-size 4 × 7 array. This was done by adding one or two fuel elements at a time, followed by a startup to check the rod positions after each addition in order to be certain that the reactor could not be made critical with the rods less than halfway withdrawn. A schedule of the fuel additions is given in Table 1, showing the amount of fuel per addition, the position of the addition, and the rod positions after startup.

The 4 × 7 core was used only to check the design criteria. Following the reactivity calibrations of the 4 × 7 array, the clean operating core was formed by shifting fuel elements one at a time and adding two new elements. Each step was followed by a startup to check the rod positions at criticality. The changes are tabulated in Table 2.

During the reactivity measurements with simulated core experiments in place, it became obvious that the location of two experiments and a fuel element would have to be changed in order to better the symmetry of the core and to increase the worth of one of the shim rods. Figures 7, 8, 9, and 10 show the four core arrangements.

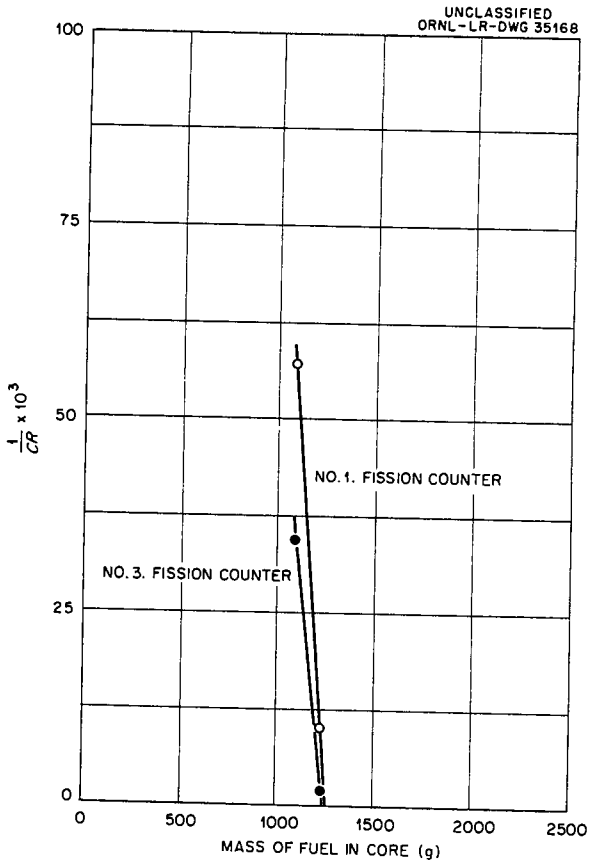
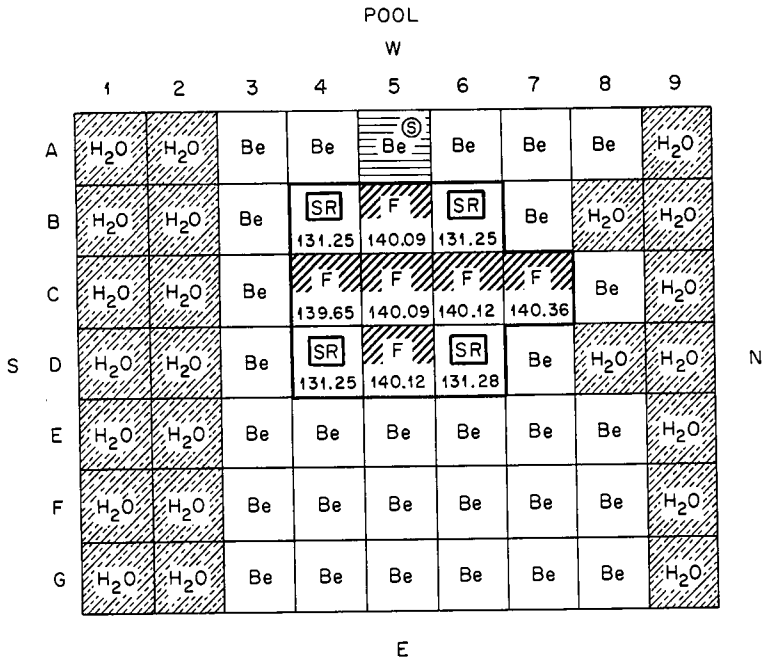


Fig. 5. Second Approach to Criticality.

CORE AND ROD CALIBRATIONS

Two methods for measuring the excess reactivity and calibrating the control and shutdown rods are in general use. One is the direct measurement of the worth of increments of a rod by the period induced when that increment is removed from or inserted into a reactor. The other is the introduction of a neutron absorber distributed throughout the core to cause the rods to be withdrawn some increment to maintain criticality. The reactivity value of the neutron absorber can be calculated to give the reactivity value of the rod increment. The total excess reactivity of a core can be determined by adding a sufficient quantity of the distributed absorber to require that the rods be fully withdrawn to maintain criticality.

To calibrate the total length of a rod by the period method, the other rods in the reactor must be



ROD POSITIONS AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	FULLY WITHDRAWN
4	D-4	FULLY WITHDRAWN
5	B-6	FULLY WITHDRAWN
6	B-4	26.59

H_2O LATTICE SPACE FILLED WITH WATER

Be BERYLLIUM REFLECTOR PIECE

Be S HOLLOW BERYLLIUM PIECE CONTAINING THE NEUTRON SOURCE

SR SHIM-SAFETY ROD (SR); THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

F FUEL ELEMENT; THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

Fig. 6. Second Critical Core. Total mass, 1365.46 g; core temperature, 21°C.

Table 1. Attainment of 4 × 7 Configuration

Core Positions	Changes and Fuel Additions	Net Fuel in Core (g)	Average Rod Positions at Criticality (Inches Out)	Core Temperature (°C)
B-7 and B-8	Moved beryllium from B-7 to B-8; put 139.87-g fuel element into B-7	1505.33	23.98	21
D-7, D-8, and C-7	Moved beryllium from D-7 to D-8; removed 140.36-g fuel element from C-7; put 69.87-g fuel element into D-7; put 69.87-g fuel element into C-7	1504.71	24.90	20
D-2 and D-3	Moved beryllium from C-3 to C-2; put 69.96-g fuel element into C-3	1574.67	24.6	21

Table 1 (continued)

Core Positions	Changes and Fuel Additions	Net Fuel in Core (g)	Average Rod Positions at Criticality (Inches Out)	Core Temperature (°C)
B-2, B-3, and C-5	Moved beryllium from B-3 to B-2; moved 140.09-g fuel element from C-5 to B-3; put 69.96-g fuel element into C-5	1714.59	24.88	22
C-8 and C-9	Moved beryllium from C-8 to C-9; put 140.36-g fuel element into C-8	1854.95	23.20	22
B-8 and B-9	Moved beryllium from B-8 to B-9; put 140.12-g fuel element into B-8	1995.07	22.27	24
D-8 and D-9	Moved beryllium from D-8 to D-9; put 140.12-g fuel element into D-8	2135.19	20.77	24
C-1 and C-2	Moved beryllium from C-2 to C-1; put 139.65-g fuel element in C-2	2274.84	20.19	24
A-1, B-1, B-2, D-5, and G-8	Moved beryllium from G-8 to A-2; moved beryllium from B-2 to B-1; moved 140.12-g fuel element from D-5 to B-2; put 69.87-g fuel element into D-5	2344.71	20.90	26
D-1, D-2, E-2, and E-5	Moved beryllium from D-2 to D-1; moved beryllium from E-5 to E-2; put 139.82-g fuel element into D-2; put 70.16-g fuel element into E-5	2554.69	19.15	26
E-1, E-4, E-6, and E-9	Moved beryllium from E-4 to E-1; moved beryllium from E-6 to E-9; put 139.87-g fuel element into E-4; put 70.16-g fuel element into E-6	2764.72	17.67	26
E-3, E-7, F-2, and F-9	Moved beryllium from E-3 to F-2; moved beryllium from E-7 to F-9; put 139.65-g fuel element into E-3; put 140.19-g fuel element into E-7	3044.50	16.10	26
E-2, E-4, E-5, E-8, F-1, G-2, A-1, A-9, G-1, G-8, and G-9	Moved beryllium from E-8 to F-1; moved beryllium from E-2 to G-2; moved 139.87-g fuel element from E-4 to E-5; moved 70.16-g fuel element from E-5 to E-4; put 139.46-g fuel element into E-8; put 139.87-g fuel element into E-2; put Al reflector pieces into A-1, A-9, G-1, G-8, and G-9	3323.83	15.42	28

Table 2. Attainment of First Operating Core

Core Positions	Changes and Fuel Additions	Net Fuel in Core (g)	Average Rod Positions (Inches Out)	Core Temperature (°C)
A-3 and A-5	Moved beryllium from A-3 to A-5; moved source from A-5 to A-3	3323.83	15.18	27
B-2 and D-1	Moved 140.12-g fuel element from B-2 to D-1; moved beryllium from D-1 to B-2	3323.83	15.48	26
B-8, D-9, and G-1	Removed aluminum reflector piece from G-1, leaving water-filled space; moved 140.12-g fuel element from B-8 to D-9; moved beryllium from D-9 to B-8	3323.83	15.48	26
C-2 and E-1	Moved 139.65-g fuel element from C-2 to E-1; moved beryllium from E-1 to C-2	3323.83	15.84	26
C-8 and E-9	Moved 140.36-g fuel element from C-8 to E-9; moved beryllium from E-9 to C-8	3323.83	16.27	26
A-5 and B-3	Moved 140.09-g fuel element from B-3 to A-5; moved beryllium from A-5 to B-3	3323.83	16.55	26
A-4	Removed beryllium from A-4; put 140.10-g fuel element into A-4	3463.93	16.36	26
A-6, G-1, and G-8	Moved aluminum from G-8 to G-1; moved beryllium from A-6 to G-8; put 140.11-g fuel element into A-6	3604.04	16.00	26

moved in order that the rod being calibrated may be repositioned at each step of the calibration. In a small core, such as that of the ORR, the distortion of the spatial flux distribution caused by the presence of nearby partially inserted rods would cause great inaccuracies in the calibration of individual rods. Also there would be no way to evaluate the group worth of the rods. For these reasons, no attempt was made to calibrate any of the rods by the period method.

The distributed-neutron-absorber method has been used to calibrate the safety-shim rods at the LITR, the MTR, the ETR (*2*), and other similar reactors, and some work was being done at the BSR (*3*) during the time that the ORR calibrations were being planned. The distributed absorber used in the LITR calibration was type 347 stainless steel strips. Since these displaced the moderator when inserted into the fuel elements, some error was introduced into the calibration. The MTR and ETR calibrations were done with polyethylene tape impregnated with elemental boron. Since the hydrogen content of the tape was roughly equivalent to that of the water displaced, the core calibrations obtained were considered good. The polyethylene tape is very flexible and somewhat difficult to insert into the fuel elements. At the ETR, the strips of tape were inserted manually after lifting the fuel elements out of the core. This is a somewhat time-consuming procedure if personnel exposure to radiation is to be avoided. The work at the BSR was done with Plexiglas strips impregnated with 325-mesh boron carbide. These strips were much less flexible than the polyethylene tape and could be inserted between fuel plates in the core without removal of the fuel elements. They were, however, somewhat brittle and required that a strainer be installed in the bottom of each fuel element to catch any pieces that might break off. Measurements had also been made at the BSR which showed that the insertion of a great number of pure Plexiglas

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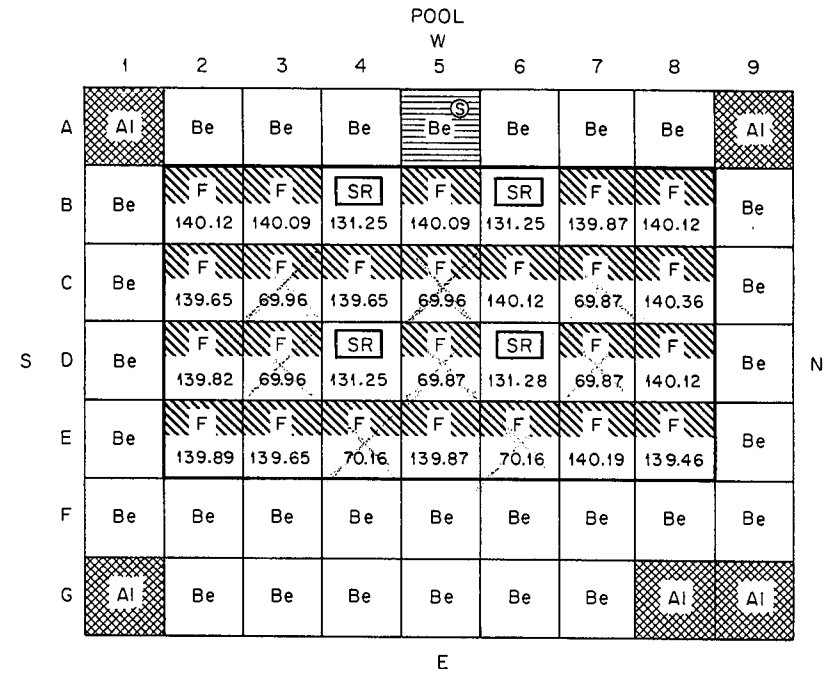


ROD POSITION AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	15.43
4	D-4	15.42
5	B-6	15.42
6	B-4	15.41

Al — ALUMINUM REFLECTOR PIECE

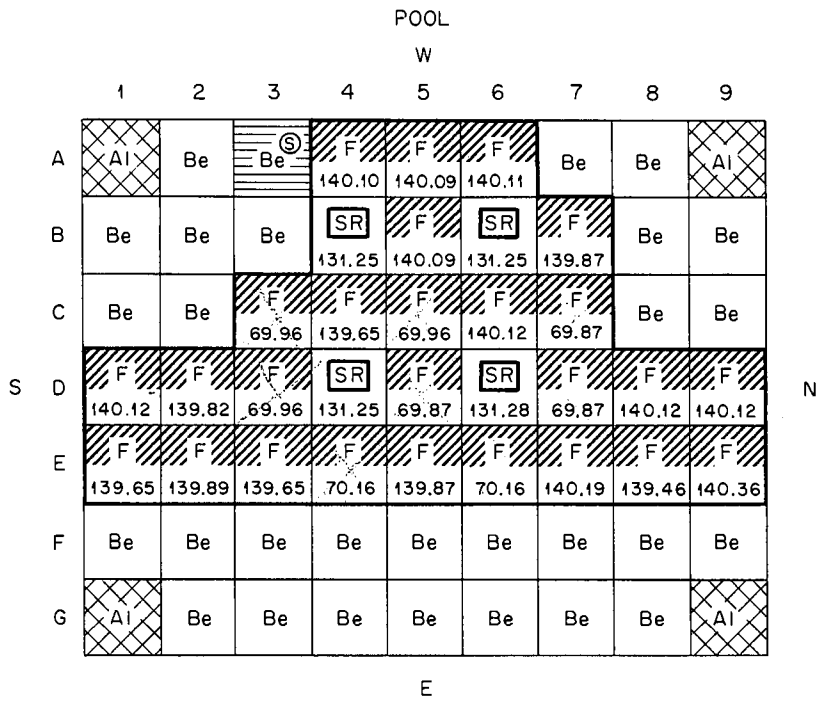
Be — BERYLLIUM REFLECTOR PIECE

Be (S) — HOLLOW BERYLLIUM PIECE CONTAINING THE NEUTRON SOURCE

SR — SHIM-SAFETY ROD (SR). THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

F — FUEL ELEMENT; THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

Fig. 7. The 4 × 7 Test Core. Total mass, 3323.83 g; excess reactivity, 13.94% $\Delta k/k$; core temperature, 28°C.



ROD POSITIONS AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	16.01
4	D-4	16.01
5	B-6	16.00
6	B-4	16.00

Al — ALUMINUM REFLECTOR PIECE

Be — BERYLLIUM REFLECTOR PIECE

Be Ⓢ — HOLLOW BERYLLIUM PIECE CONTAINING THE NEUTRON SOURCE

SR — SHIM-SAFETY ROD (SR); THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

F — FUEL ELEMENT; THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

Fig. 8. First Operating Core Without Experiments. Total mass, 3604.12 g; excess reactivity, 13.90% $\Delta k/k$; core temperature, 26.5°C.

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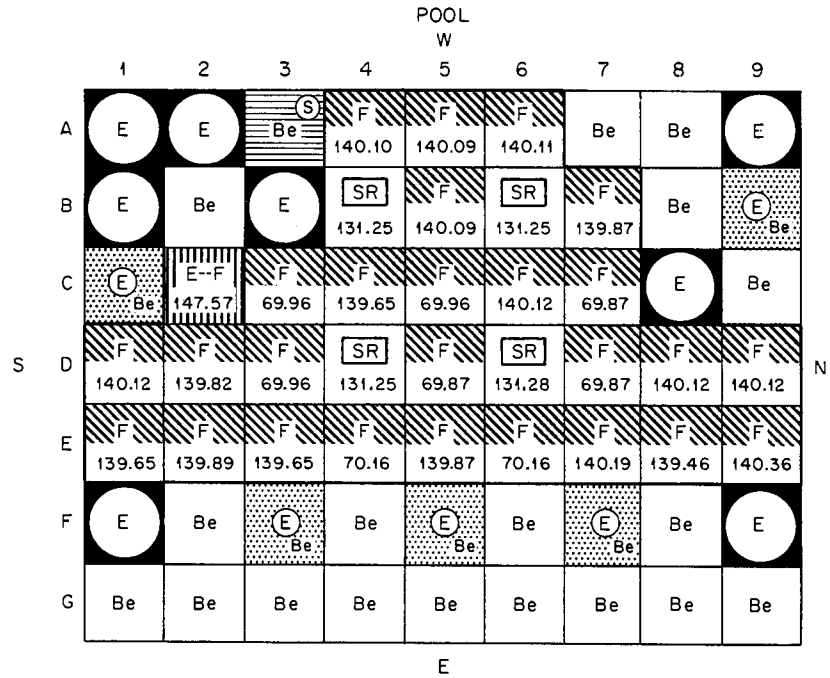


ROD POSITION AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	19.21
4	D-4	19.21
5	B-6	19.21
6	B-4	19.21

Be — BERYLLIUM REFLECTOR PIECE

(S) Be — HOLLOW BERYLLIUM PEICE CONTAINING THE NEUTRON SOURCE

(E) — EXPERIMENT OCCUPYING FULL-SIZED LATTICE SPACE

(E) Be — HOLLOW BERYLLIUM PIECE CONTAINING AN EXPERIMENT OR RADIOISOTOPE FACILITY

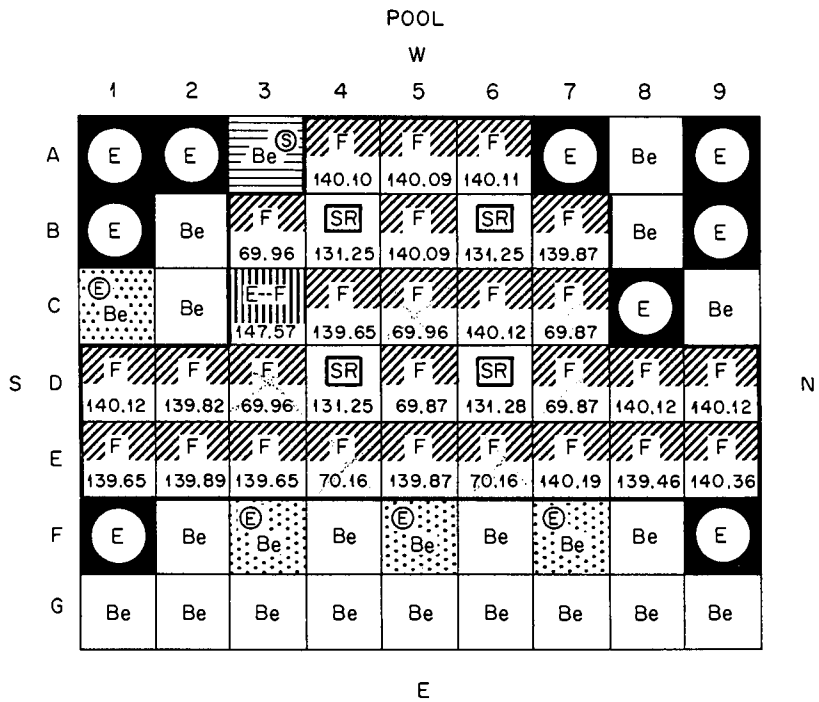
E--F — PARTIAL FUEL ELEMENT WITH EXPERIMENT. FUEL WEIGHT IN GRAMS IS SHOWN

SR — SHIM-SAFETY ROD (SR); THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

F — FUEL ELEMENT; THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

Fig. 9. First Operating Core with Experiments. Total mass, 3751.69 g; excess reactivity, 7.72% $\Delta k/k$; core temperature, 24°C.

UNCLASSIFIED
ORNL—LR—DWG 35173



ROD POSITION AT CRITICAL

ROD NO.	POSITION	INCHES OUT
3	D-6	18.14
4	D-4	18.14
5	B-6	18.14
6	B-4	18.14

Be — BERYLLIUM REFLECTOR PIECE

Be(S) — HOLLOW BERYLLIUM PIECE CONTAINING THE NEUTRON SOURCE

E — EXPERIMENT OCCUPYING FULL-SIZED LATTICE SPACE

(E) Be — HOLLOW BERYLLIUM PIECE CONTAINING AN EXPERIMENT OR RADIOISOTOPE FACILITY

E--F — PARTIAL FUEL ELEMENT WITH EXPERIMENT; FUEL WEIGHT IN GRAMS IS SHOWN

SR — SHIM-SAFETY ROD (SR); THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

F — FUEL ELEMENT; THE INCLUDED NUMBER IS THE FUEL WEIGHT IN GRAMS

Fig. 10. Revised Operating Core with Experiments. Total mass, 3751.69 g; excess reactivity, 9.12% $\Delta k/k$; core temperature, 29°C.

strips into the core had no appreciable effect upon the reactivity. Since three core calibrations were to be made during the ORR startup, the use of the boron carbide–impregnated Plexiglas strips was considered the more desirable method from the time-saving viewpoint.

The distributed-neutron-absorber method for reactivity calibration assumes that the introduction of the absorber changes only the thermal utilization of the core. Thus,

$$f_0 = \frac{\Sigma_a^F}{\Sigma_a^C}$$

and

$$f = \frac{\Sigma_a^F}{\Sigma_a^C + \Sigma_a^P} ,$$

where

f_0 = thermal utilization of the clean core,

f = thermal utilization of poisoned core,

Σ_a^F = macroscopic absorption cross section of the fuel,

Σ_a^C = macroscopic absorption cross section of all the materials in the clean core,

Σ_a^P = macroscopic cross section of the distributed neutron absorber or poison.

If all other conditions remain constant, then

$$\frac{k}{k_0} = \frac{f}{f_0} ;$$

therefore

$$k = k_0 \frac{f}{f_0} ,$$

where

k_0 = multiplication constant of the core before introducing the absorber, and

k = multiplication constant of the core after introducing the absorber;

it follows that

$$k = k_0 \frac{\dfrac{\Sigma_a^F}{\Sigma_a^C + \Sigma_a^P}}{\dfrac{\Sigma_a^F}{\Sigma_a^C}} = k_0 \frac{\Sigma_a^C}{\Sigma_a^C + \Sigma_a^P} = \frac{k_0}{1 + \dfrac{\Sigma_a^P}{\Sigma_a^C}} .$$

The change in k, Δk, is

$$\Delta k = k_0 - k$$

or

$$k_0 = k + \Delta k ;$$

so that

$$k \left(1 + \frac{\Sigma_a^P}{\Sigma_a^C}\right) = k + \Delta k ,$$

and

$$\frac{\Delta k}{k} = \frac{\Sigma_a^P}{\Sigma_a^C} .$$

Since the volume of the core and the volume throughout which the poison is distributed are the same,

$$\frac{\Delta k}{k} = \frac{\text{total absorption cross section of poison}}{\text{total absorption cross section of clean core}}$$

Procurement and Calibration of Boron Carbide–Impregnated Plexiglas Strips

The maximum excess reactivity of the cores to be calibrated was to be about 14% $\Delta k/k$, and the maximum number of ¾-in.-wide × 2-ft-long Plexiglas strips which could easily be put into a fuel element would be six; these conditions defined the minimum concentration of boron carbide needed per square centimeter of strip area which was computed in the following manner:

$$\frac{\Sigma_a^P}{\Sigma_a^C} = 0.14 ,$$

$$\Sigma_a^P = 0.14\,\Sigma_a^C \cong 0.14 \times 0.06 \text{ (ref 1)} = 0.0084 \text{ cm}^{-1} ,$$

$$\sigma_a \text{ of boron} = 6.65 \times 10^{-22} \text{ cm}^2 \text{ (for average thermal energy)},$$

$$\Sigma_a^P = \frac{\sigma_a^B \times \text{Avogadro's number} \times \text{g/cm}^3}{\text{atomic weight of boron}} ,$$

$$0.0084 \text{ cm}^{-1} = \frac{6.65 \times 10^{-22} \times 6.02 \times 10^{23} \times \text{g/cm}^3}{10.82} ,$$

$$\frac{\text{g}}{\text{cm}^3} = \frac{0.0084 \times 10.82}{6.65 \times 10^{-22} \times 10^{23}} = 2.27 \times 10^{-4} .$$

The volume of the 4 × 7 core is 9.9×10^4 cm^3. The weight of boron required would be

$$2.27 \times 10^{-4} \text{ g/cm}^3 \times 9.9 \times 10^4 \text{ cm}^3 = 22.5 \text{ g} \quad .$$

The surface area of Plexiglas in the reactor when fully poisoned would be

$$6 \text{ strips} \times 24 \text{ fuel elements} \times 0.75 \text{ in.} \times 24 \text{ in.} \times \times \frac{(2.54 \text{ cm})^2}{\text{in.}} = 1.67 \times 10^4 \text{ cm}^2 \; ;$$

$$\frac{\text{g of B}}{\text{cm}^2} = \frac{22.5}{1.67 \times 10^4} = 0.00135, \text{ minimum} \quad ;$$

$$\frac{\text{g of } B_4C}{\text{cm}^2} = \frac{0.00135 \times 55.28}{43.28} = 0.0017, \text{ minimum} \quad .$$

The Plexiglas was made to order by Rohm and Haas Company of Knoxville, Tennessee, and the 325-mesh boron carbide was furnished by ORNL. The boron carbide surface density of the Plexiglas used was nominally 0.0027 g/cm^2, in order to reduce the number of strips necessary per fuel element.

The Plexiglas was purchased in the form of 36 × 48 × 0.060 in. sheets, which were sawed into strips. The strips were connected to aluminum adapters which enabled them to be inserted into the core through 10 ft of water, by use of a handling tool. The poison strip assembly and handling tool are shown in Fig. 11*a* and *b*.

Since, in the manufacturing process, the boron carbide powder must be mixed with the Plexiglas in liquid form and the mixture poured upon glass to harden, the distribution of the boron carbide through the plastic was not very uniform. Also, some settling occurred during the hardening, causing nonuniformity through the thickness. This somewhat poor distribution had been predicted by the manufacturer and was accepted.

Calibration of the strips was first attempted on an averaging basis, according to the weight of boron in random samples of the Plexiglas. The degree of nonuniformity was found to be too great and possible self-shadowing too likely for use of a calculated average absorption cross section derived in that manner. Therefore, the absorption cross section of each strip was evaluated separately.

The strip calibrations were done in the LITR, where the reactivity value of the regulating rod per unit length is constant over the mid-part of the rod. Thus, the absorption cross section of an unknown material may be determined by comparison with material of known cross section from a simple ratio of the regulating rod displacements caused by the two materials when placed singly in or near the reactor core. The standards were copper and stainless steel, which are moderate neutron absorbers; thus, the self-shadowing in a thin strip is negligible. The size of the metal strips was the same as that of the Plexiglas strips being calibrated; therefore, the same reactor region would be involved in all the measurements. The cross sections of the standards were calculated from the handbook values of the microscopic absorption cross sections for the elements involved and were also checked with the oscillator in the Graphite Reactor. In order to allow for some expected breakage, 120 full-width (0.75 in.) strips and 29 half-width strips were calibrated. For the full-width strips, absorption cross sections ranged from 5.36 cm^2 to 11.15 cm^2 per strip; for the half-width strips, the range was from 3.40 cm^2 to 4.64 cm^2 for 0.025-ev neutrons. The total for all strips was 1149.31 cm^2 for 0.025-ev neutrons (1018.29 for thermal neutrons at ~25°C), which would be worth 15.4% $\Delta k/k$ in the 4 × 7 core and 14.3% $\Delta k/k$ in the operating core. This was considered to be a sufficient number of strips, since 14% $\Delta k/k$ was not to be exceeded.

Core and Rod Calibration Procedure and Results

The individual rod calibrations and the group rod calibrations were made as the cores were being poisoned to determine the total core worths. By use of this method, all the data for the rod calibration curves had been gathered when the core was fully poisoned, except for the worth of the rods between their all-the-way-inserted position and the first calibration point. This could have been determined by very tedious juggling of the amount of poison in the core to establish the reactivity value of the core with criticality occurring with three rods fully withdrawn and the rod in question fully inserted. Since that method was considered too time-consuming, the value for each rod from zero inches out to the first point on the calibration was determined by the following procedure after the poison strips were removed from the core.

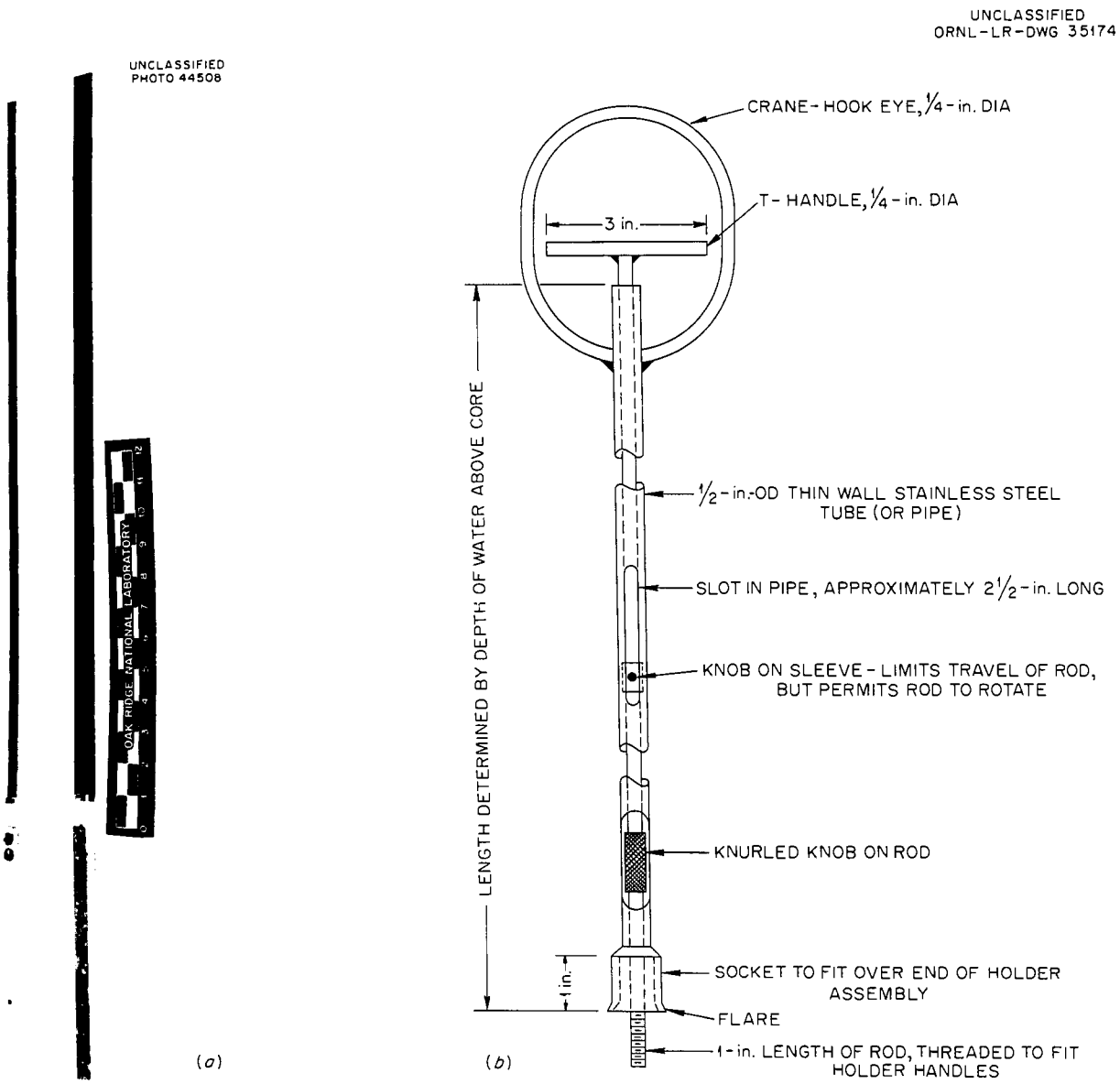


Fig. 11. Boron Carbide–Impregnated Plexiglas Strips and Handling Tool.

1. The reactor was brought to criticality with the rod being calibrated remaining fully inserted, two rods fully withdrawn, and the other rod used as control and positioned as required to maintain criticality. The rod positions were recorded.

2. While maintaining criticality with the rod used for control, the rod being calibrated was withdrawn to the point where its calibration began. The rod positions were again recorded.

3. The change in $\Delta k/k$ caused by moving the rod being calibrated from zero inches out to the first calibration point was determined from a graph of the calibration of the rod used as control (plotted with an arbitrary zero).

This procedure gives a possibly slightly erroneous value for the total worth of the rod because of the perturbation added by the second rod. The error is probably small, however, since the region of the rod which is being calibrated is some distance from the flux depression caused by the rod which is being used for control. The slopes of the curves in the mid-region and the upper

ends will, however, be as nearly correct as the absorption cross sections used. Tables 3, 4, and 5 list the data taken during the calibration runs. The rod calibration curves are given in Figs. 12 through 24. Some additional points on some of the curves were obtained later by intercomparison of the rods.

The individual rod calibrations obtained for the first operating core are not valid for the revised operating core, although the No. 3 and No. 4 rod calibrations should not have changed much. The group rod calibration, however, should remain nearly correct. This was reasonably verified during the measurement of the reactivity effects of fuel additions in regions far from the lattice positions where the revisions were made.

The rod calibrations were used to measure the reactivity effects produced by introducing voids around the core, the temperature coefficient of each core, and the reactivity changes resulting from introducing experiments and additional fuel into various regions of the operating core.

TEMPERATURE COEFFICIENT MEASUREMENTS

In order to avoid the reactivity effect of fission products, the temperature coefficient was measured by heating the reactor water with the main circulating pumps and by using steam on the heat exchangers. The combined heat input was sufficient to raise the water temperature at the rate of 3 to 4°F per hour. Plots of the reactivity vs

Table 3. Core and Rod Calibrations for 4 × 7 Core

The absorption cross section of the clean core was calculated to be 6604.5 cm^2 for thermal neutrons

Poison in the Core (cm^2 of Absorber)	Worth of Poison (% $\Delta k/k$)	Change in Reactivity (% $\Delta k/k$)	Group Rod Position (Inches Out)	Rod Position at Criticality with the Others Fully Withdrawn (Inches Out)		% $\Delta k/k$ Added to Core by Withdrawing the Rod to the Given Position	
				Number 4	Number 6	Number 4	Number 6
0	0	0	15.42				
50.75	0.768	0.77	15.90				
96.41	1.46	0.69	15.98				
145.13	2.20	0.74	16.43				
235.57	3.57	1.37	17.27				
281.23	4.26	0.69	17.66				
323.50	4.90	0.64	17.99				
368.65	5.58	0.68	18.35	4.66		0.23[a]	
416.83	6.31	0.73	18.86	9.81		0.96	
459.98	6.97	0.66	19.25	11.41		1.61	
510.03	7.72	0.75	19.65	12.67		2.37	
558.29	8.45	0.73	20.07	13.69		3.10	
599.07	9.07	0.62	20.60	14.92	9.13	3.72	1.08[b]
657.05	9.95	0.88	21.70	16.95	13.65	4.60	1.96
706.15	10.69	0.74	22.50	18.35	15.97	5.34	2.70
742.77	11.24	0.55	23.25	19.70	17.68	5.89	3.25
786.56	11.91	0.67	23.98	20.90	19.20	6.56	3.92
827.60	12.53	0.62	24.65	22.00	20.53	7.18	4.54
870.74	13.18	0.65	25.92	24.05	23.12	7.83	5.19
913.70	13.83	0.65	27.70	26.90	26.50	8.48	5.84
916.95	13.88	0.05			27.30		5.89
920.22	13.94	0.06	Fully withdrawn	Fully withdrawn	Fully withdrawn	8.58	5.95

[a]Measured by use of No. 6 rod.
[b]Measured by use of No. 4 rod.

Table 4. Core and Rod Calibrations for the First Clean Operating Core

The absorption cross section of the clean core was calculated to be 7116.4 cm^2 for thermal neutrons

Poison in the Core (cm^2 of Absorber)	Worth of Poison (% $\Delta k/k$)	Change in Reactivity (% $\Delta k/k$)	Group Rod Position (Inches Out)	Rod Position at Criticality with the Others Fully Withdrawn (Inches Out)				% $\Delta k/k$ Added to Core by Withdrawing the Rod to the Given Position			
				No. 3	No. 4	No. 5	No. 6	No. 3	No. 4	No. 5	No. 6
0	0	0	16.00								
111.50	1.57	1.57	16.70								
204.50	2.88	1.31	17.40								
280.02	3.94	1.06	17.90	4.45				0.124[a]			
368.77	5.18	1.24	18.70	10.68	2.28			1.37			
420.47	5.91	0.73	19.14	11.94	9.74			2.10	0.974[b]		
482.97	6.79	0.88				3.25				0.043[c]	
513.92	7.22	0.43	20.00	14.13	12.75	7.96		3.41	2.29	0.478[c]	
557.45	7.83	0.61	20.49	15.00	14.18	10.50	4.90	4.02	2.90	1.09	0.11[d]
639.40	8.99	1.14	21.28	16.46	15.85	13.53	11.65	5.17	4.05	2.24	1.22
696.91	9.79	0.80	21.90	17.54	16.92	15.28	13.78	5.98	4.86	3.05	2.03
744.15	10.46	0.67	22.55	18.53	18.16	16.67	15.55	6.65	5.52	3.71	2.69
798.13	11.22	0.76	23.33	19.81	19.59	18.16	17.45	7.40	6.28	4.47	3.45
842.67	11.84	0.62	23.97	20.85	20.70	19.48	18.75	8.03	6.91	5.10	4.08
902.04	12.68	0.84	25.04	22.55	22.47	21.66	21.17	8.86	7.74	5.93	4.91
931.01	13.08	0.40	25.80	23.70	23.75	22.95	22.70	9.27	8.15	6.34	5.32
960.47	13.50	0.42	26.84	25.26	25.37	24.76	24.69	9.69	8.56	6.75	5.73
974.91	13.70	0.20	27.41	26.22	26.42	25.75	25.80	9.89	8.77	6.96	5.94
982.54	13.81	0.11	27.80	26.80	27.05	26.50	26.54	10.00	8.87	7.06	6.04
985.99	13.85	0.04	28.25	27.60	27.85	27.45	27.50	10.04	8.92	7.11	6.09
989.24	13.90	0.05	Fully withdrawn	Fully withdrawn	Fully withdrawn	Fully withdrawn	Fully withdrawn	10.09	8.97	7.16	6.14

[a]Measured by use of No. 6 rod.
[b]Measured by use of No. 5 rod.
[c]Measured by use of No. 4 rod.
[d]Measured by use of No. 3 rod.

Table 5. Core and Rod Calibrations for First Operating Core with Experiments in Place

The absorption cross section of the clean core was calculated to be 7331.0 cm^2 for thermal neutrons

Poison in the Core (cm^2 of Absorber)	Worth of Poison (% $\Delta k/k$)	Change in Reactivity (% $\Delta k/k$)	Group Rod Position (Inches Out)	Rod Position at Criticality with the Others Fully Withdrawn (Inches Out)				% $\Delta k/k$ Added to the Core by Withdrawing the Rod to the Given Position			
				No. 3	No. 4	No. 5	No. 6	No. 3	No. 4	No. 5	No. 6
0	0	0	19.21	11.69	11.74			2.65[a]	2.65[b]		
52.06	0.710	0.71	19.82	13.11	13.26			3.36	3.36		
85.61	1.17	0.46	20.11			5.73				0.09[c]	
109.26	1.49	0.32	20.34	14.32	14.31	8.74		4.14	4.14	0.47	
140.70	1.92	0.43	20.69				4.90				0.08[d]
158.58	2.16	0.24	20.81	15.24	15.37	11.30	7.54	4.81	4.81	1.14	0.28[d]
269.60	3.68	1.52	22.01	17.42	17.66	14.89	13.62	6.33	6.33	2.66	1.79
369.63	5.04	1.36	23.39	19.71	19.95	18.01	17.28	7.69	7.69	4.02	3.16
480.11	6.55	1.51	25.46	23.12	23.32	22.13	21.73	9.20	9.20	5.53	4.67
533.15	7.27	0.72	26.84	25.33	25.54	24.75	24.55	9.92	9.92	6.25	5.39
554.66	7.57	0.30	28.00	27.10	27.28	26.66	26.61	10.22	10.22	6.55	5.68
558.70	7.62	0.055	28.70	28.10	28.10	27.70	27.66	10.27	10.27	6.60	5.74
565.89	7.72	0.098	Fully withdrawn	Fully withdrawn	Fully withdrawn	Fully withdrawn	Fully withdrawn	10.37	10.37	6.70	5.84

[a]Measured by use of No. 4 rod.
[b]Measured by use of No. 6 rod.
[c]Measured by use of No. 4 rod.
[d]Measured by use of No. 3 rod.

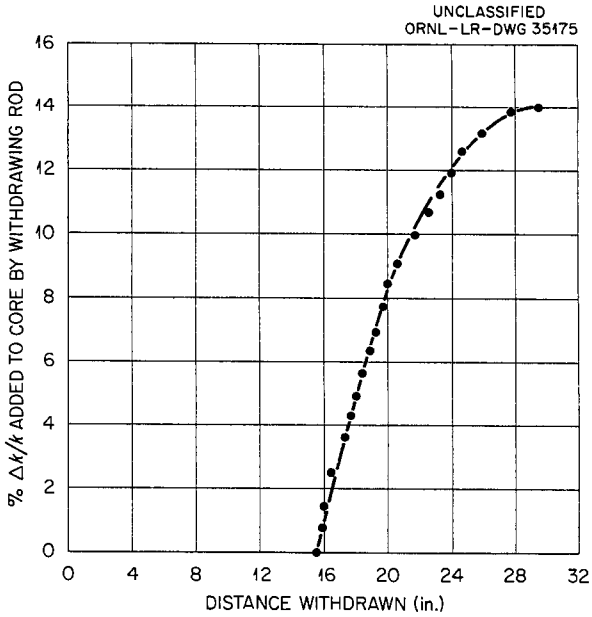


Fig. 12. Gang Rod Calibration for 4 × 7 Test Core. Core worth, 13.94% $\Delta k/k$; central slope, (1.73% $\Delta k/k$)/in.

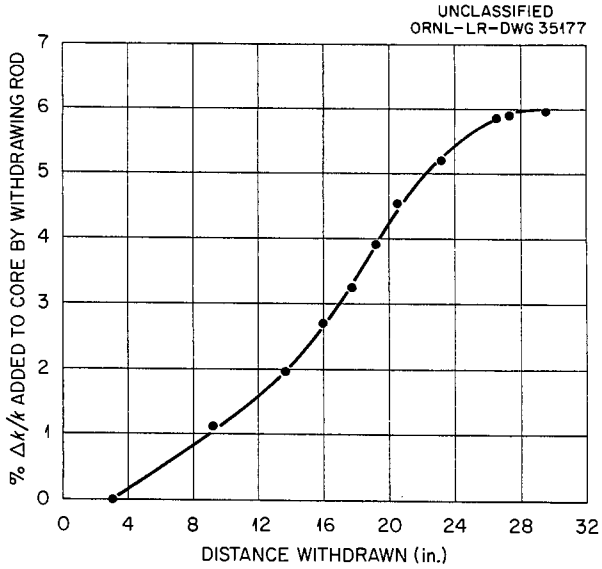


Fig. 14. Number 6 Rod Calibration for 4 × 7 Test Core. Total worth, 5.95% $\Delta k/k$; central slope, (0.346% $\Delta k/k$)/in.

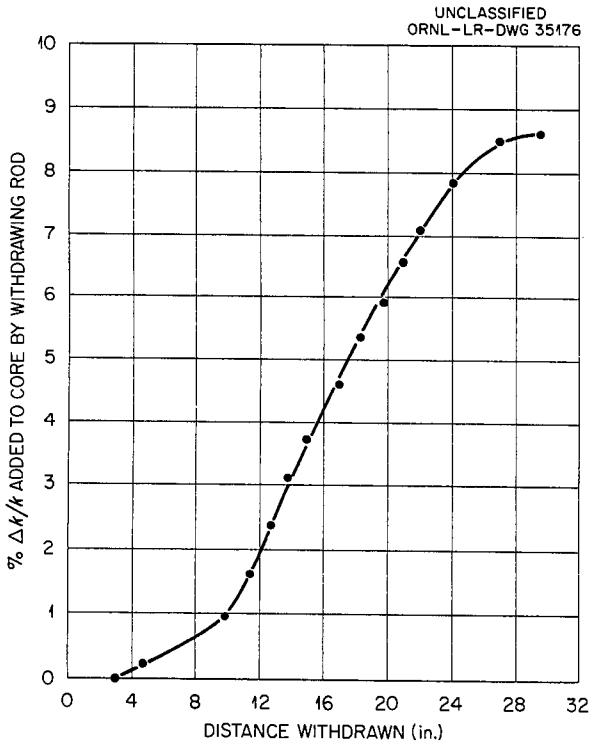


Fig. 13. Number 4 Rod Calibration for 4 × 7 Test Core. Total worth, 8.59% $\Delta k/k$; central slope, (0.5% $\Delta k/k$)/in.

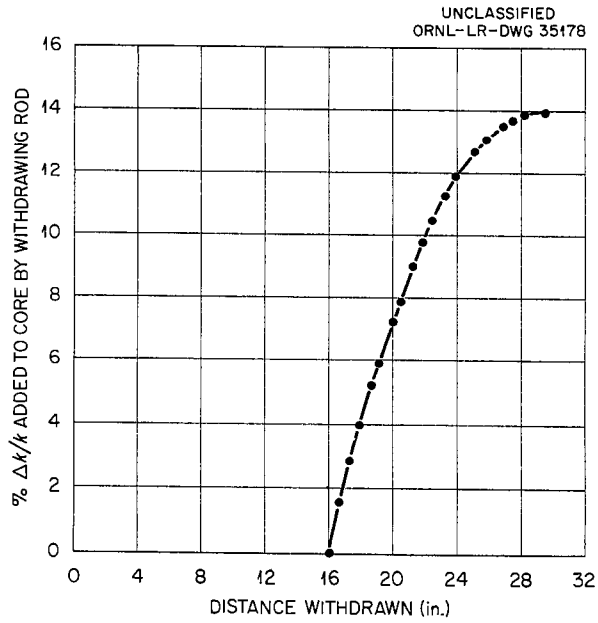


Fig. 15. Gang Rod Calibration for Clean Operating Core. Core worth, 13.90% $\Delta k/k$; central slope, (1.57% $\Delta k/k$)/in.

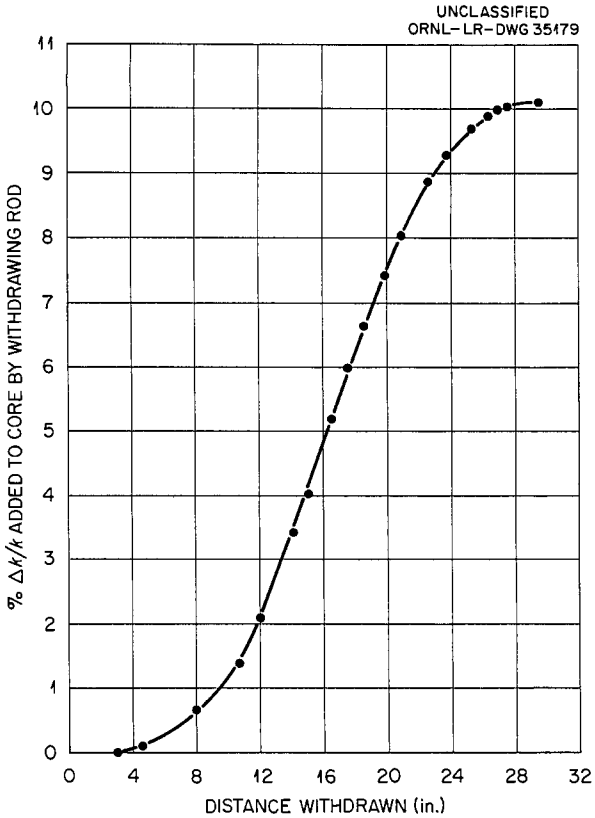


Fig. 16. Number 3 Rod Calibration for Clean Operating Core. Total worth, 10.09% $\Delta k/k$; central slope, (0.675% $\Delta k/k$)/in.

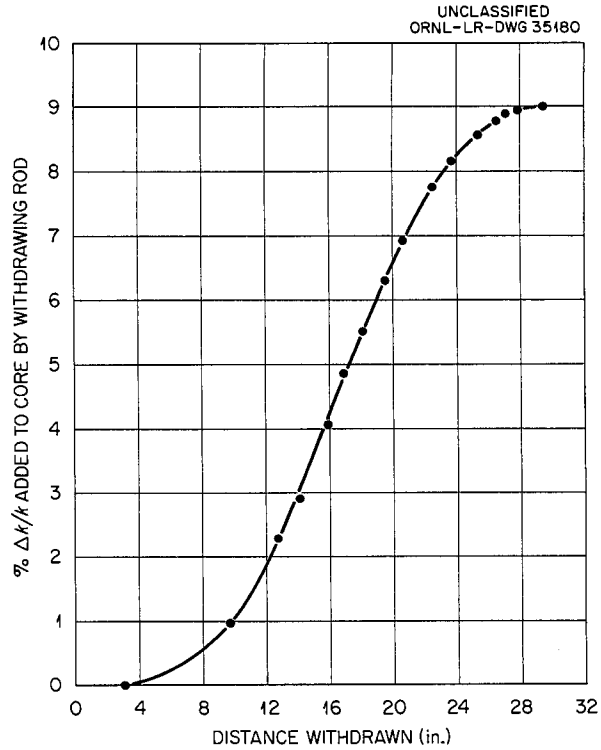


Fig. 17. Number 4 Rod Calibration for Clean Operating Core. Total worth, 8.97% $\Delta k/k$; central slope, (0.60% $\Delta k/k$)/in.

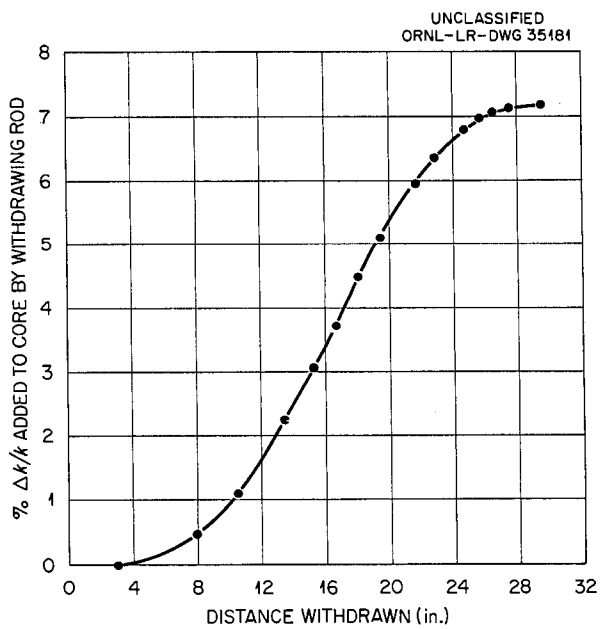


Fig. 18. Number 5 Rod Calibration for Clean Operating Core. Total worth, 7.16% $\Delta k/k$; central slope, (0.47% $\Delta k/k$)/in.

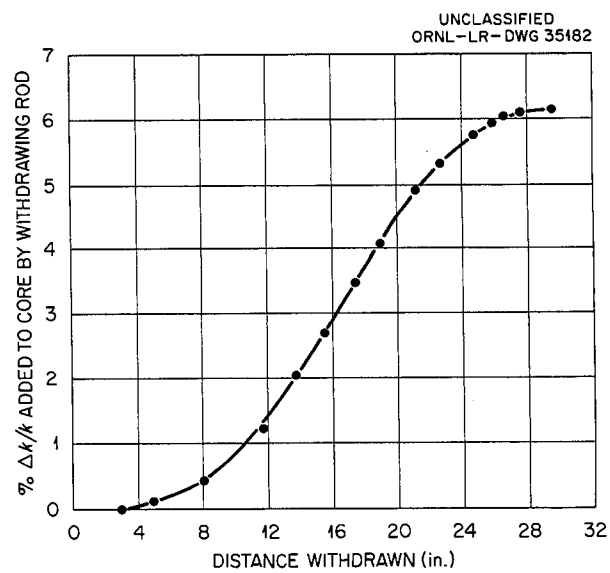


Fig. 19. Number 6 Rod Calibration for Clean Operating Core. Total worth, 6.14% $\Delta k/k$; central slope, (0.39% $\Delta k/k$)/in.

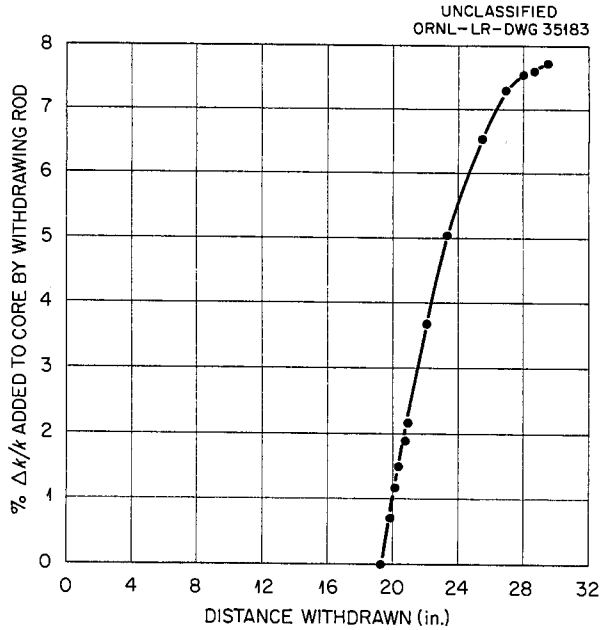


Fig. 20. Gang Rod Calibration for Operating Core with Experiments. Core worth, 7.72% $\Delta k/k$; central slope, (1.30% $\Delta k/k$)/in.

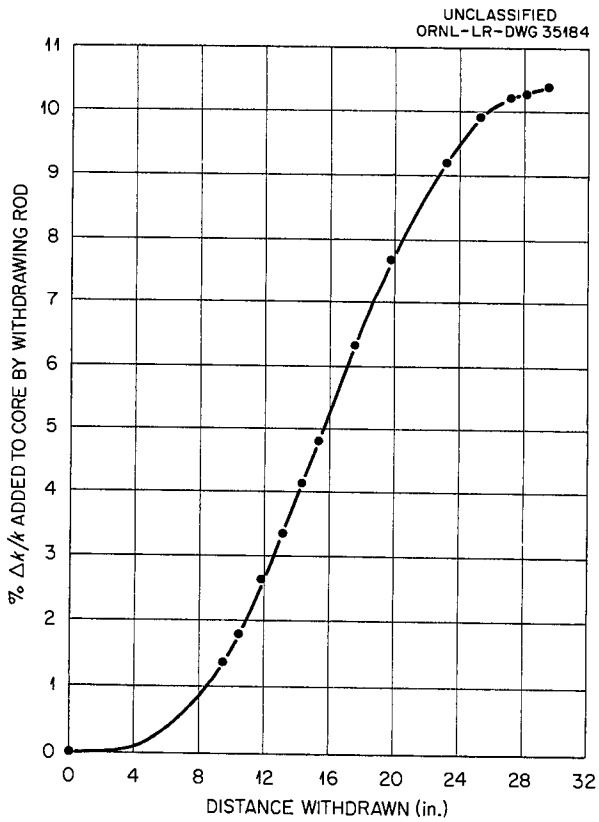


Fig. 21. Number 3 Rod Calibration for Operating Core with Experiments. Total worth, 10.35% $\Delta k/k$; central slope, (0.64% $\Delta k/k$)/in.

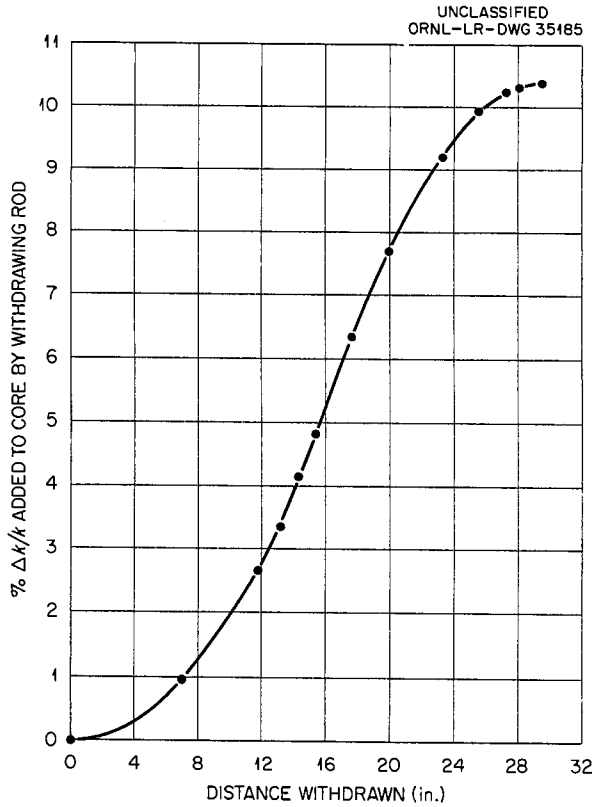


Fig. 22. Number 4 Rod Calibration for Operating Core with Experiments. Total worth, 10.37% $\Delta k/k$; central slope, (0.63% $\Delta k/k$)/in.

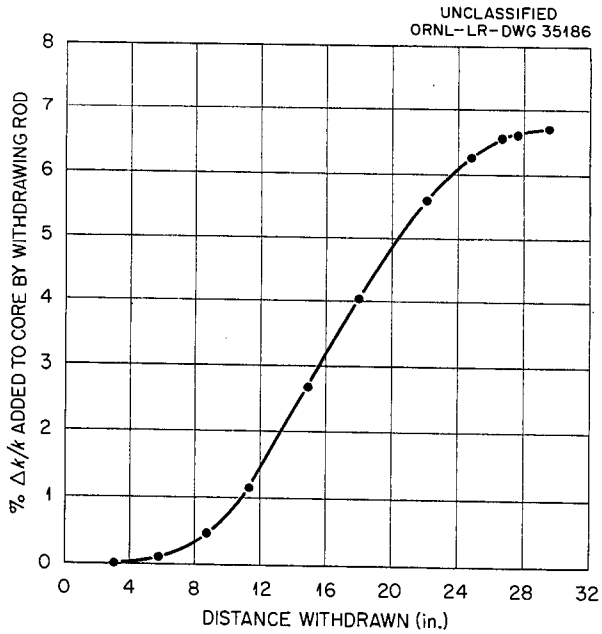


Fig. 23. Number 5 Rod Calibration for Operating Core with Experiments. Total worth, 6.70% $\Delta k/k$; central slope, (0.43% $\Delta k/k$)/in.

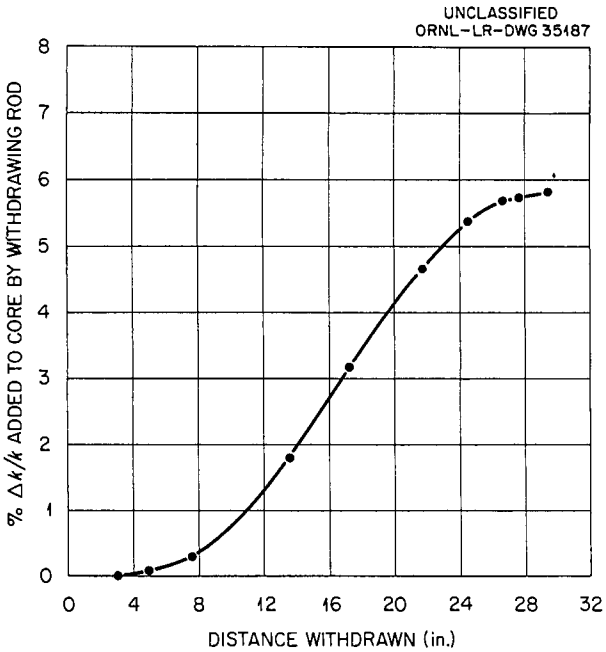


Fig. 24. Number 6 Rod Calibration for Operating Core with Experiments. Total worth, 5.84% $\Delta k/k$; central slope, (0.35% $\Delta k/k$)/in.

temperature are given in Fig. 25 for the 4 × 7 core, the first clean operating core, and the first clean operating core with experiments. Since there is little difference in the slopes of the curves, it may be concluded that altering the shape of the core or inserting the particular group of mocked-up experiments had little or no effect upon the temperature coefficient.

MEASUREMENT OF THE REACTIVITY WORTH OF VOIDS NEAR THE REACTOR CORE

The beam holes and the large north and south facilities may be operated as voids or filled with water (Fig. 26). Also, an air-filled pressurized tank will be fitted into the recess in the reactor tank on the pool side of the core to provide a path for neutrons to reach the easily accesible regions on the pool side. When any of these voids become filled with water, the net neutron leakage from the core is reduced and an increase in reactivity occurs.

The reactivity measurements of these effects were made in reverse because that was considered the safest procedure; that is, the negative reactivity change caused by emptying water from the various regions was measured. The results obtained with the 4 × 7 core and the clean, first operating core are given in Tables 6 and 7.

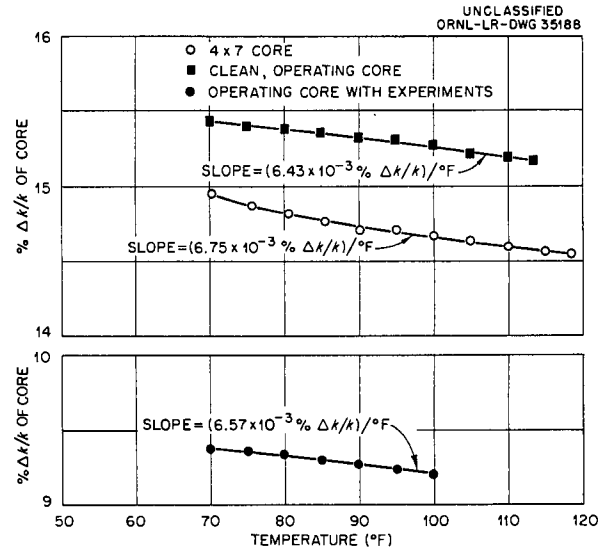


Fig. 25. Temperature Coefficients.

Table 6. Summary of Void Worths with 4 × 7 Core

Condition	% $\Delta k/k$
HB-1 drained	−0.035
HB-1 and HB-2 drained	−0.049
HB-1, HB-2, and HB-3 drained	−0.074
HB-2 and HB-3 drained	−0.054
HB-3 drained	−0.047
HB-1, HB-2, HB-3, HB-5, and HB-6 drained	−0.127
HB-2 drained	−0.017
HN drained	−0.470

Table 7. Summary of Void Worths with Clean Operating Core

Condition	% $\Delta k/k$
HB-1 drained	−0.038
HB-1 and HB-2 drained	−0.042
HB-1, HB-2, and HB-3 drained	−0.113
HB-2 and HB-3 drained	−0.080
HB-3 drained	−0.065
HB-1, HB-2, HB-3, HB-5, and HB-6 drained	−0.201
HN drained	−0.863
Pool-side void inserted	−0.97

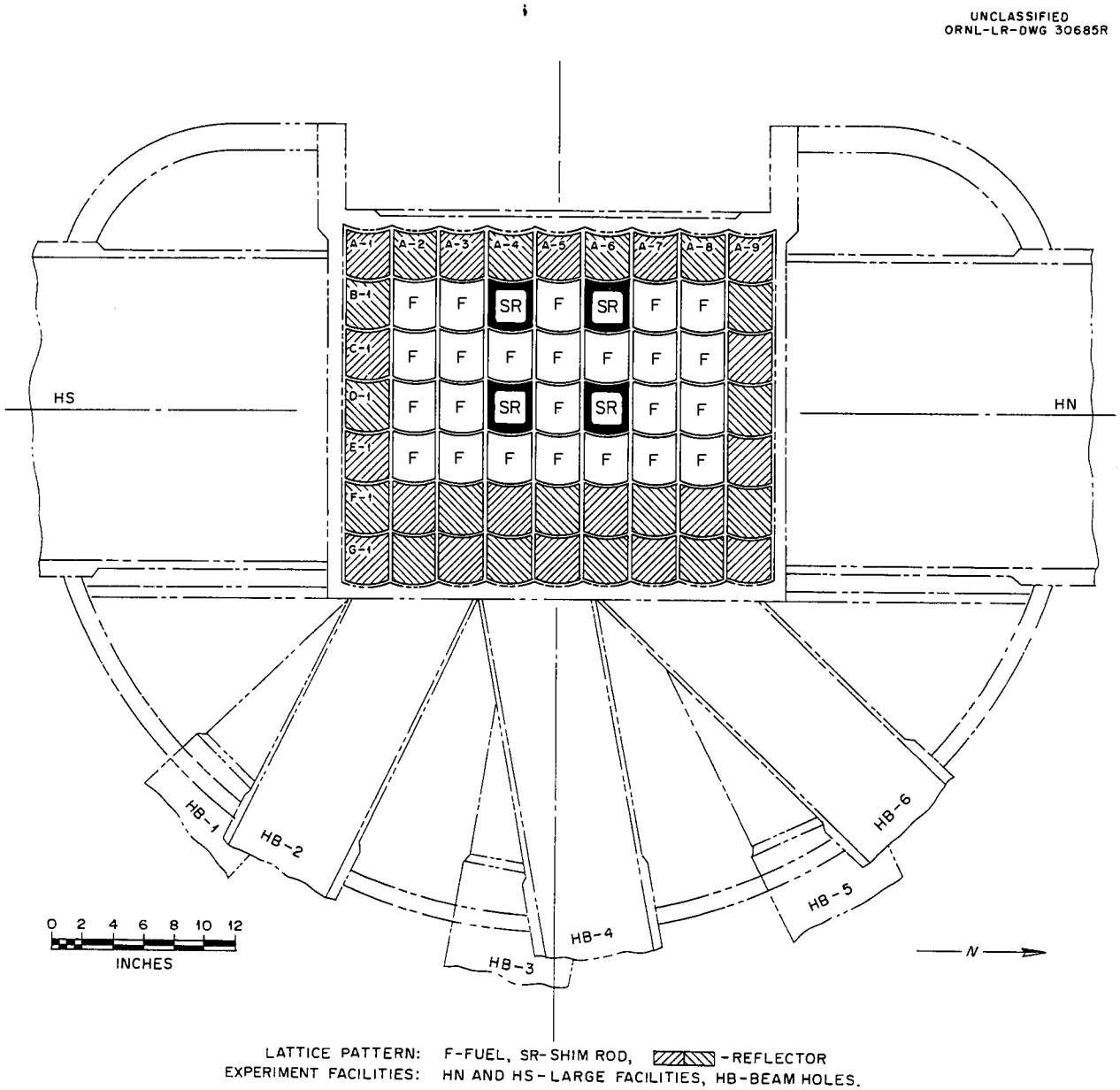


Fig. 26. ORNL Research Reactor; Horizontal Section Through Reactor Center Line; Design Reference Core 4 × 7.

Assuming that the effect of draining HS is the same as that for HN and that draining HB-4 is the same as that for HB-3, the total effect of draining all holes would be $-1.114\%\ \Delta k/k$.

Assuming that the effect of draining HS is the same as that for HN and that draining HB-4 is the same as that for HB-3, the total effect of draining all holes is $-1.99\%\ \Delta k/k$ not including the pool-side facility. With the pool-side void included, the total is $-2.96\%\ \Delta k/k$.

THE REACTIVITY EFFECTS OF INSTALLING EXPERIMENTS AND RADIOISOTOPE PRODUCTION FACILITIES

In order to know the reactivity changes that would be caused by replacing beryllium reflector pieces with experiment and radioisotope production facilities, the groups which would be using the reactor were requested to furnish either actual or mocked-up facilities for measurements during the

initial tests. This was desirable in order to determine whether the chosen operating core configuration needed to be revised. Some revision was necessary and is discussed in the section entitled "Revision of the Operating Core Configuration."

No detailed description of the various experiments is included in this report. They are, however, identified either by project name or by the name of the person in charge of the experiment. They may be considered as typical experiments for this type of reactor. The measurements are listed in Table 8.

REVISION OF THE OPERATING CORE CONFIGURATION

After the rod calibrations had been completed for the first clean operating core and the first operating core with experiments, it became obvious that the effectiveness of the No. 6 safety should be improved. Also, the experiment facility in

Table 8. Summary of Reactivity Values of Experiment Insertions and Related Measurements

Core Position	Change	Reactivity Change (% $\Delta k/k$)
A-1 and A-2	Beryllium replaced by APPR (Army Package Power Reactor) experiment facility	−0.72
A-1 and A-2	GCRE (Gas-Cooled Reactor Experiment) facility flooded with water	+0.024
A-1 and A-2	Fuel test inserted into A-1 (dry)	+0.12
A-1 and A-2	Fuel test inserted into A-2 (dry)	+0.24
A-9	Beryllium insert replaced by J. McBride's experiment	−<0.05
B-1	Beryllium replaced by hollow, water-filled aluminum adapter	−0.38
B-1	Hollow, air-filled tube inserted into adapter	−0.27
B-1	Air-filled tube flooded with water	+0.11
B-3	Beryllium replaced by radioisotope production facility (later moved to position A-7)	−1.67
A-7	Beryllium replaced by radioisotope production facility	−0.96
B-9	Beryllium insert replaced by G. Morgan's experiment facility	−0.09
C-1	Beryllium insert replaced by G. Morgan's experiment facility	−0.35
C-2	Beryllium replaced by M. Wittel's half fuel element (later moved to C-3)	+1.31
B-3, C-2, and C-3	M. Wittel's half fuel element moved from C-2 to C-3; fuel from C-3 moved to B-3; beryllium from B-3 moved to C-2	+1.57
C-8	Beryllium replaced by R. Berggren's experiment	−2.26
F-1	Beryllium replaced by J. Zukas's experiment	−0.66
F-3	Beryllium insert replaced by radioisotope production facility	−0.68
F-5	Beryllium insert replaced by radioisotope production facility	−0.59
F-7	Beryllium insert replaced by radioisotope production facility	−0.35
F-9*	Beryllium replaced by W. Browning's experiment	
Pool side	Void chamber installed	−0.98
Pool side	Void chamber filled with water	+0.98

*The experiment mockup would not fit into the core.

position C-2 was a partial fuel element, which further distorted the core from a symmetrical arrangement. The following changes were made with the accompanying changes in reactivity:

Change	Reactivity Change (% $\Delta k/k$)
Radioisotope tray in B-3 moved to A-7; beryllium put into B-3	+0.71
Fuel in C-3 moved to B-3 and partial fuel moved from C-2 to C-3; beryllium put into C-2	+0.26
Total change in reactivity	+0.97

NEUTRON FLUX MEASUREMENTS

Absolute Flux Measurements

A minimum number of absolute flux measurements were made during the low-power runs. Some measurements were made with gold foils to determine the approximate power level of both the first critical core and the full-size cores vs instrument readings, since it was undesirable then to raise the power level sufficiently to obtain a heat-output measurement. In these cases the gold foils were irradiated at the center of the core (Fig. 27), and the power level was determined from the calculated maximum-to-average flux ratios (ref *1*).

Absolute flux measurements were also made in certain experiment facilities. These had to be accompanied by some absolute flux measurements in the core in order to establish the correct power level after the true average flux was determined by a complete mapping of the core. This is discussed under "Relative Flux Measurements," which follows. With the exception of gold foil measurements, the absolute fluxes were determined from foil data by the Activation Analysis Department of the Analytical Chemistry Division. The gold foil measurements were made by Operations Division personnel with aid from the Neutron Physics Division.

Relative Flux Measurements

In a reactor such as the ORR, which is cooled by forced convection in such a way that an accurate measurement of the power level can be determined by the heat output, the neutron flux at any place can be determined from a relation of the flux at that point to either the average or the maximum flux in the core. In the ORR this was done by the following procedure:

1. A sheathed 10-mil copper wire the length of the fuel section was inserted into each fuel element (Fig. 28). Wires were also inserted into such beryllium reflector pieces, vertical experiment facilities, and horizontal beam holes as desired. The wires were irradiated for 1 hr at an estimated central thermal neutron flux of 10^{11} neutrons·cm^{-2}·sec^{-1}.
2. A plot of the radioactivity, in arbitrary units, along the length of each wire was obtained by use of the wire scanner at the BSF (Bulk Shielding Facility) reactor.
3. Readings of the radioactivity at 1-in. increments were tabulated, corrected for decay, and expressed relative to the maximum value in the core region.
4. The average relative thermal neutron flux per vertical 1-in. increment of fuel in each element was determined. This involved the assumption that the flux does not vary appreciably over the cross-sectional area of a fuel element. The average relative neutron flux for the core was

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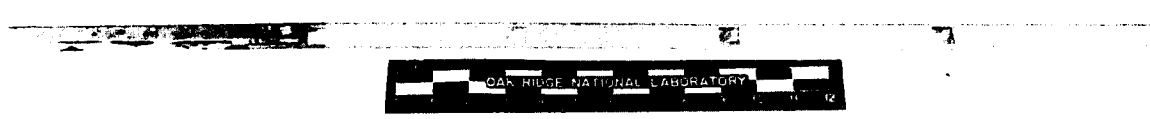

Fig. 27. Holder for Flat Foils.

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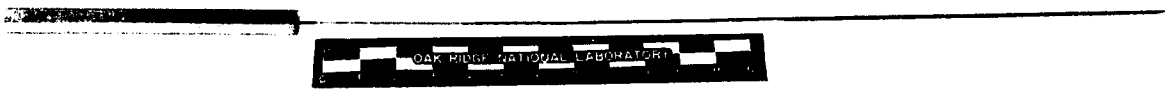

Fig. 28. Wire Holder.

considered to be the average of the fluxes in all the 1-in. increments. The maximum-to-average ratio is the reciprocal of the average relative flux.

Measurements made at the BSF in a single fuel element yielded the following relation (4):

$$\text{Power in watts} = \text{grams of } U^{235} \times \bar{\phi} \times 4.264 \times 10^{-11} ,$$

or

$$\bar{\phi} = \frac{\text{power in watts}}{\text{grams of } U^{235} \times 4.264 \times 10^{-11}} .$$

This indicates that, if 3.1×10^{10} fissions/sec produces 1 w of power, the microscopic fission cross section for U^{235} in this type of reactor is 5.15×10^{-22} cm^2. This is in good agreement with the quoted cross section for thermal neutrons. The average neutron flux in the reactor core can thus be calculated at any time if the fuel content and power level are known. Fluxes in the other regions can then be calculated from the average flux.

Summaries of the measurements made are given in Tables 9, 10, and 11. Detailed tabulations of the traverses made with the copper wires are given in Tables 12, 13, and 14.

To aid in determining the effects of experiments placed between the core and the beam holes, vertical flux traverses made in the beryllium reflector adjacent to the inner ends of the beam holes have been plotted with and without the experiments in place. Also, traverses within the beam holes have been plotted for the same cases. These are shown in Figs. 29–39, where the flux is expressed relative to the average flux in the core ($\phi/\bar{\phi}$).

The neutron flux was very much depressed in the upper portion of the core because of the rod positions. This distortion will tend to become less pronounced as burnup proceeds during an operating cycle and the rods are withdrawn more. The distortion will not, however, completely disappear even if burnout progresses sufficiently for the rods to be almost fully withdrawn, because the fuel distribution will have become distorted, being of a higher concentration at the top. Thus, the distorted spatial flux distribution will be prolonged.

Because of the low fuel concentration in some of the elements used during the startup tests, the neutron flux was considerably peaked in those elements. In later loadings, which will have a more uniform fuel distribution, the irregularities shown in the horizontal traverses will be somewhat evened out. The distortion caused by the rods, however, cannot be easily remedied. Horizontal and vertical flux traverses are shown in Figs. 40 and 41.

Epithermal Fluxes

Detailed spectrum determinations in the core and experiment facilities were not attempted because of the urgency of completing the checkout of the reactor at high power levels. Cadmium ratios were, however, determined for manganese, cobalt, and copper in certain regions. These are listed in Table 15.

Table 9. Summary of Thermal Neutron Flux Measurements in the 4 × 7 Core Relative to the Highest Flux in the Core

Average flux relative to maximum in normal core, 0.403
Maximum-to-average ratio, 2.48
Maximum flux at 20 Mw, 3.44×10^{14} neutrons•cm^{-2}•sec^{-1}
Average flux at 20 Mw, 1.39×10^{14} neutrons•cm^{-2}•sec^{-1}

Core Position	Average for Position	Maximum for Position	Core Position	Average for Position	Maximum for Position
B-2	0.24	0.37	D-2	0.37	0.53
B-3	0.29	0.46	D-3	0.54	0.84
B-4	0.44	0.91	D-4	0.49	1.04
B-5	0.30	0.53	D-5	0.55	1.00
B-6	0.36	0.71	D-6	0.48	1.03
B-7	0.32	0.54	D-7	0.51	0.87
B-8	0.26	0.38	D-8	0.37	0.55
C-2	0.33*	0.51*	E-2	0.35	0.52
C-3	0.50	0.77	E-3	0.40	0.60
C-4	0.39	0.64	E-4	0.50	0.82
C-5	0.47	0.81	E-5	0.41	0.64
C-6	0.39	0.69	E-6	0.51	0.83
C-7	0.47	0.74	E-7	0.40	0.63
C-8	0.34	0.51	E-8	0.33	0.49

*Obtained by interpolation.

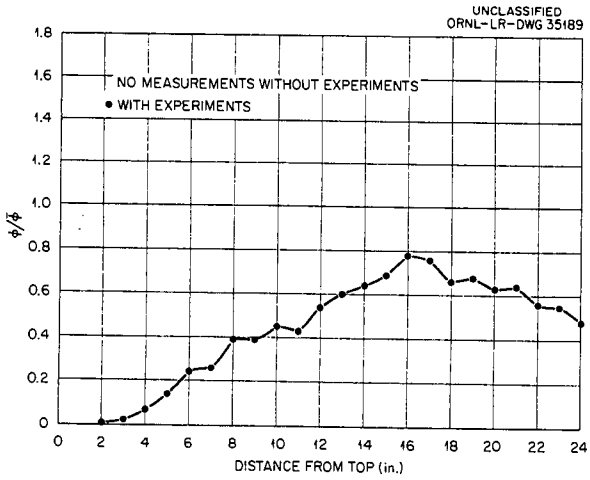

Fig. 29. Thermal Neutron Flux Traverse, Position G-1.

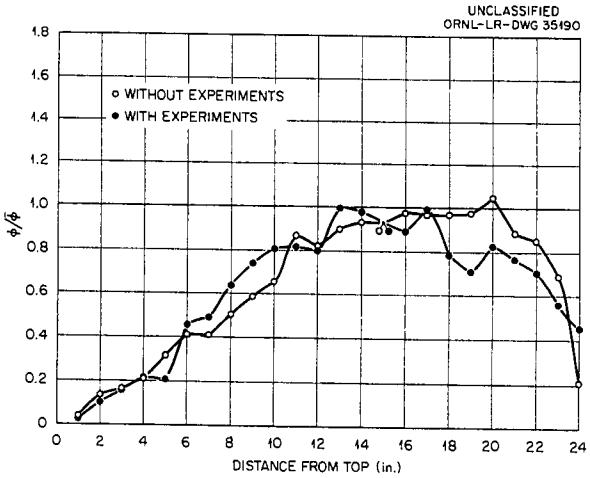

Fig. 30. Thermal Neutron Flux Traverse, Position G-2.

Table 10. Summary of Thermal Neutron Flux Measurements in the Clean Revised Operating Core Relative to the Highest Flux in the Core

Average flux relative to maximum in normal core, 0.39

Maximum-to-average ratio, 2.56

Maximum flux at 20 Mw (calculated), 3.38×10^{14} neutrons•cm^{-2}•sec^{-1}

Average flux at 20 Mw (calculated), 1.32×10^{14} neutrons•cm^{-2}•sec^{-1}

Core Position	Average for Position	Maximum for Position	Core Position	Average for Position	Maximum for Position
A-4	0.19	0.35	D-1	0.23	0.36
A-5	0.18	0.32	D-2	0.36	0.53
A-6	0.23	0.45	D-3	0.58	0.89
B-3	0.37	0.65	D-4	0.52*	
B-4	0.30*		D-5	0.55	1.00
B-5	0.28	0.51	D-6	0.52*	
B-6	0.29*		D-7	0.53	0.81
B-7	0.28	0.49	D-8	0.36	0.52
			D-9	0.20*	
C-3	0.32	0.52	E-1	0.21	0.33
C-4	0.37	0.68	E-2	0.37	0.53
C-5	0.53	0.93	E-3	0.46	0.71
C-6	0.38	0.65	E-4	0.58	0.95
C-7	0.56	0.89	E-5	0.46	0.73
			E-6	0.58	0.96
			E-7	0.46*	
			E-8	0.35	0.52
			E-9	0.18	0.28

*Obtained by interpolation.

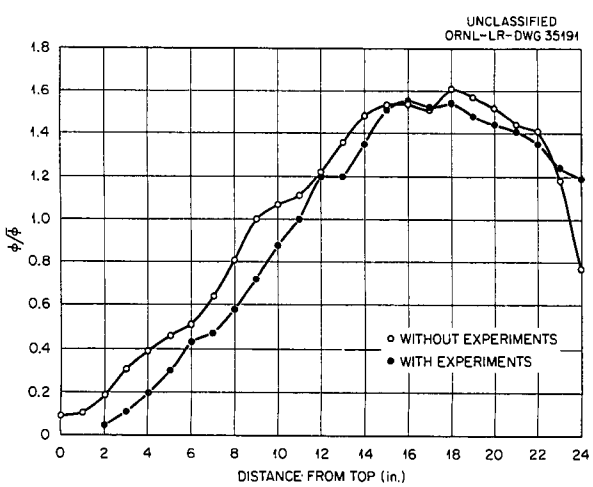

Fig. 31. Thermal Neutron Flux Traverses, Position G-3.

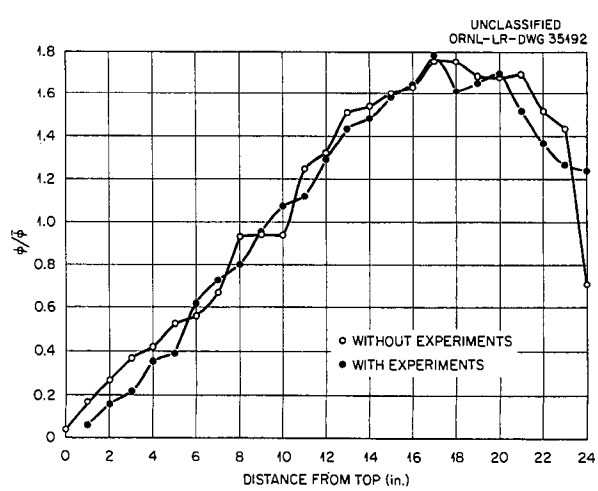

Fig. 32. Thermal Neutron Flux Traverses, Position G-4.

Table 11. Summary of Thermal Neutron Flux Measurements in the Revised Operating Core with Experiments Relative to the Highest Flux in the Core

Average flux relative to maximum in normal core, 0.35

Maximum-to-average ratio, 2.85

Maximum flux at 20 Mw (calculated), 3.67×10^{14} neutrons•cm^{-2}•sec^{-1}

Average flux at 20 Mw (calculated), 1.29×10^{14} neutrons•cm^{-2}•sec^{-1}

Core Position	Average for Position	Maximum for Position	Core Position	Average for Position	Maximum for Position
A-4	0.16	0.27	D-1	0.18	0.27
A-5	0.18	0.30	D-2	0.44	0.68
A-6	0.13	0.22	D-3	0.61	0.93
			D-4	0.54*	
B-3	0.40	0.66	D-5	0.60	1.00
B-4	0.34*		D-6	0.49*	
B-5	0.36	0.56	D-7	0.44	0.68
B-6	0.28*		D-8	0.19	0.30
B-7	0.23	0.37	D-9	0.12	0.18
C-3	0.37	0.54			
C-4	0.43	0.75	E-1	0.16	0.28
C-5	0.61	1.00	E-2	0.29	0.41
C-6	0.39	0.64	E-3	0.44	0.64
C-7	0.30	0.46	E-4	0.53	0.92
			E-5	0.44	0.70
			E-6	0.52	0.82
			E-7	0.32	0.47
			E-8	0.18	0.31
			E-9	0.10	0.18

*Obtained by interpolation.

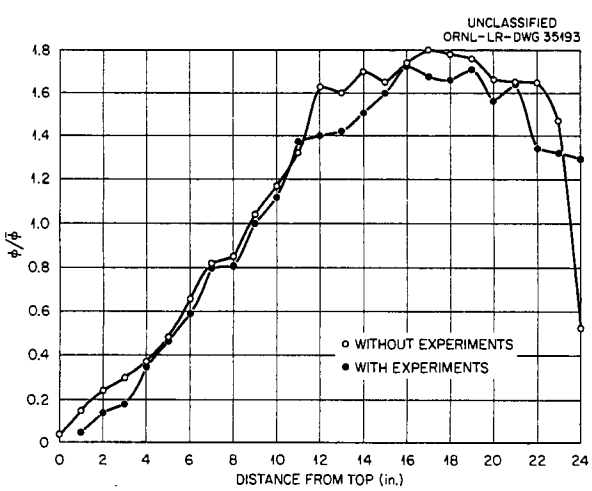

Fig. 33. Thermal Neutron Flux Traverses, Position G-5.

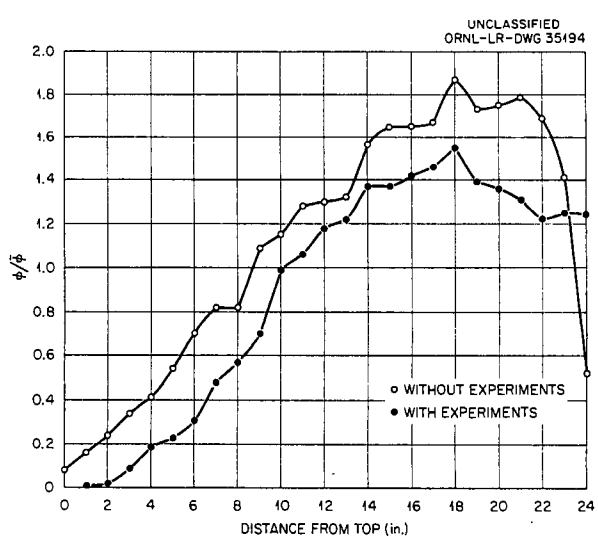

Fig. 34. Thermal Neutron Flux Traverses, Position G-6.

Table 12. Thermal Neutron Flux Measurements, Expressed as ϕ/ϕ_{max}, with 4 × 7 Core

ϕ_{max} in core at 20 Mw = 3.4×10^{14} neutrons·cm^{-2}·sec^{-1}

Distance from Top (in.)	Reflector Position				Core Position		Shim Rod	Core Position	Shim Rod	Core Position		Reflector Position		Core Position						Reflector Position
	A-2	A-5	A-6	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-3	C-4	C-5	C-6	C-7	C-8	C-9
0	0.012	0.012	0.002	0.019	0.11	0.094		0.035		0.092	0.095	0.032	0.063	0.14	0.080	0.073	0.071	0.12	0.14	0.049
1	0.027	0.017	0.013	0.031	0.087	0.072		0.035		0.081	0.088	0.044	0.078	0.13	0.059	0.074	0.064	0.12	0.10	0.073
2	0.037	0.024	0.029	0.058	0.083	0.066		0.041		0.067	0.090	0.064	0.11	0.14	0.068	0.078	0.064	0.13	0.11	0.11
3	0.043	0.032	0.035	0.066	0.087	0.094		0.069		0.088	0.11	0.078	0.12	0.19	0.085	0.11	0.075	0.15	0.14	0.12
4	0.062	0.037	0.060	0.072	0.12	0.10		0.076		0.10	0.13	0.091	0.16	0.22	0.11	0.14	0.089	0.20	0.18	0.15
5	0.067	0.067	0.069	0.11	0.14	0.13		0.10		0.13	0.15	0.13	0.18	0.26	0.15	0.18	0.12	0.24	0.23	0.17
6	0.086	0.075	0.089	0.12	0.17	0.17		0.11		0.15	0.18	0.14	0.20	0.32	0.19	0.22	0.16	0.26	0.25	0.20
7	0.10	0.10	0.10	0.14	0.20	0.19		0.13		0.19	0.21	0.16	0.25	0.36	0.22	0.24	0.19	0.30	0.29	0.24
8	0.11	0.12	0.13	0.17	0.21	0.22		0.14		0.23	0.24	0.20	0.28	0.39	0.24	0.28	0.21	0.34	0.31	0.27
9	0.14	0.14	0.15	0.19	0.24	0.26		0.17		0.23	0.26	0.22	0.32	0.46	0.29	0.34	0.25	0.39	0.36	0.31
10	0.16	0.17	0.17	0.23	0.27	0.29		0.22		0.29	0.29	0.25	0.35	0.51	0.36	0.38	0.28	0.45	0.37	0.33
11	0.18	0.20	0.20	0.24	0.28	0.32		0.27		0.33	0.30	0.27	0.38	0.58	0.43	0.45	0.36	0.51	0.41	0.37
12	0.19	0.24	0.24	0.26	0.31	0.36		0.34		0.37	0.34	0.29	0.42	0.64	0.48	0.54	0.40	0.55	0.43	0.38
13	0.21	0.27	0.29	0.27	0.33	0.38		0.40		0.42	0.36	0.31	0.45	0.68	0.57	0.64	0.48	0.63	0.46	0.42
14	0.22	0.33	0.35	0.30	0.34	0.41	0.85	0.47	0.56	0.48	0.37	0.31	0.48	0.73	0.63	0.71	0.57	0.68	0.48	0.45
15	0.24	0.39	0.41	0.32	0.35	0.44	0.91	0.49	0.71	0.50	0.38	0.34	0.49	0.76	0.64	0.76	0.59	0.70	0.49	0.48
16	0.28	0.44	0.47	0.33	0.37	0.46	0.84	0.51	0.59	0.53	0.38	0.35	0.50	0.77	0.64	0.78	0.65	0.72	0.49	0.51
17	0.27	0.47	0.52	0.35	0.35	0.45	0.52	0.52	0.50	0.54	0.38	0.38	0.51	0.77	0.63	0.81	0.67	0.74	0.51	0.53
18	0.29	0.50	0.53	0.36	0.33	0.46	0.49	0.53	0.51	0.53	0.37	0.34	0.50	0.72	0.62	0.79	0.69	0.71	0.46	0.52
19	0.29	0.51	0.54	0.37	0.30	0.42	0.48	0.50	0.51	0.48	0.34	0.33	0.48	0.69	0.60	0.76	0.67	0.68	0.42	0.49
20	0.28	0.52	0.56	0.33	0.29	0.38	0.52	0.45	0.48	0.43	0.31	0.33	0.47	0.63	0.57	0.72	0.64	0.64	0.38	0.49
21	0.27	0.53	0.55	0.33	0.26	0.36	0.49	0.45	0.44	0.42	0.27	0.32	0.45	0.56	0.51	0.68	0.60	0.57	0.35	0.49
22	0.25	0.53	0.52	0.32	0.23	0.34	0.45	0.41	0.41	0.37	0.25	0.32	0.43	0.51	0.48	0.63	0.58	0.53	0.31	0.47
23	0.24	0.48	0.49	0.29	0.24	0.34	0.42	0.45	0.38	0.41	0.26	0.30	0.39	0.42	0.51	0.66	0.63	0.58	0.32	0.41
24	0.037	0.093	0.046	0.25	0.28	0.39	0.37	0.58	0.30	0.55	0.34	0.051	0.053	0.58	0.64	0.70	0.68	0.64	0.39	0.055
25							0.32		0.25											
26							0.29		0.20											
27							0.19		0.13											
28							0.15		0.080											
29							0.068		0.040											
30							0.034		0.003											
31							0.003		<0.003											
32							<0.003		<0.003											
33							<0.003		<0.003											
34							<0.003		<0.003											
35							<0.003		<0.003											
36							<0.003		<0.003											
37							<0.003		<0.003											

Table 12 (continued)

ϕ_{max} in core at 20 Mw = 3.4×10^{14} neutrons·cm^{-2}·sec^{-1}

Distance from Top (in.)	Reflector Position	Core Position		Shim Rod	Core Position	Shim Rod	Core Position		Reflector Position		Core Position							Reflector Position				
	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8	E-9	F-2	F-5	F-8	G-5
0	0.061	0.14	0.16		0.053		0.086	0.18	0.054	0.038	0.17	0.14	0.13	0.14	0.12	0.12	0.15	0.048	0.058	0.075	0.040	0.039
1	0.081	0.12	0.14		0.057		0.083	0.16	0.067	0.054	0.14	0.13	0.13	0.13	0.11	0.091	0.12	0.061	0.072	0.11	0.061	0.068
2	0.10	0.14	0.17		0.057		0.11	0.14	0.098	0.093	0.14	0.11	0.16	0.10	0.14	0.12	0.12	0.084	0.10	0.15	0.093	0.11
3	0.15	0.18	0.20		0.088		0.13	0.17	0.13	0.12	0.16	0.13	0.18	0.13	0.17	0.13	0.14	0.12	0.14	0.17	0.10	0.12
4	0.18	0.22	0.25		0.13		0.17	0.19	0.16	0.14	0.20	0.17	0.22	0.15	0.21	0.17	0.17	0.13	0.17	0.21	0.12	0.16
5	0.22	0.26	0.28		0.16		0.20	0.23	0.19	0.15	0.23	0.21	0.17	0.18	0.24	0.20	0.22	0.18	0.21	0.28	0.14	0.21
6	0.24	0.29	0.33		0.22		0.24	0.27	0.21	0.21	0.27	0.23	0.30	0.21	0.29	0.24	0.26	0.21	0.23	0.32	0.16	0.25
7	0.26	0.31	0.38		0.23		0.31	0.31	0.26	0.23	0.30	0.28	0.33	0.24	0.31	0.27	0.17	0.23	0.28	0.38	0.20	0.29
8	0.31	0.37	0.44		0.31		0.34	0.32	0.28	0.25	0.34	0.32	0.36	0.27	0.37	0.32	0.31	0.28	0.31	0.44	0.23	0.31
9	0.36	0.38	0.49		0.35		0.38	0.36	0.31	0.30	0.37	0.34	0.41	0.32	0.41	0.34	0.33	0.31	0.35	0.47	0.26	0.36
10	0.41	0.41	0.54		0.41		0.47	0.42	0.37	0.32	0.38	0.39	0.50	0.38	0.47	0.39	0.36	0.39	0.40	0.54	0.29	0.40
11	0.45	0.45	0.60		0.53		0.55	0.42	0.40	0.36	0.43	0.44	0.57	0.42	0.56	0.43	0.40	0.37	0.43	0.61	0.33	0.44
12	0.47	0.50	0.66		0.61		0.66	0.47	0.43	0.41	0.46	0.49	0.64	0.47	0.65	0.50	0.43	0.42	0.47	0.66	0.34	0.47
13	0.51	0.50	0.72		0.79		0.72	0.49	0.45	0.42	0.49	0.52	0.71	0.56	0.73	0.55	0.45	0.43	0.50	0.73	0.37	0.53
14	0.54	0.51	0.75	1.04	0.84	1.00	0.82	0.51	0.49	0.46	0.52	0.55	0.76	0.59	0.78	0.58	0.46	0.46	0.53	0.76	0.41	0.54
15	0.53	0.52	0.82	1.04	0.95	1.03	0.84	0.51	0.52	0.48	0.52	0.60	0.76	0.59	0.81	0.61	0.47	0.46	0.56	0.80	0.43	0.58
16	0.58	0.53	0.82	0.68	0.95	0.69	0.87	0.55	0.51	0.50	0.52	0.60	0.78	0.62	0.82	0.62	0.49	0.48	0.57	0.86	0.43	0.60
17	0.56	0.51	0.84	0.63	0.97	0.67	0.82	0.52	0.51	0.47	0.48	0.60	0.82	0.64	0.83	0.63	0.47	0.46	0.57	0.87	0.44	0.61
18	0.54	0.48	0.81	0.63	1.00	0.66	0.81	0.51	0.54	0.50	0.48	0.58	0.73	0.64	0.77	0.60	0.47	0.45	0.54	0.84	0.45	0.61
19	0.52	0.45	0.77	0.60	0.95	0.65	0.76	0.49	0.53	0.48	0.44	0.59	0.73	0.61	0.74	0.54	0.40	0.42	0.55	0.85	0.46	0.59
20	0.46	0.40	0.69	0.59	0.88	0.59	0.70	0.43	0.50	0.45	0.38	0.58	0.67	0.57	0.68	0.54	0.39	0.42	0.53	0.86	0.43	0.58
21	0.44	0.36	0.63	0.59	0.82	0.56	0.65	0.42	0.49	0.42	0.36	0.54	0.61	0.54	0.60	0.49	0.33	0.41	0.54	0.81	0.42	0.55
22	0.45	0.36	0.58	0.53	0.74	0.52	0.57	0.38	0.49	0.43	0.30	0.49	0.56	0.47	0.59	0.42	0.31	0.40	0.49	0.79	0.39	0.53
23	0.41	0.35	0.61	0.48	0.76	0.42	0.55	0.37	0.42	0.42	0.33	0.49	0.56	0.51	0.60	0.45	0.33	0.37	0.43	0.72	0.36	0.50
24	0.068	0.36	0.62	0.42	0.68	0.38	0.63	0.39	0.12	0.079	0.43	0.59	0.57	0.69	0.68	0.52	0.40	0.095	0.14	0.15	0.085	0.12
25				0.37		0.33																
26				0.30		0.27																
27				0.23		0.18																
28				0.15		0.11																
29				0.10		0.046																
30				0.038		<0.04																
31				<0.03		<0.04																
32				<0.03		<0.04																
33				<0.03		<0.04																
34				<0.03		<0.04																
35				<0.03		<0.04																
36				<0.03		<0.04																
37				<0.03		<0.04																

Table 13. Thermal Neutron Flux Measurements, Expressed as ϕ/ϕ_{max}, in Clean Operating Core

ϕ_{max} at 20 Mw = 3.4×10^{14} neutrons·cm^{-2}·sec^{-1}

Distance from Top (in.)	Core Position																					
	A-4	A-5	A-6	B-3	B-5	B-7	C-3	C-4	C-5	C-6	C-7	D-1	D-2	D-3	D-5	D-7	D-8	E-1	E-2	E-3	E-4	E-5
0	<0.006	0.003	<0.003	0.048	<0.01	0.039	0.095	0.036	0.049	0.057	0.13	0.054	0.10	0.15	0.062	0.13	0.14	0.056	0.16	0.13	0.17	0.13
1	0.006	0.003	<0.003	0.051	<0.01	0.033	0.079	0.027	0.039	0.037	0.13	0.064	0.071	0.10	0.062	0.16	0.13	0.066	0.12	0.13	0.16	0.096
2	0.013	0.012	0.003	0.061	0.012	0.039	0.052	0.019	0.072	0.044	0.14	0.091	0.13	0.17	0.075	0.17	0.12	0.066	0.10	0.13	0.19	0.11
3	0.019	0.022	0.026	0.077	0.026	0.067	0.059	0.049	0.10	0.066	0.19	0.11	0.14	0.22	0.071	0.22	0.13	0.091	0.13	0.17	0.22	0.12
4	0.032	0.022	0.035	0.12	0.045	0.078	0.10	0.065	0.14	0.087	0.25	0.13	0.18	0.26	0.15	0.26	0.16	0.11	0.17	0.21	0.25	0.18
5	0.063	0.048	0.054	0.13	0.054	0.11	0.12	0.12	0.16	0.12	0.30	0.18	0.26	0.32	0.19	0.31	0.23	0.16	0.21	0.25	0.34	0.23
6	0.076	0.074	0.077	0.18	0.081	0.14	0.17	0.13	0.22	0.14	0.37	0.19	0.26	0.35	0.21	0.35	0.25	0.19	0.28	0.31	0.36	0.29
7	0.069	0.10	0.080	0.23	0.081	0.17	0.18	0.16	0.29	0.17	0.40	0.23	0.32	0.42	0.27	0.44	0.27	0.20	0.31	0.37	0.43	0.33
8	0.12	0.11	0.13	0.28	0.13	0.20	0.23	0.18	0.33	0.21	0.44	0.24	0.36	0.47	0.31	0.46	0.37	0.23	0.36	0.39	0.50	0.37
9	0.15	0.13	0.14	0.31	0.14	0.23	0.24	0.25	0.39	0.27	0.50	0.27	0.41	0.61	0.38	0.54	0.37	0.25	0.38	0.43	0.55	0.40
10	0.17	0.17	0.19	0.38	0.21	0.25	0.30	0.30	0.47	0.31	0.56	0.29	0.45	0.76	0.45	0.59	0.43	0.26	0.38	0.50	0.50	0.44
11	0.21	0.19	0.23	0.42	0.28	0.31	0.36	0.36	0.55	0.32	0.65	0.31	0.46	0.88	0.54	0.62	0.48	0.27	0.42	0.52	0.70	0.50
12	0.26	0.24	0.26	0.47	0.38	0.32	0.39	0.48	0.65	0.44	0.71	0.33	0.50	0.73	0.64	0.65	0.48	0.30	0.49	0.57	0.75	0.56
13	0.29	0.25	0.30	0.52	0.46	0.39	0.43	0.54	0.75	0.52	0.77	0.32	0.53	0.82	0.73	0.72	0.49	0.31	0.49	0.63	0.85	0.64
14	0.29	0.25	0.37	0.57	0.50	0.41	0.47	0.57	0.84	0.63	0.86	0.34	0.50	0.81	0.92	0.77	0.52	0.32	0.48	0.63	0.84	0.71
15	0.31	0.32	0.40	0.63	0.47	0.44	0.49	0.63	0.87	0.62	0.89	0.36	0.52	0.84	1.00	0.81	0.55	0.33	0.48	0.71	0.88	0.71
16	0.33	0.32	0.42	0.61	0.51	0.49	0.51	0.66	0.89	0.63	0.89	0.33	0.53	0.88	0.96	0.80	0.50	0.29	0.49	0.68	0.95	0.72
17	0.35	0.31	0.45	0.60	0.51	0.45	0.52	0.68	0.93	0.63	0.87	0.34	0.50	0.82	0.96	0.79	0.51	0.30	0.53	0.66	0.88	0.73
18	0.29	0.31	0.40	0.65	0.46	0.46	0.49	0.67	0.92	0.64	0.82	0.31	0.46	0.81	0.99	0.81	0.47	0.26	0.51	0.61	0.83	0.69
19	0.28	0.27	0.39	0.59	0.44	0.43	0.50	0.66	0.85	0.65	0.76	0.26	0.41	0.76	0.93	0.73	0.43	0.25	0.48	0.61	0.82	0.61
20	0.26	0.27	0.42	0.55	0.45	0.41	0.47	0.60	0.82	0.59	0.74	0.23	0.40	0.69	0.83	0.64	0.41	0.22	0.48	0.58	0.69	0.57
21	0.24	0.24	0.37	0.47	0.38	0.39	0.39	0.56	0.77	0.57	0.61	0.20	0.35	0.61	0.81	0.56	0.34	0.20	0.42	0.55	0.63	0.50
22	0.23	0.23	0.32	0.45	0.37	0.36	0.39	0.48	0.68	0.49	0.56	0.20	0.31	0.53	0.74	0.55	0.34	0.15	0.41	0.52	0.60	0.49
23	0.29	0.26	0.32	0.39	0.45	0.33	0.42	0.50	0.68	0.59	0.64	0.20	0.38	0.54	0.65	0.59	0.43	0.15	0.44	0.63	0.81	0.53
24	0.27	0.29	0.32	0.37	0.50	0.41	0.58	0.55	0.72	0.71	0.66	0.041	0.35	0.54	0.68	0.35	0.41	0.095	0.48	0.56		0.68

Table 13 (continued)

ϕ_{max} at 20 Mw = 3.4 × 10^{14} neutrons·cm^{-2} sec^{-1}

Distance from Top (in.)	Core Position			Reflector Position															Distance from Inner End (in.)	HB-3	HB-4
	E-6	E-8	E-9	A-2	A-8	C-1	C-2	F-2	F-3	F-5	F-8	G-2	G-3	G-4	G-5	G-6	G-7	G-8			
0	0.13	0.11	0.065	<0.01	<0.01	<0.05	0.19	0.027	0.060	0.057	0.031	<0.01	0.035	0.015	0.015	0.032	0.015	<0.01	0	<0.1	<0.1
1	0.15	0.11	0.047	<0.01	<0.01	0.051	0.066	0.056	0.083	0.076	0.061	0.015	0.042	0.066	0.058	0.063	0.040	0.012	1	<0.1	<0.1
2	0.15	0.13	0.044	<0.01	0.018	0.063	0.093	0.12	0.11	0.12	0.077	0.053	0.074	0.10	0.094	0.095	0.058	0.016	2	0.14	0.17
3	0.22	0.16	0.095	0.011	0.030	0.081	0.13	0.15	0.16	0.17	0.092	0.065	0.12	0.14	0.12	0.13	0.099	0.036	3	0.13	0.15
4	0.24	0.20	0.11	0.026	0.037	0.11	0.14	0.16	0.21	0.21	0.17	0.085	0.15	0.16	0.15	0.16	0.12	0.048	4	0.11	0.14
5	0.30	0.22	0.10	0.044	0.045	0.16	0.20	0.21	0.29	0.28	0.20	0.20	0.18	0.21	0.19	0.21	0.18	0.096	5	0.10	0.12
6	0.35	0.26	0.14	0.048	0.096	0.16	0.23	0.25	0.34	0.34	0.26	0.16	0.20	0.22	0.26	0.27	0.21	0.12	6	0.088	0.11
7	0.41	0.31	0.17	0.084	0.11	0.22	0.28	0.28	0.38	0.39	0.27	0.16	0.25	0.26	0.32	0.32	0.25	0.14	7	0.079	0.098
8	0.47	0.33	0.18	0.11	0.12	0.26	0.32	0.32	0.44	0.45	0.31	0.20	0.32	0.36	0.33	0.32	0.32	0.17	8	0.069	0.084
9	0.49	0.40	0.22	0.18	0.14	0.33	0.32	0.36	0.51	0.48	0.36	0.23	0.39	0.37	0.41	0.43	0.36	0.24	9	0.062	0.072
10	0.55	0.39	0.24	0.14	0.19	0.35	0.41	0.41	0.56	0.55	0.38	0.26	0.42	0.37	0.46	0.45	0.39	0.25	10	0.049	0.064
11	0.63	0.45	0.24	0.15	0.20	0.39	0.47	0.45	0.62	0.63	0.46	0.34	0.44	0.49	0.52	0.50	0.41	0.29	11	0.044	0.055
12	0.76	0.46	0.27	0.19	0.21	0.45	0.55	0.48	0.70	0.73	0.50	0.32	0.48	0.52	0.64	0.51	0.45	0.32	12	0.037	0.045
13	0.79	0.49	0.26	0.23	0.26	0.49	0.58	0.58	0.71	0.76	0.50	0.35	0.53	0.59	0.63	0.52	0.48	0.31	13	0.032	0.036
14	0.91	0.51	0.27	0.24	0.28	0.50	0.62	0.59	0.77	0.88	0.57	0.36	0.58	0.61	0.67	0.62	0.51	0.34	14	0.026	0.029
15	0.96	0.52	0.28	0.23	0.28	0.52	0.67	0.62	0.83	0.71	0.58	0.36	0.60	0.63	0.65	0.65	0.55	0.39	15	0.023	0.026
16	0.95	0.52	0.24	0.30	0.31	0.57	0.73	0.65	0.89	0.93	0.55	0.38	0.60	0.64	0.68	0.65	0.54	0.36	16	0.019	0.019
17	0.93	0.48	0.25	0.31	0.33	0.57	0.75	0.65	0.93	0.96	0.61	0.38	0.59	0.69	0.70	0.65	0.54	0.35	17	0.016	0.016
18	0.87	0.56	0.23	0.35	0.27	0.58	0.73	0.65	0.86	0.98	0.61	0.38	0.63	0.69	0.70	0.73	0.57	0.35	18	0.013	0.012
19	0.84	0.45	0.22	0.34	0.33	0.56	0.76	0.65	0.89	1.01	0.65	0.38	0.62	0.66	0.69	0.68	0.54	0.36	19	0.011	0.010
20	0.79	0.39	0.20	0.35	0.36	0.56	0.71	0.65	0.86	1.02	0.61	0.41	0.60	0.66	0.65	0.69	0.55	0.37	20	0.008	0.006
21	0.73	0.33	0.18	0.31	0.30	0.52	0.73	0.60	0.78	0.98	0.58	0.35	0.57	0.66	0.65	0.70	0.53	0.31	21	0.006	0.005
22	0.65	0.30	0.12	0.30	0.33	0.65	0.69	0.53	0.74	0.86	0.54	0.33	0.55	0.60	0.65	0.66	0.52	0.25	22	0.004	<0.005
23	0.61	0.33	0.13	0.27	0.28	0.63	0.66	0.50	0.72	0.86	0.47	0.27	0.46	0.57	0.58	0.55	0.51	0.22	23	0.003	<0.005
24	0.67	0.30		0.19	0.19	0.30	0.26	0.23	0.23	0.35	0.20	0.085	0.30	0.28	0.20	0.21	0.20	0.084	24	0.002	<0.005

Table 14. Thermal Neutron Flux Measurements, Expressed as ϕ/ϕ_{max}, in Operating Core with Experiments

ϕ_{max} at 20 Mw = 3.2×10^{14} neutrons·cm^{-2}·sec^{-1}

Distance from Top (in.)	Core Position			Reflector Position		Core Position			Reflector Position	Core Position					Reflector Position	Core Position										
	A-4	A-5	A-6	A-8	B-2	B-3	B-5	B-7	C-2	C-3	C-4	C-5	C-6	C-7	C-9	D-1	D-2	D-3	D-5	D-7	D-8	D-9	E-1	E-2	E-3	E-4
0	0.008	0.032	0.008	<0.008	<0.02	0.076	0.031	0.035	0.032	0.13	0.084	0.091	0.062	0.062	<0.002	0.088	0.18	0.14	0.083	0.094	0.084	0.043	0.081	0.13	0.17	0.024
1	0.017	0.017	0.008	<0.008	0.023	0.085	0.027	0.043	0.051	0.12	0.064	0.081	0.051	0.066	0.002	0.067	0.13	0.14	0.089	0.084	0.052	0.032	0.033	0.10	0.13	0.069
2	0.026	0.026	0.008	<0.008	0.046	0.11	0.035	0.039	0.087	0.095	0.074	0.11	0.045	0.072	0.010	0.058	0.16	0.16	0.093	0.11	0.056	0.022	0.059	0.099	0.12	0.14
3	0.028	0.028	0.008	<0.008	0.060	0.12	0.047	0.057	0.12	0.12	0.12	0.15	0.059	0.093	0.021	0.094	0.15	0.23	0.14	0.13	0.058	0.028	0.066	0.13	0.17	0.17
4	0.045	0.055	0.026	0.008	0.075	0.13	0.086	0.067	0.15	0.16	0.13	0.22	0.094	0.13	0.029	0.10	0.20	0.25	0.19	0.20	0.099	0.054	0.094	0.14	0.21	0.15
5	0.074	0.068	0.036	0.019	0.11	0.18	0.12	0.11	0.19	0.21	0.19	0.24	0.14	0.16	0.037	0.13	0.25	0.34	0.26	0.20	0.10	0.076	0.12	0.19	0.25	0.21
6	0.074	0.091	0.074	0.036	0.12	0.23	0.15	0.13	0.21	0.21	0.24	0.32	0.18	0.22	0.052	0.16	0.31	0.41	0.31	0.28	0.14	0.098	0.13	0.22	0.31	0.25
7	0.10	0.10	0.083	0.057	0.14	0.30	0.22	0.16	0.26	0.26	0.29	0.44	0.23	0.22	0.083	0.19	0.35	0.47	0.36	0.33	0.17	0.095	0.15	0.26	0.36	0.31
8	0.14	0.14	0.12	0.076	0.17	0.32	0.33	0.19	0.31	0.32	0.39	0.47	0.29	0.30	0.083	0.23	0.40	0.56	0.52	0.40	0.19	0.11	0.19	0.32	0.40	0.37
9	0.15	0.16	0.12	0.089	0.22	0.37	0.38	0.24	0.35	0.35	0.45	0.59	0.35	0.35	0.10	0.24	0.45	0.69	0.67	0.44	0.21	0.13	0.21	0.33	0.44	0.41
10	0.18	0.19	0.13	0.094	0.27	0.43	0.43	0.25	0.37	0.44	0.56	0.68	0.43	0.37	0.14	0.25	0.46	0.70	0.78	0.47	0.24	0.16	0.21	0.34	0.51	0.46
11	0.21	0.23	0.15	0.12	0.28	0.52	0.48	0.30	0.43	0.47	0.58	0.75	0.50	0.39	0.15	0.24	0.54	0.80	0.85	0.56	0.24	0.15	0.24	0.38	0.56	0.54
12	0.23	0.25	0.19	0.14	0.30	0.53	0.51	0.31	0.48	0.50	0.64	0.84	0.54	0.41	0.19	0.27	0.62	0.83	0.87	0.59	0.28	0.17	0.24	0.40	0.57	0.68
13	0.23	0.26	0.19	0.16	0.34	0.57	0.52	0.33	0.49	0.51	0.72	0.88	0.58	0.43	0.20	0.27	0.60	0.93	0.88	0.65	0.29	0.18	0.28	0.38	0.60	0.72
14	0.25	0.27	0.19	0.19	0.37	0.59	0.54	0.37	0.54	0.53	0.72	0.96	0.64	0.46	0.20	0.24	0.63	0.90	0.92	0.63	0.30	0.18	0.25	0.38	0.61	0.75
15	0.27	0.30	0.22	0.19	0.39	0.63	0.56	0.37	0.58	0.54	0.75	0.97	0.63	0.46	0.22	0.25	0.68	0.88	1.00	0.68	0.30	0.17	0.24	0.40	0.64	0.81
16	0.26	0.29	0.21	0.21	0.41	0.66	0.56	0.34	0.60	0.54	0.69	1.00	0.62	0.44	0.23	0.23	0.67	0.90	0.98	0.65	0.28	0.17	0.22	0.41	0.62	0.88
17	0.24	0.26	0.20	0.22	0.43	0.59	0.55	0.34	0.63	0.53	0.66	0.94	0.63	0.45	0.23	0.22	0.65	0.85	0.95	0.64	0.28	0.17	0.20	0.38	0.62	0.92
18	0.24	0.26	0.18	0.21	0.43	0.59	0.56	0.35	0.64	0.51	0.62	0.92	0.61	0.44	0.25	0.20	0.58	0.85	0.91	0.65	0.27	0.16	0.19	0.35	0.61	0.86
19	0.23	0.24	0.19	0.21	0.41	0.55	0.49	0.31	0.61	0.47	0.56	0.87	0.58	0.39	0.22	0.18	0.60	0.77	0.79	0.58	0.22	0.15	0.14	0.34	0.56	0.87
20	0.21	0.24	0.17	0.21	0.41	0.51	0.43	0.29	0.62	0.43	0.53	0.80	0.51	0.36	0.23	0.18	0.53	0.74	0.74	0.56	0.21	0.13	0.13	0.29	0.55	0.77
21	0.21	0.22	0.16	0.21	0.41	0.45	0.39	0.27	0.57	0.38	0.52	0.74	0.46	0.34	0.21	0.15	0.48	0.67	0.67	0.48	0.20	0.12	0.12	0.28	0.47	0.68
22	0.20	0.20	0.16	0.20	0.39	0.43	0.38	0.24	0.53	0.39	0.41	0.68	0.44	0.27	0.18	0.13	0.44	0.56	0.61	0.44	0.15	0.067	0.098	0.25	0.42	0.73
23	0.18	0.22	0.15	0.17	0.36	0.36	0.49	0.21	0.49	0.47	0.46	0.62	0.48	0.25	0.20	0.14	0.44	0.52	0.57	0.42	0.16	0.067	0.11	0.26	0.46	0.60
24	0.26	0.29	0.16	0.17	0.37	0.41	0.54	0.23	0.47	0.53	0.61	0.70	0.54	0.26	0.17	0.22	0.48	0.40	0.57	0.49	0.22	0.12	0.15	0.34	0.54	0.61

Table 14 (continued)

ϕ_{max} at 20 Mw = 3.2×10^{14} neutrons·cm^{-2}·sec^{-1}

Distance from Top (in.)	Core Position					Reflector Position											Distance from Inner End (in.)	HB-3	HB-4	Distance from Top (in.)	Experiment			
	E-5	E-6	E-7	E-8	E-9	F-4	F-6	G-1	G-2	G-3	G-4	G-5	G-6	G-7	G-8	G-9					B-1	B-9	C-1	F-9
0	0.14	0.11	0.074	0.070	0.034	0.029	0.029	<0.002	<0.01	<0.01	<0.02	<0.018	<0.003	<0.01	<0.01	<0.02	0	<0.1	<0.1	0	0.011	<0.01	0.033	<0.005
1	0.13	0.11	0.067	0.058	0.017	0.066	0.047	<0.002	0.010	<0.01	0.022	0.018	0.003	0.010	<0.01	<0.02	1	<0.1	<0.1	1	0.022	<0.01	0.055	<0.005
2	0.093	0.13	0.053	0.053	0.017	0.091	0.084	0.002	0.035	0.015	0.056	0.048	0.008	0.018	<0.01	<0.02	2	0.15	<0.1	2	0.022	<0.01	0.055	0.005
3	0.11	0.15	0.11	0.068	0.036	0.15	0.12	0.007	0.057	0.038	0.076	0.063	0.031	0.046	0.010	<0.02	3	0.12	0.17	3	0.044	0.016	0.093	0.005
4	0.16	0.22	0.14	0.092	0.066	0.20	0.19	0.025	0.077	0.068	0.13	0.12	0.067	0.066	0.064	<0.02	4	0.11	0.14	4	0.044	0.022	0.10	0.026
5	0.19	0.26	0.17	0.11	0.058	0.27	0.20	0.049	0.072	0.10	0.13	0.16	0.078	0.094	0.062	<0.02	5	0.087	0.12	5	0.071	0.022	0.10	0.032
6	0.27	0.31	0.20	0.12	0.095	0.31	0.24	0.084	0.16	0.15	0.21	0.21	0.11	0.13	0.090	0.021	6	0.081	0.096	6	0.11	0.071	0.22	0.047
7	0.27	0.38	0.26	0.18	0.092	0.36	0.33	0.089	0.17	0.16	0.25	0.28	0.17	0.18	0.095	0.036	7	0.68	0.074	7	0.13	0.10	0.21	0.063
8	0.31	0.43	0.26	0.16	0.11	0.45	0.37	0.13	0.22	0.20	0.28	0.28	0.20	0.20	0.13	0.064	8	0.051	0.072	8	0.14	0.12	0.25	0.076
9	0.39	0.55	0.32	0.21	0.13	0.51	0.43	0.13	0.26	0.25	0.33	0.45	0.24	0.21	0.15	0.059	9	0.043	0.055	9	0.14	0.12	0.28	0.084
10	0.46	0.62	0.41	0.24	0.15	0.59	0.48	0.16	0.28	0.31	0.37	0.39	0.34	0.26	0.16	0.059	10	0.038	0.052	10	0.14	0.14	0.31	0.084
11	0.53	0.65	0.39	0.26	0.13	0.63	0.56	0.15	0.28	0.35	0.41	0.48	0.37	0.30	0.19	0.082	11	0.032	0.039	11	0.14	0.15	0.30	0.084
12	0.60	0.73	0.44	0.27	0.16	0.71	0.60	0.19	0.28	0.42	0.45	0.49	0.41	0.35	0.20	0.11	12	0.031	0.029	12	0.15	0.15	0.34	0.076
13	0.63	0.78	0.43	0.28	0.16	0.74	0.75	0.21	0.35	0.42	0.50	0.49	0.43	0.36	0.24	0.093	13	0.024	0.021	13	0.20	0.18	0.31	0.097
14	0.63	0.79	0.47	0.29	0.18	0.84	0.77	0.22	0.34	0.47	0.51	0.52	0.48	0.40	0.25	0.095	14	0.019	0.019	14	0.18	0.17	0.32	0.076
15	0.68	0.78	0.47	0.31	0.17	0.89	0.76	0.24	0.32	0.53	0.55	0.56	0.48	0.37	0.27	0.11	15	0.013	0.012	15	0.15	0.20	0.32	0.068
16	0.70	0.82	0.45	0.31	0.14	0.92	0.81	0.27	0.31	0.54	0.57	0.60	0.49	0.43	0.30	0.11	16	0.011	0.006	16	0.15	0.21	0.31	0.060
17	0.68	0.77	0.46	0.28	0.16	0.93	0.84	0.26	0.35	0.53	0.62	0.58	0.51	0.40	0.31	0.13	17	0.007	0.006	17	0.14	0.16	0.31	0.058
18	0.64	0.77	0.42	0.26	0.15	0.94	0.87	0.23	0.27	0.54	0.56	0.58	0.54	0.37	0.32	0.11	18	0.007	<0.006	18	0.16	0.15	0.26	0.052
19	0.63	0.71	0.42	0.23	0.11	0.94	0.82	0.24	0.25	0.51	0.57	0.59	0.48	0.39	0.27	0.11	19	<0.007	<0.006	19	0.15	0.15	0.24	0.047
20	0.59	0.66	0.39	0.18	0.11	0.92	0.85	0.22	0.29	0.50	0.59	0.54	0.47	0.38	0.30	0.10	20	<0.007	<0.006	20	0.15	0.076	0.20	0.047
21	0.50	0.63	0.35	0.15	0.080	0.82	0.80	0.22	0.27	0.49	0.53	0.57	0.46	0.38	0.25	0.11	21	<0.007	<0.006	21	0.082	0.060	0.20	0.032
22	0.46	0.55	0.30	0.036	0.058	0.77	0.74	0.19	0.25	0.45	0.48	0.47	0.43	0.29	0.24	0.10	22	<0.007	<0.006	22	0.016	0.055	0.20	0.024
23	0.45	0.45	0.27	0.058	0.070	0.71	0.69	0.19	0.20	0.41	0.44	0.46	0.43	0.25	0.23	0.098	23	<0.007	<0.006	23	<0.01	0.011	0.19	0.021
24	0.55	0.50	0.43	0.18	0.078	0.65	0.63	0.17	0.16	0.41	0.43	0.45	0.43	0.17	0.18	0.069	24	<0.007	<0.006	24	<0.01	0.005	0.038	0.021

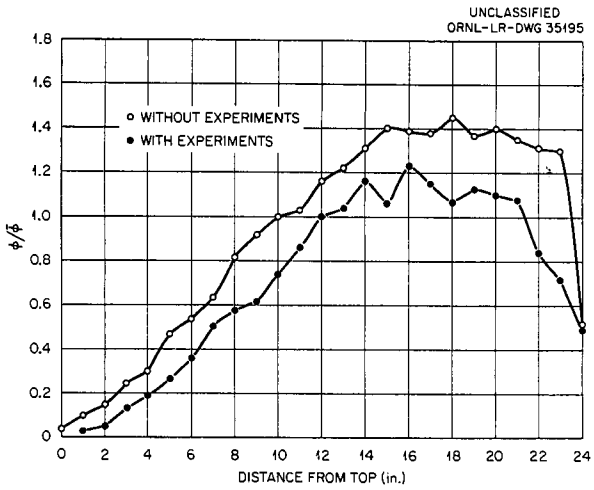

Fig. 35. Thermal Neutron Flux Traverses, Position G-7.

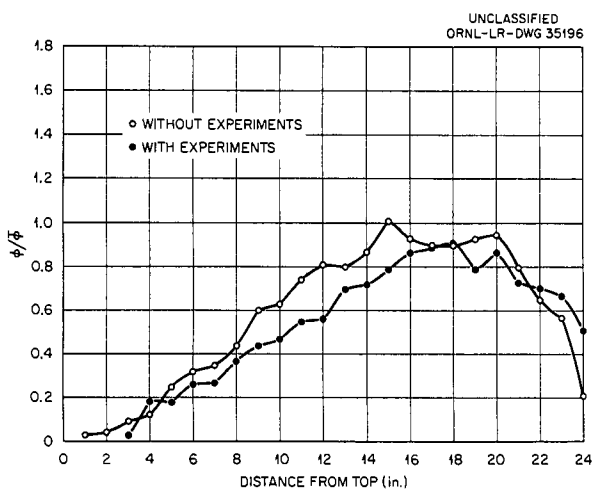

Fig. 36. Thermal Neutron Flux Traverses, Position G-8.

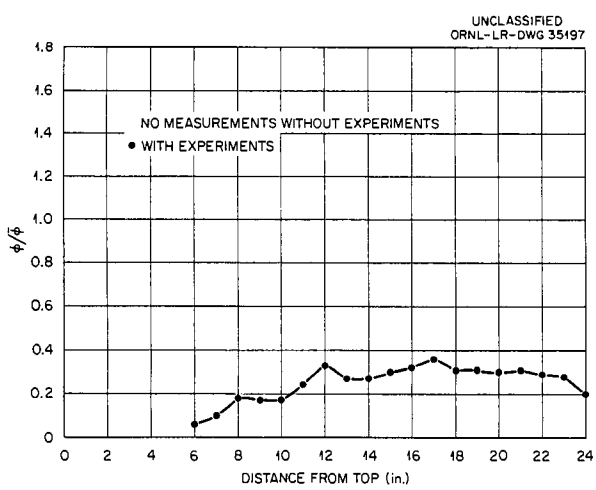

Fig. 37. Thermal Neutron Flux Traverse, Position G-9.

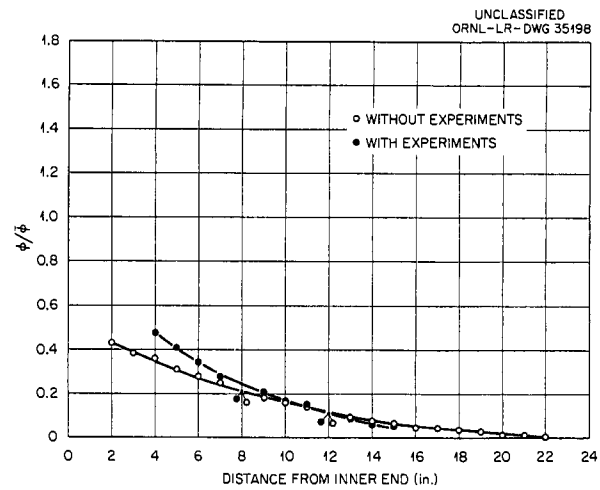

Fig. 38. Thermal Neutron Flux Traverses, Position HB-4.

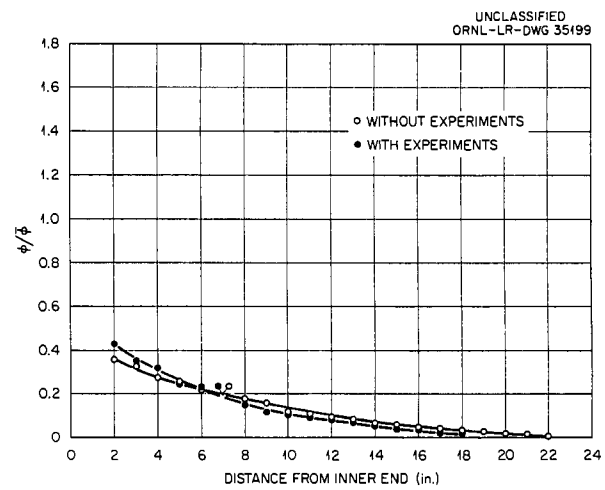

Fig. 39. Thermal Neutron Flux Traverses, Position HB-3.

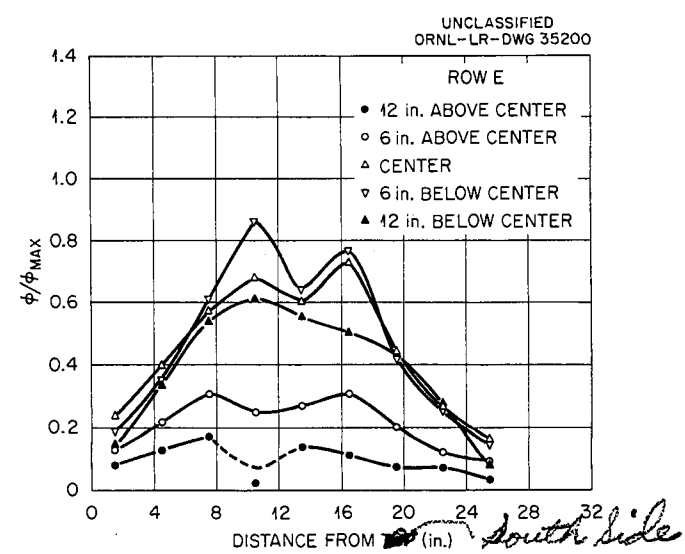

Fig. 40. Horizontal Thermal Neutron Flux Traverses; Operating Core with Experiments.

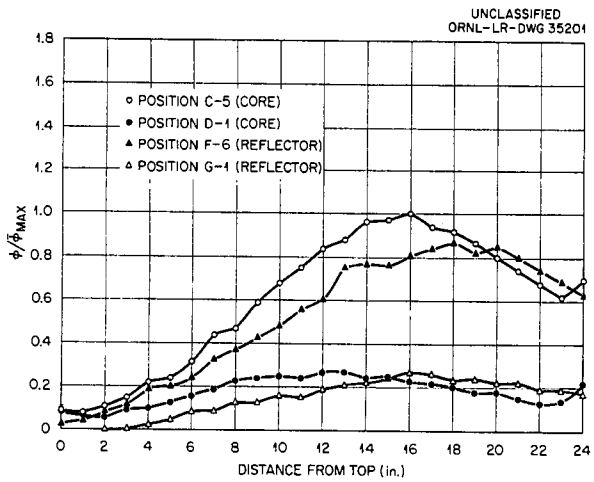

Fig. 41. Vertical Thermal Neutron Flux Traverses; Operating Core with Experiments.

Table 15. Cadmium Ratios in Revised Operating Core with Experiments

Position	Mn	Co	Cu
A-5			
6 in. above center	2.61	1.72	9.15
Center	3.63	7.20	11.30
6 in. below center	7.36	4.00	9.89
C-5			
6 in. above center		5.90	13.60
Center		7.30	14.18
6 in. below center		5.24	14.19
D-1			
6 in. above center	1.23	4.09	15.27
Center	1.85	8.69	15.03
6 in. below center	2.70	5.33	13.26
E-5			
6 in. above center	2.11	5.24	11.43
Center		5.06	14.55
6 in. below center		7.20	11.60
HB-4			
2 in. from inner end		7.69	
14 in. from inner end		>2.30	

REACTIVITY EFFECTS OF FUEL ADDITIONS

The gain in reactivity due to fuel additions into various core positions was measured in both the first operating core configuration and the revised operating core configuration with the dummy experiments in place. The measurements were made with both cores in order to check the validity of the assumption that the gang rod calibration for the first core would be correct for the revised core. Agreement was good, particularly in the regions far from the changes of fuel placement. Table 16 summarizes the reactivity changes measured.

In order to have some idea of the reactivity gain that can be expected as a result of fuel additions in the future, a relationship between the neutron flux and the expected gain in reactivity per amount of fuel added was sought for each core position. Table 17 gives the ratios of $(\Delta k/k)/(\Delta m/m)$ to the average relative neutron flux, to the square of the average relative neutron flux, to the maximum relative neutron flux, and to the square of the maximum relative neutron flux for each position checked in the revised operating core. The best relation, with the exception of position E-1, appears to be the ratio of $(\Delta k/k)/(\Delta m/m)$ to the first power of the average relative thermal neutron flux. Thus, on the average,

$$\frac{(\Delta k/k)/(\Delta m_i/m)}{\bar{\phi}_i} \cong 1.00 \text{ (omitting position E-1)} ,$$

where

$\Delta k/k$ = gain in reactivity,

Δm_i = weight of fuel added in a certain core position,

m = total weight of fuel in core before the addition,

$\bar{\phi}_i$ = average thermal neutron flux in the core position.

From this relation, the gain in reactivity for any reloading can be estimated if the amount of fuel per position prior to the reloading is known. It must also be recognized that fuel additions to positions E-1, E-9, D-1, and D-9 will be worth only from 50 to 60% of the calculated gain.

Since the above formula is the result of only one group of measurements for a unique fuel distribution which was far from ideal, the formula may be expected to need revision as further data are gathered.

Table 16. Summary of Reactivity Changes as a Result of Fuel Additions in Old and Revised Operating Cores

Fuel mass in core before additions = 3751.69 g

Core Position	Δm (g)	Reactivity Change (%)		$(\Delta k/k)/(\Delta m_i/m)$		$(\% \Delta k/k)/g_i$	
		Old Core	Revised Core	Old Core	Revised Core	Old Core	Revised Core
A-5	+60.19	+0.28		0.174		0.00465	
A-6	+60.17	+0.27	+0.22	0.168	0.137	0.00449	0.00365
B-5	+60.19	+0.58	+0.54	0.362	0.337	0.00964	0.00897
B-7	+60.41	+0.44	+0.33	0.273	0.205	0.00728	0.00546
C-5	+130.32	+2.06	+1.92	0.593	0.553	0.01581	0.01473
C-6	+60.16	+0.78	+0.65	0.487	0.405	0.01297	0.01080
C-7	+130.41	+1.48	+1.18	0.426	0.339	0.01135	0.00904
D-5	+130.41	+2.05	+2.01	0.589	0.578	0.01571	0.01541
E-1	+60.63	+0.16	+0.14	0.0990	0.0867	0.00264	0.00231
E-3	+60.63	+0.64	+0.65	0.396	0.402	0.01056	0.01072
E-5	+60.41	+0.83	+0.75	0.515	0.466	0.01374	0.01242

Table 17. Relation of Average Thermal Neutron Flux in Core Positions to $(\Delta k/k)/(\Delta m_i/m)$ in Revised Operating Core with Experiments

Position	$\bar{\phi}_i$	$(\Delta k/k)/(\Delta m_i/m)$	$\frac{(\Delta k/k)/(\Delta m_i/m)}{\bar{\phi}_i}$	$\frac{(\Delta k/k)/(\Delta m_i/m)}{(\bar{\phi}_i)^2}$	ϕ_i^{max}	$\frac{(\Delta k/k)/(\Delta m_i/m)}{\phi_i^{max}}$	$\frac{(\Delta k/k)/(\Delta m_i/m)}{(\phi_i^{max})^2}$
A-6	0.127	0.137	1.079	8.496	0.219	0.626	2.858
B-5	0.335	0.337	1.006	3.003	0.555	0.607	1.094
B-7	0.227	0.205	0.903	3.978	0.371	0.553	1.491
C-5	0.606	0.553	0.913	1.507	1.000	0.553	0.553
C-6	0.392	0.405	1.033	2.635	0.643	0.630	0.980
C-7	0.302	0.339	1.123	3.719	0.464	0.731	1.575
D-5	0.604	0.578	0.957	1.584	0.996	0.580	0.582
E-1	0.160	0.0867	0.542	3.388	0.284	0.305	1.074
E-3	0.440	0.402	0.914	2.077	0.642	0.626	0.975
E-5	0.437	0.466	1.066	2.439	0.704	0.662	0.940

TIME ANALYSIS OF THE ORR POST NEUTRON MEASUREMENTS

Before the post neutron tests were performed, the measurements and tests to be made were carefully planned in as much detail as possible. The core patterns and the location of experiments in the lattice had also been decided. With these decisions made, it was possible to write detailed procedures for most of the program, with each step outlined. These procedures, in addition to acquainting all personnel with the work to be done, minimized the time elapsed between the various measurements so that the work was finished in a very reasonable time. Some revisions of the procedures were necessary, but these were mostly confined to the combining of steps to save time.

As an aid to future work, a time analysis of the work done has been made and is given in Tables 18 and 19. Table 19 lists the various jobs in the order of their performance. This sequence was chosen to minimize the number of core rearrangements and to confine those measurements requiring higher fluxes to the latter part of the program.

Table 18. Summary of Times Spent in Making Post Neutron Tests

Procedure	Time (hr)
Approaches to criticality and attainment of full-size cores, including the installation of mocked-up experiments	80.7
Initial instruments and controls checkouts	32.7
Core and rod calibrations and associated work	107.1
Temperature coefficient measurements	76.6
Measuring the reactivity effects of voids, experiments, and fuel additions	80.2
Neutron flux measurements	74.4
Total time spent on measurements	451.7
Time spent between procedures in instrument checks and miscellaneous work	49.1
Time down for revision of holddown arms, controls, etc.	722.9
Time no work was scheduled	201.0
Total time	1424.7

Table 19. Time Breakdown for Post Neutron Tests

Procedure	Time (hr)
First approach to criticality	2.1
Instruments and controls checks	32.7
Second approach to criticality	5.8
Extension of core to 4×7	24.8
Installing strainers in the bottoms of the fuel elements	7.0
Calibration of core and rods for the 4×7 configuration	39.3
Preliminary temperature coefficient check	2.4
Measuring the effect of voids on the 4×7 core	14.5
Measuring the worth of the rods from all the way in, to the first point on the calibration curves for the 4×7 core	1.1
Extension to the clean operating core	5.2
Calibration of the core and rods with the clean operating core	45.8
Measuring the effect of voids with the clean operating core	11.5
Measuring the worth of the rods from all the way in, to the first point on the calibration curves for the clean operating core	2.2
Inserting mocked-up experiments	42.8
Calibration of the core and rods for the first operating core with the mocked-up experiments in place	9.1
Measuring the worth of the rods from all the way in, to the first point on the calibration curves for the first operating core with the mocked-up experiments in place	2.6
Measuring the reactivity worth of experiments	10.9
Conversion to the revised operating core and measuring the effect of fuel additions on the reactivity	23.2
Conversion to the first operating core and measuring the effect of fuel additions on the reactivity	20.1
Measuring the temperature coefficient for the first operating core with experiments	17.6
Conversion to revised operating core and neutron-flux mapping	21.3
Conversion to 4×7 core and neutron-flux mapping	20.6
Measuring the temperature coefficient for the 4×7 core	30.3
Conversion to the clean, revised operating core and neutron-flux mapping	9.2
Measuring the temperature coefficient for the clean operating core	26.3
Reinsertion of some experiments and remeasuring neutron fluxes	8.8
Conversion to 4×7 core and recheck of some neutron-flux measurements	5.8
Measuring the neutron flux in the shim rods in the 4×7 core	8.7
Total	451.7

APPENDIX

Preparation for ORR Nuclear Tests

The following preparations must be made:

1. The fuel to be used must be in a portable container or easily accessible nonportable container. A list of fuel element numbers and corresponding fuel content must be made, with several copies.
2. A short-handled (12 ft) fuel tool must be provided.
3. A storage place for slightly radioactive fuel must be provided either inside or outside the reactor vessel.
4. A neutron source equivalent to a 30-curie Po-Be source must be provided and suspended on a cable or wire so that it can be positioned in a hollow beryllium piece in the core and removed at will. If Sb-Be is to be used, a marker should be placed on the cable to indicate the depth of water necessary for personnel shielding.
5. An adapted core piece must be provided to permanently contain the source subsequent to the criticality run and the calibration runs.
6. Two additional neutron counting chambers must be provided with necessary instrumentation. One of these chambers should be located in beam hole HB-4, the other in core position F-2. The chambers must be checked with sources.
7. A sufficient number of poison strips to poison out a 4×7 core must be preassembled.
8. A sufficient number of loaded foil holders must be preassembled.
9. A log book must be kept for recording all events, startup times, run times, shutdown times, etc. This will not be the same book or books used for the hydraulic tests.
10. Handling experience should be acquired by all personnel involved. This includes operation of the reactor rod drives, taking readings on counters, inserting and removing fuel elements, inserting and removing poison strips, inserting and removing foils, etc.
11. A preassignment of scanner time and counter time must be arranged with the BSF and counter room personnel for monitoring copper wires and gold foils.
12. It must be known that all reactor components are functioning properly.
13. The reactor pool must be filled with water to the top of the reactor tank.
14. A reliable communication system must be established between the control room and the top of the reactor tank.
15. Dummy experiments must be on hand, if possible, and tested in place in the lattice positions to be occupied.
16. Beam hole shielding must be provided for all holes.
17. Beam hole flux measuring devices must be on hand, with proper handling tools.
18. Health Physics instruments must be in proper locations and functioning.
19. A core layout board for control room should be provided.

Personnel Requirements for Approach to Criticality

An absolute minimum of three people will be required for an approach-to-critical operation. One man *must* be stationed at the reactor controls and *two must* be at the tank top. (These two will *not* stay at the tank top during rod withdrawal.) There must be constant communication between the two stations. It is preferred to have five people present if possible. These people would have the following jobs:

1. One man in the control room will operate the reactor controls and read normal instruments. He should be a technical man or a very well trained nontechnical man.
2. One man in the control room will read special instruments and communicate with tank top station. He must be a technical man.
3. One man will be stationed at the tank top to insert and remove fuel elements and/or beryllium pieces. He need not be technical.
4. One man at the tank top will handle communications, keep records, and both supervise and aid the other man. He must be technical.
5. One man will handle other jobs such as keeping up with component operation (water system, etc.), checking rod positions when necessary, answering telephones, handling usual interferences. He need not be a technical man.
6. A technical man, free to go anywhere, will be in charge. In addition, a health physics surveyor, an instrument mechanic, an electrician, and a millwright should be available.

Record Keeping for ORR Nuclear Tests

The primary record for all events will be the log book. All information relating to core changes, startup, shutdowns, etc., with times, must be recorded in the log book.

In addition to the log book, forms will be prepared for use in recording core changes for the approach-to-critical run, core and shim rod calibrations, flux mappings, and position-vs-reactivity runs for fuel and experiments. During the approach-to-critical run, a graph will be made of the reciprocal of the counting rate (for each fission counter) vs fuel mass in the core in order to predict the critical loading before it is actually reached. All forms and graphs will be made a part of the permanent record by stapling either a copy or the original into the log book.

Equipment check sheets will be used and should become part of the permanent records. They will apply to instrument and controls and to the general over-all condition of the reactor system.

The supervisor of each shift will see that all records are properly kept.

Startup Check List – ORR

March 13, 1958

	Initials of Checker
1. All work in core completed	_____
2. Log N amplifier set at "ground"	_____
3. All utility services are in order and turned on	_____
4. "Reactor operate" key switch is off	_____
5. All nuclear instruments turned on at least ½ hr prior to operation of reactor	_____
6. All ion chambers fully inserted	_____
7. Log N sensitivity increased by a factor of 100 and calibrated accordingly	_____
8. Safety channel preamps grid resistor increased by a factor of 10 (to 300 megohms)	_____
9. Safety channels checked out by introducing proper voltages and/or currents to ascertain that the channels are working satisfactorily and that the corresponding recorders are tracking	_____
10. (*a*) "Cal-Use" switch on count rate meters at "Use"	_____
(*b*) All counting rate channel chambers inserted (total of 3) to obtain a reasonable counting rate (2–10 counts/sec)	_____
11. All counting rates and positions of corresponding chambers recorded	_____
12. Rod-raise test performed	_____
13. All magnet amplifier currents set at ____(to be determined)	_____
14. Each rod raised 1 in. (one rod at a time), and scrammed by means of the "Jordan" scram button on the sigma amplifiers	_____
15. Step 14 repeated for each of the three "Jordan" scram buttons	_____
16. Step 14 repeated, but each rod scrammed individually by switching the Log N from "ground" to "hi-calibrate" quickly	_____
17. Safety monitor working and annunciator "normal"	_____
18. No water being circulated through reactor tank; all pumps off	_____
19. All components operating properly and reactor ready for startup	_____
(*a*) Beam holes checked	_____
(*b*) All reactor-control mode switches set at "neutral" or "normal" except "water-test" switch	_____
(*c*) "Water test" switch set ot "test" and information stored on corresponding annunciator	_____
(*d*) Temperature indicator connected and working for reactor tank water	_____
(*e*) Air monitors and switches operating and annunciator at "normal"	_____
20. Log N set at "operate"	_____
21. Micromicroammeter set at 1×10^{-9} amp	_____
22. Intercoms working	_____
23. All personnel alerted	_____

First Approach to Criticality and Instrument Performance Checkout

General Remarks

Due to the limited number of fuel elements on hand and to the variety of weights available (70, 140, 168, and 200 g), the first approach to criticality will be conducted with 168-g elements, with the 140-g elements being reserved for tests requiring the full-size core. Following attainment of criticality, a complete checkout of instruments and controls will be conducted. This will include mechanical, electronic, and reactor-response tests and will involve a rough power-vs-instrument calibration by use of gold foils. The core size used will depend upon the excess k required, which should be quite small.

After the instruments and controls checkout, the fuel will be removed from the reactor, and the second approach to criticality conducted with 140-g elements. (An alternative would be to replace the 168-g elements with 140-g elements in stepwise fashion, keeping the core loading just above the critical mass throughout the procedure.) It is necessary to remove the 168-g elements because they will have acquired an appreciable amount of radioactivity during the instrument checks. The core calibrations to be done with the full-size core require that the elements be handled subsequent to attaining criticality; therefore, the elements used must have acquired only a very low level of radioactivity.

Procedure

1. Be sure that the desired initial conditions are in order:

(*a*) personnel familiar with procedure to be followed and sufficient personnel present,
(*b*) all records being kept,
(*c*) fuel supply at hand,
(*d*) handling tools available and operable,
(*e*) no other work scheduled which will interrupt the proceedings,
(*f*) reactor system check list completed, including such items as condition of pools and tank, health physics instrumentation, condition of beam hole shielding, location of any special equipment in building, etc.,
(*g*) instruments and controls check list completed, including such items as performance of instruments and controls, special conditions of the instruments and controls, neutron source placement, communications, etc.,
(*h*) any other obvious requirements.

2. Load shim rods into positions B-4, B-6, D-4, and D-6 if they are not already loaded. Record the weight of fuel in each rod on the forms provided. Check the functioning of the rods.

3. Load beryllium pieces into the following positions if not already loaded: A-3, A-4, A-5, A-6, A-7, A-8, B-3, B-7, C-3, C-7, D-3, D-7, E-3, E-4, E-5, E-6, E-7, E-8, F-3, F-4, F-5, F-6, F-7, F-8, G-3, G-4, G-5, G-6, G-7, G-8. The beryllium piece for A-5 must be a hollow piece with the insert removed. This will be the neutron-source position. All other beryllium pieces must be solid pieces or hollow pieces with the center inserts in place. Load exactly as shown on beryllium placement pattern. (A fission counter chamber will be located in position F-2.)

4. Insert the source half way down into A-5. Check the response of the fission counters.

5. Load 168-g elements into positions B-5, C-5, and D-5 while watching the response of the fission counter channels. The shim rods must be inserted all the way while this is being done and during any subsequent core changes. Record fuel weights and add up the total fuel mass including that in the rods. The fission counters must be showing readings at this point. The readings should be greater than 2 counts/sec on at least two channels. If these requirements are met, withdraw the shim rods groupwise. Record the counting rate for each fission counter channel after the reading levels out (provided that the assembly is not critical). Calculate the reciprocal of the counting rate and start a plot of the reciprocal of the counting rate for each counting channel vs the fuel mass in the core.

6. Insert all rods fully or scram (as desired). Slowly insert a 168-g element into C-4 while watching the fission counters. Some small rise in the counting rate will be noted but should immediately level out. Do not detach the handling tool from the fuel element until the counting rate has leveled out. (If the counting rate should continue to increase, immediately withdraw the fuel element.) Withdraw the shim rods groupwise until the rods are all the way out or until a stable positive period is attained; adjust to a long positive period with the shim rods. Remove the source from A-5 to determine whether the instrument readings are sustained by the fuel only.

If a positive stable period does not occur upon complete withdrawal of the shim rods with the source in place, record the fission counter readings with the rods fully withdrawn. Plot the reciprocal of the counting rate of each counter vs the fuel weight in the core. Note: The positions of the fission chambers and the BF_3 chamber should not be altered throughout the approach to criticality. (It is not likely that criticality will be attained in step 6 for position C-4; step 7, however, should result in a very nearly critical core.)

7. Repeat step 6 for position C-6.

8. Insert all rods or scram (as desired). Transfer the beryllium from C-7 to C-8. Slowly insert a 168-g element into C-7 while watching the fission counters. Some small rise in the counting rate will be noted but should immediately level out. (If the counting rate should continue to increase, immediately withdraw the fuel element.) Do not detach the handling tool from the fuel element until the counting rate has leveled out. Withdraw shim rods until the rods are all the way out or until a stable positive period is attained. If a positive stable period is attained, adjust to a long positive period with the shim rods. Remove the source from A-5 to determine whether the instrument readings are sustained by the fuel only. If a positive stable period does not occur upon complete withdrawal of the shim rods with the source in place, record the fission counter readings with the rods fully withdrawn. Plot the reciprocal of the counting rate for each counter vs the fuel weight in the core.

9. Repeat step 8 for the positions in the following list in the order listed until criticality is reached. As the plot of the reciprocal of the counting rate vs fuel mass approaches zero, even greater caution must be exercised when inserting additional fuel elements. It may be that the final one or two fuel elements should be 70-g elements. (This decision will be made at the time by the person in charge.)

Position	Changes
B-7	Beryllium to B-8, fuel into B-7
D-7	Beryllium to D-8, fuel into D-7
C-3	Beryllium to C-2, fuel into C-3
B-3	Beryllium to B-2, fuel into B-3
D-3	Beryllium to D-2, fuel into D-3

10. After criticality is attained, adjust the excess k to the desired amount ($\sim$0.5%) by further fuel additions if required. This can be estimated from the rod positions.

11. Perform the instruments and controls checks and calibrations.

Second Approach to Criticality and Attaining 4 × 7 Core

General Remarks

The second approach to criticality will be done with fuel elements containing approximately 140 g of U^{235} each. After criticality has been attained, the core will be expanded to the first full-size 4 × 7 configuration by use of 140-g and 70- and 168-g elements as dictated by the positions of the shim rods at just-critical. At no time should the amount of fuel in the core be such that supercriticality is accomplished with the four shim rods less than halfway out. Elements with greater amounts of fuel may be substituted for some in the core, if desirable, after the final size of the lattice has been attained and if the shim rod worth allows this to be done. The first core configuration will be a 4 × 7 arrangement which will later be deformed to the proposed operating configuration. During this procedure the power level must not be raised above the value necessary to confirm criticality.

Procedure

1. Check all equipment and personnel:

(*a*) three fission chambers and associated instrumentation functioning, other instruments operating;
(*b*) rod drives, scram circuits, reverse circuits, etc., checked;
(*c*) personnel familiar with procedure to be followed and sufficient personnel present;
(*d*) water at proper level in tank and pool;
(*e*) handling tools available and operable;
(*f*) fuel supply at hand;
(*g*) all records being kept;
(*h*) neutron source in tank and checked by instruments;
(*i*) no other work scheduled which will interrupt the proceedings;
(*j*) communication system functioning;
(*k*) any other obvious requirements.

2. Load shim rods into positions B-4, B-6, D-4, and D-6 if they are not already loaded. Record the weight of fuel in each rod on the forms provided. Check the functioning of the rods.

3. Load beryllium pieces into the following positions (if not already done): A-3, A-4, A-5, A-6, A-7, A-8, B-3, B-7, C-3, C-7, D-3, D-7, E-3, E-4, E-5, E-6, E-7, E-8, F-3, F-4, F-5, F-6, F-7, F-8, G-3, G-4, G-5, G-6, G-7, and G-8. The beryllium piece for A-5 must be a hollow piece with the center insert removed. This will be the source position. All other beryllium pieces must be solid pieces or hollow pieces with the center inserts in place. Load exactly as shown on the beryllium placement pattern.

4. Insert the source halfway down into A-5. Check the response of the fission counters.

5. Load 140-g elements into positions B-5, C-4, C-5, C-6, and D-5 while watching the response of the fission counters. The shim rods must be all the way inserted while this is being done and during any subsequent core changes. Record the fuel weights and add up the total mass of fuel including that in the rods. The fission counters must be showing readings at this point. The readings must be greater than 2 counts/sec on at least two channels. If these requirements are met, withdraw the shim rods. Record the counting rate for each fission counter after the reading levels out. Calculate the reciprocal of the counting rate and start a plot of the reciprocal of the counting rate for each channel vs the fuel mass in the core.

6. Insert all rods or scram (as desired). Transfer beryllium from C-7 to C-8. Slowly insert a 140-g element into C-7 while watching the fission counters. Some small rise in the counting rate will be noted but should immediately level out. (If the counting rate should continue to increase, immediately withdraw the fuel element.) Do not detach the handling tool from the fuel element until the counting rate has leveled out. Withdraw the shim rods until they are all the way out or until a positive period is attained. If a positive period is attained, adjust to a long positive period with the shim rods. Remove the source from A-5 to determine whether the instrument readings are sustained by the fuel only. If a positive period does not occur, record the fission counter readings with the rods fully withdrawn. Plot on the graph the reciprocal of the counting rate for each counter vs the fuel weight.

7. Repeat step 6 for the positions in the following list in the order listed. Continue until criticality is attained. As the plot of the reciprocal of the counting rate vs the fuel mass approaches zero, even greater caution must be exercised in inserting additional fuel elements.

Position	Changes
B-7	Beryllium to B-8, fuel into B-7
D-7	Beryllium to D-8, fuel into D-7
C-3	Beryllium to C-2, fuel into C-3
B-3	Beryllium to B-2, fuel into B-3
D-3	Beryllium to D-2, fuel into D-3
C-8	Beryllium to C-9, fuel into C-8
B-8	Beryllium to B-9, fuel into B-8
D-8	Beryllium to D-9, fuel into D-8
C-2	Beryllium to C-1, fuel into C-2
G-8	Beryllium to A-2, aluminum into G-8
B-2	Beryllium to B-1, fuel into B-2
D-2	Beryllium to D-1, fuel into D-2
E-5	Beryllium to E-2, fuel into E-5
E-6	Beryllium to E-1, fuel into E-6
E-4	Beryllium to E-9, fuel into E-4
E-7	Beryllium to F-9, fuel into E-7
E-3	Beryllium to F-2, fuel into E-3
E-8	Beryllium to F-1, fuel into E-8
E-2	Beryllium to G-2, fuel into E-2
A-1	Aluminum into A-1
A-9	Aluminum into A-9
G-1	Aluminum into G-1
G-9	Aluminum into G-9
A-5	Beryllium and source to A-3, beryllium from A-3 to A-5

8. Since criticality will be reached before all the fuel additions listed in step 7 have been completed, the 4 × 7 configuration will not have been attained. The order of further fuel additions will be that of step 7. After each fuel addition, withdraw the rods until the reactor is critical, and record the rod positions with all four rods at about the same distance out. Also keep a complete record of the fuel added and an accurate record of the total fuel in the core at all times. If the system should become critical before the rods have been withdrawn half way, insert all rods and reduce the fuel mass in the core before further rod withdrawals. This will be done by replacing some elements with others containing

less fuel per element. The condition of having more fuel in the core than desirable can likely be avoided by careful observation of the effect of each fuel addition upon the rod positions and predicting when the mass must be reduced in order to allow the core size to be extended. When element replacement is necessary, a recheck of the rod positions at criticality must be made before extending the core size. Continue until the 4 × 7 configuration is attained within the described rod position limitations.

Core and Rod Calibrations (4 × 7 Core)

General Comments

Calibrations of the rods and the determination of the total excess reactivity of the core will be done by use of the distributed poison technique and will be done concurrently. Rod calibrations will be made individually and groupwise. The placement of poison strips will, to a great extent, be dictated by the results of preceding placements so that a detailed schedule cannot be completely foretold.

Before starting the calibration, the 4 × 7 configuration will have been attained with the fuel distributed as evenly throughout the core as can be accomplished with the fuel elements available and with criticality occurring when the four rods are withdrawn a little more than halfway.

Instruments for recording the core temperature must be operating, and means for keeping the temperature as nearly constant as possible must be available.

Procedure

1. Install catch baskets in the bottom of each fuel element in the core. Withdraw all four rods until the reactor is critical. Adjust the rods so that they are evenly withdrawn, and record the positions. Insert one rod fully while withdrawing the other three to maintain criticality. Adjust the position of the three partly withdrawn rods until they are evenly withdrawn. Record positions of all four rods. Repeat for the remaining three rods, being careful to keep complete records. Record core temperature. (This step will be repeated following each position addition. Eventually, criticality will not be maintained with one rod fully inserted and the other three partly withdrawn. When this condition occurs, maintain criticality with the one rod partly inserted and the other three fully withdrawn. Record all rod positions and the core temperature. Since the reactivity worth of the rods will differ, this will likely occur for different amounts of poison in the core for the different rods.) Insert all rods.
2. Insert a poison strip into C-3, C-5, C-7, D-3, D-5, and D-7. Keep careful records of the poison strips as to whether they are full size, half size, or less. Repeat step 1.
3. Insert a poison strip into B-3, B-5, B-7, E-3, E-5, and E-7. Repeat step 1.
4. Insert a poison strip into B-2, B-8, C-4, C-6, E-2, and E-8. Repeat step 1.
5. Insert a poison strip into C-2, C-8, D-2, D-8, E-4, and E-6. Repeat step 1.
6. Repeat steps 2, 3, 4, and 5 to complete the insertion of two poison strips per fuel element.
7. If the positions of the rods show that more than two-thirds of the excess reactivity has been poisoned out, repeat steps 2, 3, 4, and 5, using half strips.
8. When the reactor is barely supercritical with the rods fully withdrawn, start up to criticality after each strip insertion until the total excess reactivity is just barely poisoned out with all four rods fully withdrawn.
9. Insert all rods and remove the poison strips. (Before removing strips see the procedure, immediately following, on "Reactivity Effects of Beam Holes.")
10. After the poison strips have been removed, measure the value of each rod from zero inches out to the first calibration point of that rod by the use of the calibrated portion of another rod.

Reactivity Effects of Beam Holes

General Comments

Following the calibration of the shim rods in the 4 × 7 core, the effects produced upon reactivity by draining the beam holes will be measured. This will be done with only part of the poison strips removed so that criticality is attained with the No. 4 or the No. 6 rod in the range of 15 to 18 in. withdrawn.

Procedure

1. Bring the reactor to criticality with three rods fully withdrawn and the No. 4 rod partly withdrawn. Record the rod positions and the core temperature. Repeat for No. 6 rod. Insert rod

No. 4 or rod No. 6 (whichever is being used as the control). Leave the other rods withdrawn.

2. Drain HB-1. Repeat step 1.
3. Drain HB-2. Repeat step 1.
4. Drain HB-3. Repeat step 1.
5. Flood HB-1. Repeat step 1.
6. Flood HB-2. Repeat step 1.
7. Drain HB-1, 2, 5, and 6. Repeat step 1.
8. Flood HB-1, 3, 5, and 6. Repeat step 1.
9. Flood HB-2. Repeat step 1.
10. Drain HN. Repeat step 1.
11. Flood HN. Repeat step 1. Scram.
12. Complete the removal of the poison strips.

Conversion to Clean Operating Core

General Comments

The 4 × 7 configuration will be deformed, piece by piece, to the proposed operating configuration rather than by building it up through a new approach to criticality. Since the operating configuration is far from ideal according to a neutron economy standpoint, a somewhat large change in reactivity is expected as a result of the deformation. The operating core will contain two more fuel elements than the 4 × 7 configuration; this will compensate to some extent for reactivity losses due to less compactness.

The fuel in the 4 × 7 core will be shifted first, followed by the addition of the other two elements. It may be that some of the low-weight elements will have to be replaced by elements containing more fuel. At completion of the changeover, criticality should be achieved with the rods withdrawn a little more than halfway.

Procedure

1. Place the neutron source in position A-3.
2. Move the fuel from B-2 to D-1. Move the beryllium from D-1 into B-2.
3. Bring the reactor to criticality with all rods evenly withdrawn. Record rod positions and core temperature. Insert all rods.
4. Move the fuel from B-8 to D-9. Move the beryllium from D-9 into B-8. Repeat step 3.
5. Move the fuel from C-2 to E-1. Move the beryllium from E-1 into C-2. Repeat step 3.
6. Move the fuel from C-8 to E-9. Move the beryllium from E-9 into C-8. Repeat step 3.
7. Move the fuel from B-3 to A-5. Move the beryllium from A-5 into B-3. Repeat step 3.
8. Remove the beryllium from A-4 to storage. Insert a new 140- or 70-g fuel element into A-4. Judge the weight of fuel needed by the position of the shim rods in the preceding step. Repeat step 3.
9. Remove the aluminum from G-8 to storage. Move the beryllium from A-6 to G-8. Insert a new 140- or 70-g fuel element into A-6. Repeat step 3.
10. Interchange the beryllium pieces in B-2 and G-2.
11. Adjust the fuel content of the core so that it is distributed as uniformly as possible with the available fuel elements and with criticality occurring with the rods withdrawn halfway. An accurate record of the fuel element number and fuel content for each core position must be kept.

Core and Rod Calibrations (Clean Operating Core)

General Comments

Because of the great change in configuration from the 4 × 7 to the operating core, the worth of the rods should be changed appreciably; therefore a new calibration of the rods and core must be made. The worth of individual rods will also vary much more. Because of the lack of symmetry in this core, the selection of poison locations for the first few points in order that the total poison in the core can be considered "distributed" is difficult to make. The most reliable calibration points will be those for which each fuel element contains the same amount of poison. These considerations will be used to judge how best to plot calibration curves from the resulting data.

The core temperature must be held as nearly constant as possible during the calibration.

Procedure

1. Place the neutron source at the mid-point of A-3.
2. Withdraw the shim rods until criticality is reached. The rods should be about halfway out. Adjust the rods until they are evenly withdrawn. Record the rod positions and the core temperature. Insert one rod all the way while withdrawing the other three to maintain criticality. Adjust the three partly withdrawn rods until they are evenly withdrawn. Record the rod positions and the core temperature. Repeat for each of the rods. (This step will be repeated following each poison addition. Eventually, criticality will not be maintained with one rod fully inserted and the other

three partly withdrawn. When this condition occurs, maintain criticality with the one rod partly inserted and the other three fully withdrawn. Record all rod positions and the core temperature. Since the reactivity worth of the rods will differ, this will probably occur for different rods with different amounts of poison in the core.) Insert all rods.

3. Insert a poison strip into A-5, C-5, D-2, D-8, E-2, E-5, E-8, A-4, C-4, D-1, D-5, E-3, E-6, and E-9. Repeat step 2.

4. Insert a poison strip into A-6, C-3, C-6, D-7, D-9, E-4, B-5, B-7, C-7, D-3, E-1, E-7, and C-2. Repeat step 2.

5. Repeat steps 3 and 4 to complete the insertion of two poison strips per element.

6. If the positions of the rods show that more than two-thirds of the excess reactivity has been poisoned out, repeat steps 3 and 4 with half strips, or make two steps each of steps 3 and 4 using whole strips, doing the first half and then the second half of each fuel element group.

7. When the reactor is barely supercritical with the rods fully withdrawn, start up to criticality after each strip insertion until the total excess reactivity is just barely poisoned out with all four rods fully withdrawn.

8. Insert all rods and remove the poison strips.

9. After the poison strips have been removed, measure the value of zero to the first calibration reading as before for each rod by the use of the calibrated portion of another rod.

Insertion of Dummy Experiments

General Comments

The insertion of dummy experiments will have to be done piece by piece in order to determine their effects upon reactivity and to allow substitution, as needed, of fuel elements having a greater fuel content for low-weight elements. Since a large part of the beryllium reflector will be replaced by experiments, the total reactivity change should be large. Also, the spatial distribution of the flux will likely be altered sufficiently to warrant a new core and rod calibration with the experiments in place. The amount of fuel in the core should be such that criticality is attained with the rods withdrawn between one-half and three-quarters of the full distance out.

Procedure

1. With the operating configuration and no experiments in place, perform a check of the effect of draining the beam holes and placing a void on the pool side. Follow the same procedure outlined in "Reactivity Effects of Beam Holes" but add the pool-size void. Remove the pool-side void and fill the beam holes.

2. Remove the beryllium from C-2 to storage. Insert the half fuel element into C-2.

3. Withdraw all rods until the reactor is critical. Adjust the rods until they are even. Record the rod positions and the core temperature. Insert all rods.

4. Remove the aluminum from A-9 to storage. Insert McBride's experiment piece. Repeat step 3.

5. Remove the beryllium from B-1 to storage. Insert the G-E experiment piece. Repeat step 3.

6. Remove the beryllium from B-3 to storage. Insert the radioiosopte holder into B-3. Repeat step 3.

7. Remove the aluminum from G-1 to storage. Put the beryllium from storage into G-1. Repeat step 3.

8. Remove the aluminum from G-9 to storage. Put a beryllium piece from storage into G-9. Repeat step 3.

9. Remove the core from the beryllium in B-9. Insert Morgan's experiment piece. Repeat step 3.

10. Remove the core from the beryllium in C-1. Insert Morgan's experiment piece. Repeat step 3.

11. Remove the beryllium from C-8 to storage. Insert Berggren's experiment piece. Repeat step 3.

12. Repeat for the following and in the following order:

(*a*) F-5 – radioisotope holder;
(*b*) F-3 – radioisotope holder;
(*c*) F-7 – radioisotope holder;
(*d*) F-8 – radioisotope holder;
(*e*) F-1 – Zukas' experiment piece;
(*f*) F-9 – Browning's experiment piece.

13. Remove the aluminum from A-1 to storage. Remove the beryllium from A-2 to storage. Insert the Gas-Cooled Reactor experiment into A-1 and A-2. Repeat step 3.

14. Insert the pool-side assembly (void). Repeat step 3.

Recalibration of Core and Shim Rods Following Experiment Insertion

After all the experiments are in place, perform a core and shim rod calibration by using the same procedure outlined for operating the core without experiments. One addition to the procedure must be made, and that is the insertion of poison into the half fuel element in position C-2. This should be done in step 5 of the procedure.

Temperature Coefficient Measurement (Operating Core with Experiments)

General Comments

In measuring the temperature coefficient, the heating of the reactor water will be done by the pumps and by steam on the heat exchangers. The measurement consists of finding the reactivity change ($\Delta k/k$) caused per degree of temperature change.

Before the measurement is started, the following must be done:

1. Remove the temporary neutron source from A-3. Insert the permanent neutron source into A-3.
2. Remove all the screens from the bottoms of the fuel elements.
3. Use the "old" operating core configuration as referred to in the shift instructions with one exception: remove the N_f radioisotope tray from B-3 and replace it with a solid beryllium piece.
4. Seal the tank to allow water circulation at full flow.

Procedure

1. Establish full water flow, 18,000 gpm, through the reactor tank.
2. By use of the heat exchangers, lower the temperature of the water to ~70°F (as indicated on the inlet and outlet lines on all three recorders) if possible (no lower than 70°F, however).
3. Start the reactor up to criticality. With the temperature being held as nearly constant as possible, record the No. 3 rod position with the others fully withdrawn, and record the No. 4 rod position with the others fully withdrawn. Record the temperature. If the temperature changes between the times the gang reading and the No. 5 reading are made, record the temperature at the time of *each* reading.
4. Leave the reactor operating at criticality. Shut off all heat exchangers to allow the water to start heating from the pump power and the steam on the heat exchangers.
5. Keep the reactor at criticality during the heating of the water. After each 5°F rise in the water temperature, record the temperature (all three recorders), the No. 3 rod position with the others fully withdrawn, and the No. 4 rod position with the others fully withdrawn, being careful to record the temperature *at the time* of *each* rod reading.
6. Continue, if possible, until the water temperature reaches 120°F.

Instrument Calibration

General Comments

It is assumed that up to this time, following the second approach to criticality, the reactor power level has been kept sufficiently low so that only the fission chamber and Log N have been operating.

Before proceeding further with core measurements, at least a rough check of the flux vs instrument readings will have to be made at this time in order to be able to extrapolate flux measurements made at low power levels to what the flux will be at higher power levels. The first checks will be made with gold foils in order to establish the instrument readings at which the flux mapping runs will be made. The data from the flux mapping will indicate what the power level was at that instrument reading. The instruments of greatest concern here are the compensated ionization chamber instruments.

The gold foils will have to be irradiated in a thermal neutron flux of about 1 to 100 $\times 10^7$ neutrons$\cdot$cm$^{-2}\cdot$sec^{-1}, while the flux mapping foils will have to be exposed in a thermal flux of about 1 to 5 $\times 10^{11}$. Some estimate can be made of the first flux level to be measured from the known fission counter efficiency and the distance the fission chambers are located from the core, and from previous calibrations.

Procedure

1. Load bare gold foils into position C-5. Start up reactor to such an instrument reading as is necessary to provide an estimated flux of about 10^7 neutrons$\cdot$cm$^{-2}\cdot$sec^{-1} (thermal) in the core. The startup should be done smoothly,

with a constant period of 15 to 30 sec if possible. Operate for ½ hr. Shut down and remove the foils. Record the start times (beginning of positive period and the time that the desired power level is reached), instrument readings, shutdown time, and rod positions during operation.

2. Repeat step 1 for instrument readings which increase by steps of half a decade, if desirable. (That is, if the first thermal flux level were 1×10^7, the others would be 5×10^7, 10^8, 5×10^8, and 10^9.) The counting of the foils should begin as soon as the first foils are removed. These will be counted in the Building 3001 counter room, using a calibrated counter to be assigned by the personnel there.

3. A cadmium difference will be run for the gold foils for one of the instrument readings, dictated by the radioactivity of the foils. This will be done by inserting a cadmium-covered gold foil into the position being used and operating at one of the flux levels used for the bare foils.

4. Plot a graph of the flux level vs the instrument readings.

Flux Mapping of Operating Configuration with Experiments in Place

General Comments

This will be the most important of the flux measuring procedures and will involve the greatest number of foils. In addition to the monitors in the fuel and beryllium pieces, foils of various types will be in the experiment pieces. For this reason, a great deal of time and effort could be lost if the foil-exposure run is interrupted because of an accidental shutdown. If such a shutdown should occur, all the calibration foils would have to be replaced. The copper wires, however, would not have to be replaced. Before the startup for foil exposure, every precaution should be exercised to preclude the possibllity of such a shutdown.

Procedure

1. Recheck the desired flux level by exposing copper wires and calibration foils in positions D-1 and C-5 for 1 hr at an estimated flux of 1 to 5×10^{11} neutrons·cm^{-2}·sec^{-1}. Revise the estimated operating instrument reading based upon the wire and foil radioactivities.

2. Start up to criticality with the rods evenly withdrawn. Record the rod positions and the core temperature. Insert all rods.

3. Load bare copper wires (in aluminum sheaths) into the following positions:
(*a*) each fuel element,
(*b*) the coolant channel in each solid beryllium piece,
(*c*) any experiment piece adapted to hold a copper wire.

4. Start up the reactor by withdrawing all four shim rods evenly. When criticality is reached, level the power at just critical. Record the rod positions and the core temperature. Try to keep a constant period of 15 to 30 sec during the power elevation. Operate for 1 hr at a constant instrument reading of the predetermined level for the wire exposure. Record the rod positions and the core temperature. If the water must be circulated, use as low a flow as possible to maintain low temperature. Shut down and remove the wires.

5. Load bare Mn-Al, Co-Al, and Cu foils into the following positions:
(*a*) A-5, C-5, D-1, and E-5;
(*b*) any experiment facility adapted for their insertion; load foils and copper wires into HB-3 and HB-4.

6. Start up the reactor by withdrawing all four shim rods evenly. Try to keep a constant period of 15 to 30 sec during the power elevation. Operate for 1 hr at a constant instrument reading of the predetermined level for these foils. Record the rod positions and the core temperature. If water must be circulated, use as low a flow as possible to maintain a low temperature. Shut down and remove the foils and wires. Store the foils in the pool until they can be delivered to the Activation Analysis Department.

7. Repeat steps 5 and 6, using cadmium-covered foils.

Rearranging Core to 4 × 7 Configuration

After the neutron flux measurements in the operating core and experiments have been completed, the core must be rearranged to the 4 × 7 configuration. Great care must be exercised to rebuild the exact 4 × 7 core originally attained, with the same fuel pieces in the same places and the same type of beryllium pieces in the same places. As an additional precaution for

avoiding the development of a dangerous condition, occasional startups to check the rod positions at criticality must be made during the reassembling. The frequency of such startups will best be dictated by the data previously collected; so they will not be detailed here. A procedure will be written immediately preceding the rearrangement.

After the 4 × 7 core has been reassembled, make checks of rod positions at criticality to ensure that the original core has been reassembled.

Flux Mapping of 4 × 7 Configuration

General Comments

The purpose of the flux mapping with the 4 × 7 configuration is primarily for checking the calculations of the spatial distribution which have been used in design work. It will not be necessary to make measurements in the beam holes or in the pool facility.

The flux vs instrument reading calibration must have been completed, and the core must be the exact one used for the core and shim rod calibration.

It will be of interest to know the reactivity effects of loading a large number of foils into the reactor; so reactivity data should be taken.

Procedure

1. Be sure that solid beryllium pieces are in positions A-2, A-5, A-6, B-1, B-9, C-1, C-9, D-1, D-9, E-1, E-9, F-2, F-5, F-8, and G-5. The permanent source should be in position A-3.

2. Start up the reactor to criticality by withdrawing all rods evenly. Record the rod positions and the core temperature. Insert all rods. (This is a check run and will allow the reactivity value of load of foils to be measured.)

3. Load a bare copper wire (in aluminum holder) into each of the following positions:

(*a*) each fuel piece,

(*b*) beryllium positions A-2, A-5, A-6, B-1, B-9, C-1, C-9, D-1, D-9, E-1, E-9, F-2, F-5, F-8, and G-5.

Keep accurate records.

4. Start up the reactor by withdrawing all four shim rods evenly. When criticality is reached, level the power (at just critical). Record the rod positions and the core temperature. Raise the power level to the predetermined instrument reading for the wire exposure. Try to keep a constant period of 15 to 30 sec during the power elevation. Operate for 1 hr at a constant instrument reading. Record the rod positions, startup times, shutdown time, and core temperature. If the water must be circulated, use as low a flow as possible to maintain low temperature. Shut down and remove the wires.

5. Load Mn-Al and Co-Al foils into positions B-5, C-5, E-2, and E-5.

6. Operate for 1 hr at 100 on the No. 2 safety. Shut down and remove the foils and wires after ~1 hr decay. Store the foils in the pool until they can be delivered to the Activation Analysis Department.

Preparation for Flux Mapping of the Clean Operating Core

Procedure

1. Convert from the 4 × 7 configuration to the clean operating core, taking the necessary precautions. Be certain that the exact core used for shim rod and core reactivity measurements is exactly restored, with exact fuel pieces and the same type of beryllium pieces in the same former positions except that the permanent source will be in A-3.

2. Perform a temperature coefficient measurement. Use the same procedure as was used for the operating core with experiments.

Flux Mapping of Clean Operating Configuration

General Comments

In order to obtain a complete picture of how much the core experiments affect the spatial neutron distribution in the core, a flux mapping must be done for the clean core as well as for the core with the experiments in place.

Procedure

1. Be sure that the original clean operating configuration has been exactly restored, with the exception of the permanent source having been installed in A-3, a beryllium piece from storage put into B-9, the beryllium moved from B-9 to A-9, and the aluminum from A-9 removed to storage.

2. Recheck the desired thermal neutron flux level by exposing copper wires and calibration foils in positions D-1 and C-5 for 1 hr at an estimated thermal flux of 1 to 5 $\times$ 10^{11} neutrons$\cdot$cm$^{-2}\cdot$sec^{-1}. Revise the estimated operating instrument reading (revision to be based upon wire and foil radioactivities).

3. Start up to criticality with the rods evenly withdrawn. Record the rod positions and the core temperature. Insert all rods.

4. Load bare copper wires (in aluminum sheaths) into the following positions:

(*a*) each fuel piece,

(*b*) beryllium positions A-2, A-8, B-1, C-1, C-2, F-2, F-5, F-8, G-2, G-5, G-8, G-3, G-4, G-6, and G-7.

5. Start up the reactor by withdrawing all four shim rods evenly. When criticality has been reached, level the power (at just critical). Record the rod positions and the core temperature. Raise the power level to the predetermined instrument reading for the wire exposure. Try to keep a constant period of 15 to 30 sec during the power elevation. Operate for 1 hr at a constant instrument reading. Record the rod positions, start-up times, shutdown time, and core temperature. If the water must be circulated, use as low a flow as possible to maintain low temperature. Shut down and remove the wires.

6. Load bare Mn-Al, Co-Al, and Cu foils into positions A-5, C-5, D-1, and E-5. Load foils and copper wires into HB-3 and HB-4.

7. Operate for 1 hr at 100 on the No. 2 safety. Shut down and remove the foils and wires after a decay time of $\sim$1 hr. Store the foils in the pool until they can be delivered to the Activation Analysis Department.

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