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TORY II-C REACTOR COLD CRITICAL ASSEMBLY PROGRAM

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TORY II-C REACTOR COLD CRITICAL ASSEMBLY PROGRAM

(Title: Unclassified)

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January 17, 1964

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ABSTRACT

The cold critical experiments with the Tory II-C reactor were performed in the critical facility of the Lawrence Radiation Laboratory at Livermore. The reactor is described briefly; the experimental equipment and the arrangement for the experiments is described in detail.

The core poison was removed without difficulty, and criticality was achieved at 1624 hours July 14, 1963. With the design core configuration the shutdown margin was less than had been intended; criticality was attained at a shim rod bank position of 38.5 inches insertion rather than the expected 35 inches. All Hastelloy tie tubes were replaced by René-41.

A heated core experiment with $\Delta T = 129 \pm 7^\circ\text{F}$ above room temperature provided a measure of the temperature coefficient which was found to be $-3.9 \times 10^{-3} \pm 7\%$ inch of shim rod bank travel/ $^\circ\text{F}$.

Other experiments included flux mapping, using fission foils, fission counters and copper flux wires, transients to determine control element worths, studies of flux spectrum by means of threshold detectors, and measurements of multiplication for various shutdown configurations for purposes of operational safety. Transient measurements, critical rod configurations, and flux distributions were also measured with the core poisoned in various stages to simulate elevated temperatures.

This report is intended to be a complete presentation of experimental data. It is intended to be a source of information for analysis and interpretation of the neutronic character of the reactor.

I. INTRODUCTION

The Tory II-C reactor is a prototype model for a nuclear ramjet engine. Details of its design are based in part upon experience gained from tests of the Tory II-A reactor.^{1,2}

Tory II-C is a semihomogeneous enriched uranium-fueled* reactor, moderated and reflected with beryllium oxide. It has a fuel mass of 52.1 kg of U^{235} , a void fraction in the active core of 0.479, and an average molar ratio of moderator to fuel of about 360. A detailed description of the reactor is given in references 3 and 4. A general summary of the characteristics is given in Table I.

The core configuration for these experiments differed from design specifications in the following manner:

1. The transition tube assemblies were not in place. These components were simulated with unfueled Tory II-A-type BeO tubes.
2. The Hastelloy-C "wiper bars" were simulated with dummy mild steel bars.
3. The hafnium control elements penetrated the core to a distance of 45.52 inches from the outer surface of the cell plates, not 40 inches as in the final design configuration.
4. Sixteen thermocouples for monitoring the temperatures of the transition tubes had not been installed.

The cold critical experiments were performed in the shielded "C" containment vault in the critical facility of the Lawrence Radiation Laboratory, Livermore. The purpose of the cold critical experiments was to empirically determine various neutronic characteristics of the reactor, including the position of the rod bank at critical, control rod worths, absolute power and power distribution, and the magnitude of the temperature coefficient.

This report is a description of the cold critical experiments and a consolidated summary of the findings. It is intended to be a source of information for analysis and interpretation of the neutronic character of the reactor.

The experiments and data are described essentially in the order in which they were performed.

II. DESCRIPTION OF THE EXPERIMENTAL SYSTEM

An overall view of the complete system used during these experiments is shown in Fig. 1. The reactor was positioned vertically in a handling fixture. The core vessel opened into a ventilation system designed to control any spread of airborne radioactivity which might have occurred and to permit

*The uranium is enriched to a U^{235} content of 93.2%.

heating of the core by circulation of heated air. A schematic diagram of the ventilation system is shown in Fig. 2.

The control (shim and vernier) rods which were used were the hafnium elements designed for Tory II-C. They are shaped like a hollow asterisk in cross section with a principal diameter of 1 inch and a length of 63.25 inches. The length of the rod stroke was 40 inches beginning at 5.52 inches below the outside surface of the front cell plates. Consequently, the rods penetrated 45.52 inches into the reactor, but only 35.52 inches into the active core. This rod arrangement for the critical experiments differed from the 40-inch rod penetration of the Tory II-C design configuration.

During reactor assembly work the core contained temporary "transportation" poison rods in each tie tube. These poison rods had a T-304 stainless steel shell with an outside diameter of 0.45 inches and contained a boron carbide cartridge 0.407 inch in diameter. A variable number of these rods — usually about 10 — was fitted with actuators and retained for use as safety rods. These safety rods penetrated 54.375 inches into the reactor when fully inserted and had a stroke of 52 inches.

There were minor variations in rod locations in the reactor during the program; the usual placement of rods in the core is shown in Fig. 3.

Both the control rods and safety rods were driven by individual mechanical actuators which were designed specifically for use in the cold critical measurements. (They were not the standard rod drives for Tory II-C.) The actuators moved the rods by means of chain-sprocket systems driven by constant-speed electric motors. The control actuators are shown in Figs. 4 through 7. The rods were mechanically drawn out of the core by the actuators; the weight of the rods moved them back into the core as the chains were run down by the actuators. The rods were connected to the actuators by means of electromagnets — all the rods fell free for scram. . The travel speed for the shim and vernier rod actuators was 5 in./min; that for the safety rod actuators was 5.6 in./min.

The control system was designed so that shim and vernier rods were withdrawn singly at all times; however, they could be run down either singly or in gang. The safety rods could be run singly or in gang in either direction.

Control element positions were measured by use of variable resistors connected to the drive gears of the actuators; positions were displayed in the control room by use of voltmeters. A fast-acting digital voltmeter was used to set and measure rod positions to within ± 0.02 inch.

The nuclear instrumentation used was quite conventional. Neutron flux measurements were made with two moderated BF_3 long counters, of nominal sensitivity (10 to 10^4 $\text{n/cm}^2\text{-sec}$), driving count rate meters; two uncompensated BF_3 ion chambers, of nominal sensitivity (10^2 to 10^8 $\text{n/cm}^2\text{-sec}$), driving Beckman micromicroammeters; and an uncompensated BF_3 ion chamber, of nominal sensitivity (10^2 to 10^7 $\text{n/cm}^2\text{-sec}$), operating a high-sensitivity log N amplifier-reactor period meter. Gamma radiation levels at four locations in the vault were monitored continuously by logarithmic Victoreen safety meters.

In order to assure that temperatures in the core could not exceed those planned, the power to the control element scram magnets was routed through two fusible conductors (98% lead-2% antimony, with a melting point of 600°F) located within a centrally located tie tube. Meltdown of these conductors would have caused the control elements to scram. The fuses were shown to be neutronically innocuous.

III. AUXILIARY EXPERIMENTAL EQUIPMENT

1. Equipment for Heating Core

For heating the reactor above room temperature it was necessary to make several minor modifications to the system. An insulating cover was installed over the top of the core (see Fig. 8). The cover had openings to permit passage of the control rods and connections for attaching flexible air ducts. The system was converted to closed-cycle operation by connecting ducts between this lid and the heater located downstream of the fan unit. The overall arrangement of the ventilation system components was shown in Fig.

2. The reactor vessel and all ductwork were insulated. Based upon critical rod positions the insulation was judged to have no neutronic effect.

An overall view of the reactor ready for heating is given in Fig. 9. The core temperature was raised by recirculating heated air through the system. Interestingly, even though the lid openings for the control rods were fairly large, the system was designed to be at atmospheric pressure at that point; once the system reached the required temperature, smoke tests showed that there was no flow of air from the reactor into the cell.

Seven of the platinum/platinum-10%-rhodium core thermocouples were calibrated in an oil bath prior to installation in the reactor. Calibration data were recorded on a multipoint strip-chart recorder. For the purposes of

monitoring the core temperature during the warm critical experiment, the same thermocouples and the same recorder were utilized. One of the thermocouples could not be installed in the reactor during assembly; however, it was connected to the recorder and used to re-check the oil bath calibration after the elevated temperature experiment. The core thermocouples used in this experiment are listed below:

<u>Thermocouple</u>	<u>Unit Cell</u>
10756	P 22
10701	P 23
10702	P 24
10902	R 5
10904	R 10
11207	M 7

The first two digits of the thermocouple number refer to the kind of tube being monitored (10 = fueled, 11 = unfueled). The third digit specifies the nominal axial plane in which the junction is located (7 = $X/L = 0.7$).

2. Equipment for Fission Counter Flux Mapping

The apparatus used for fission counter flux mapping consisted of a set of 13 fission probes, a fission probe drive unit, and an automatic data-collecting system.

The fission probes were constructed of aluminum tubing of suitable diameter to pass through the reactor fuel tubes. Details of the probes are shown in Fig. 10. The detectors were silicon p-n junctions coated with enriched uranium.⁵ In order to maximize spatial resolution, the sensitive volume was made quite small: 0.080 inch in diameter and 1 micron thick.

The performance of these detectors was extremely disappointing. During the preparatory stages of the experiments the failure rate approached 100%. Day-to-day drift in the detection efficiencies was as much as $\pm 10\%$. This required time-consuming normalizations in a standard source geometry before and after each use; even then the associated uncertainties were large.

Use of very small detectors to maximize the spatial resolution made it necessary to operate the reactor at power levels of 10 to 30 watts to obtain suitable count rates. Since this type of detector is dose-limited and expected to completely deteriorate at about 10^{12} nvt, the relatively higher power levels

may have affected the detector performance. A steady decline in efficiency was observed for all detectors during later stages of the program.

A small permanent magnet was attached to the base of each fission probe for fastening to the drive unit, which is shown in Fig. 11. The drive unit consisted of a horizontal plate positioned by an electrically-powered screw drive. Figure 12 shows the position relationship between the drive plate and the control rod actuators. The fission probes could be positioned at any selected point on the drive plate by use of their magnetic couplings. With this remote drive unit, the fission probe could be positioned vertically to an accuracy of ± 0.07 inch.

The automatic data-collecting system consisted of 14 transistorized scalars with associated components for control, for rapid conversion and readout in punched card format, and for on-line display of the data from a single channel on an XY recorder. A view of the major components is shown in Fig. 13. The technical details of the automatic data system are described in reference 6.

The experimental data were reduced by TRAX, a FORTRAN-assembled code designed to operate under the IBM-7094 monitor system.

3. Auxiliary Rod Actuators

One issue of interest in the program of critical experiments was a determination of the usefulness of the four optional shim rods which could be installed in the N-ring of unit cells (Fig. 3). Operation of these rods required special actuators; space limitations restricted use of the regular actuators to alternate rings of unit cells. These actuators, shown in Fig. 14, operated through the control unit baseplate. They were not scrammable, but were similar in other respects to the standard actuators.

Also shown in Fig. 14 is a bead-chain drive unit capable of driving from one to four safety rods in the L-ring of unit cells. Use of this actuator was not required.

IV. REMOVAL OF POISON FROM CORE

Just prior to the beginning of the critical experiments, the fully assembled reactor was positioned vertically in the handling fixture. Each of the 121 tie tubes contained a boron carbide "transportation poison rod." The observed leakage multiplication was 1.60 with a 2% error due to counting statistics;

from the method described in Appendix II, this was taken to be a "corrected multiplication" of 3.2.

The hafnium shim and vernier rods were installed in two increments. This was done by first remotely withdrawing the group of poison rods to be displaced to verify that no large changes in multiplication would occur. There was no change whatever in the multiplication; the poison rods were removed manually and replaced by hafnium elements.

The core was now in the initial configuration for the cold critical experiments. Actuators were installed on these rods at the locations shown in Fig. 3. Each rod-actuator was then tested for proper drive and scram characteristics, and adjustments were made where necessary.

Clearance to begin the critical experiments was received through the San Francisco Operations Office of the USAEC on July 17, 1963.

The program of critical experiments began formally on July 18, 1963. The first task to be done was the removal of the 96 core poison rods in those locations in Fig. 3 for which an actuator is not shown. The following scheme was used for the major portion of the poison rod removal: (1) Six hafnium shim rods were held suspended to provide an automatic scram safeguard. (2) The remaining six shim rods were withdrawn so that an incremental worth in multiplication could be measured; they were then re-inserted. (3) A group of poison rods was removed manually, one at a time. (4) Removal of poison rods in (3) continued until the multiplication approached that observed in (2). (5) The six shim rods were then withdrawn again and the process was repeated. Manual removal of poison rods was completed in six cycles of this procedure. Removal began nearest to the center and proceeded to the periphery, each ring being cleared prior to moving to the next one. The data are summarized in Fig. 15 and Table II. The rods were removed from each ring of cells as symmetrically as possible. At frequent intervals during the poison removal a test was made for body tampering by erecting a stack of paraffin blocks beside the base of the reactor duct. The overall dimensions of the paraffin tamper were $9 \times 19 \times 48$ inches. At no time was there an observable increase in multiplication due to the presence of the paraffin.

Based upon multiplication changes observed during the core poison removal, the integral worth of the shim rod bank was tentatively estimated to be \$13.2.

V. CRITICAL EXPERIMENTS – INITIAL CORE CONFIGURATION

1. Initial Approach to Criticality

After the core poison rods had been removed, the final approach to critical was begun. The actuated safety rods were withdrawn one at a time. It was obvious that gross rod shadowing effects were being observed. The strong flux depressions caused the centrally-located K safety rod to be worth approximately the same as individual safety rods in the P-ring of unit cells. The two vernier rods were withdrawn fully. Based upon multiplication changes, their individual integral worth was estimated to be \$0.50. The shim rod bank was withdrawn as a unit; the individual rods were withdrawn in short steps, keeping the rods in the bank very near to a common position. The measurements during the shim rod withdrawal are tabulated in Table III and Fig. 16. Criticality was attained at 1624 hours July 14, 1963. The average position of the shim bank was 38.534,* which corresponds to an indicated ion chamber current of 1.33×10^{-9} ampere. (This was later found to correspond to a power of about 0.2 watt.)

Following the determination of the critical shim rod bank position, the plan was to perform calibrations of pairs of shim rods by the well-known scheme of step-wise exchanges between a fully inserted rod and a fully withdrawn rod to determine differential worths over the full range of rod travel. The transients were initiated from a steady-state ion current of 3 to 4×10^{-10} ampere. It soon became apparent that this procedure was not suitable for the system because of the overwhelming shadowing effect of the other rods in the shim bank; furthermore, the apparent worths of the rods were substantially less than expected. Detailed discussion of factors affecting the interpretation of transients is included in Appendix III. A considerable amount of experimenting was to be necessary before a satisfactory method could be devised for rod calibration.

2. Hot Critical Experiment

The insulation was installed on the sides of the duct, and the conversion was made to closed cycle ventilation, as described above. The shutdown

* Rod positions as cited in this report represent inches of rod penetration below the plane of the outer surface of the cell plates.

multiplication was rechecked. It was unchanged within the limits of uncertainty in measurement.

At this point the multiplications were determined for approximately the cold shutdown configurations for the Nevada tests:

<u>Configuration</u>	<u>Multiplication</u>
Shims 40.32, verniers 40.29	44.5
Shims 40.32, verniers 5.41	88.0

Prior to heating, the critical shim bank position was redetermined to evaluate the effect, if any, caused by the insulation of the system. The critical shim bank configuration at the same power as above was 38.566, indicating a very slight change from the previous value. The indicated core temperatures at this time ranged from 86 to 90°F. The measured critical point here, and that measured after cooling back to room temperature were the basis for evaluating the effect of increasing the core temperature.

When the core was heated to temperature the shutdown multiplication was rechecked. Within the limits of uncertainty, no change was produced by heating. At equilibrium the average indicated core temperature was 217°F (80% deflection on chart scale), which was corrected by recalibration to a true temperature of $209 \pm 5^\circ\text{F}$. The temperature increase in the heating process was $\Delta T = 129 \pm 7^\circ\text{F}$. The reactor was taken to critical at a power approximately the same as before. The critical shim bank position for the heated core corrected for thermal expansion was found to be 38.083. (Vernier rods are fully withdrawn to 5.41 unless otherwise indicated.) The effect of increased temperature expressed in terms of shim bank position was then

$$\frac{\Delta x}{\Delta T} = \frac{0.501 \pm 0.02 \text{ inch}}{129 \pm 7^\circ\text{F}} = 3.9 \times 10^{-3} \pm 7\% \text{ in./}^\circ\text{F},$$

and the temperature coefficient was negative.

During the warm experiment a measure of the power-dependence of the built-in source was obtained. Shims 1 through 11 were positioned at 37.884, and power was regulated with shim 12. The data are shown in Table IV. The data show that for a power change of a factor of 40 the movement in a single shim rod was 0.8 in., which corresponded to about 0.07-in. motion for the whole shim bank. Since there was no effort to assure very precise leveling of power at each of the above points, the information should be regarded as semiquantitative.

A measurement was also obtained of the worth of the reactivity swing of one vernier rod in terms of the shim rod bank. The data are summarized:

a) Vernier rods at 5.41; critical shim bank position: 38.129

b) One vernier at 5.40; one vernier at 39.885;

critical shim bank position 37.309

Worth of swing of vernier rod (34.475 in.) = 0.820 inch of shim bank travel.

The core was allowed to cool to room temperature. The critical shim bank position was again determined and found to be 38.603. This number differed slightly from that found before heating. The two numbers were averaged to obtain the temperature effect listed above.

3. Fission Counter Traverses 1-5

The equipment used in mapping flux by use of fission counters was installed. This set of measurements and all the succeeding ones were performed in the sector bounded by tie tubes M-10 and M-12 (see Fig. 3). When this equipment was in use, shims 10-12 were suspended at their operating positions, as shown in Fig. 11. The data of fission detector traverse No. 1 are listed in Table V. The traverse was made at an ion chamber current of 1×10^{-7} ampere (about 15 watts). The counter probes were found to be very unimportant neutronically; there was essentially no need to compensate their motion with the regulating rod. These measurements required about an hour of operation.

Fifteen minutes after shutting down following the flux measurements, a radiation survey was made of the reactor. Radiation levels were 190 mR/hr at the surface of the duct and 23 mR/hr at the support grid; 90 minutes after shutdown the levels were 40 mR/hr at the duct and 7 mR/hr at the grid.

The counters were repositioned for new traverses. At the same time a fission foil was positioned 110 cm into tube K-199 for use in calibrating the power level. The reactor was brought to critical at 1×10^{-7} ampere ion current and held at that level for 74 minutes. Fission detector traverse No. 2 was performed. The data are also listed in Table V. A typical flux traverse is shown in Fig. 17; the derived power map is shown in Fig. 18. An absolute fission determination showed 1.108×10^{11} fissions/gram of enriched uranium in the fission foil, which was estimated to correspond to a power level of 15 watts.

Fission traverses No. 3-5 followed in rapid succession. The data are collected in Table V.

A second, more careful evaluation was made of the power dependence of the critical rod configuration. The shim rod bank had the average position 38.239. Shim 4 was used to regulate power. There was a 10-minute wait at each power level to verify stability. The data are shown in Table VI. Here for a factor of 100 change in power the motion of a single shim rod was 0.78 inch, corresponding to about 0.07 inch for the entire shim bank.

4. Evaluation of Various Shim and Safety Rod Combinations

The fission probe drive unit was removed and several of the safety rods were relocated. The new shutdown multiplication was 12.6. The six boron-10 enriched safety rods for the Nevada test operations were installed in tie tubes L-1 through 6 with a core penetration of 45 inches.

The purpose of the following experiments was to simulate rod configurations to be used during the Nevada test operations to determine the degree of shutdown margin available. The experiments and results are summarized in Table VII.

The six safety rods were removed from the reactor, and the four optional shim rods were installed in tie tubes N-3, 8, 12, and 17. The fully shutdown multiplication for this arrangement was 9.4. The reactor was taken to critical using the bank of 16 shim rods. The verniers were fully withdrawn to 5.41. For a power corresponding to an ion chamber current of 6×10^{-9} ampere the average position of the shim rods was 35.232. For this measurement shim 12 was withdrawn about 5 inches beyond the position of the other rods in the bank. The four optional shim rods were removed from the reactor.

5. Poisoned Core Experiment

To simulate the effect of the temperature coefficient at elevated temperatures and permit withdrawal of the shim rods beyond the critical point for cold unpoisoned conditions, the core was poisoned with a number of stainless steel ribbons which contained 0.965% by weight of boron. The ribbons were inserted into the fuel element air passages and extended the full length of the reactor, including front and rear reflectors and the base blocks. The ribbons were 0.010 inch thick and 0.200 inch wide and had a density of 7.80 g/cm^3 .

For this particular set of measurements 266 ribbons were distributed in the core: two each in the K cell and cells R-1, 6, 11, 16, 21, and 26, and three in all other unit cells. With the poison installed the shutdown multiplication was 10.1. The critical shim rod bank position for this arrangement was 34.762 at a power corresponding to an ion chamber current of 6×10^{-9} ampere.

A mockup of the thermal fuse used as a high temperature scram sensor was installed in the core and the system was returned to critical as above. The critical shim bank position was 34.763. Hence the fuse had no neutronic effect. The mockup fuse was removed from the reactor.

The 16 thermocouple wires, to be used later for monitoring the temperatures of the transition tubes, were threaded through the core to investigate the neutronic worth of their lead wires in terms of shim rod bank motion. The reactor was taken to critical as described above; the critical shim bank position was 34.603. The worth of the poison was then 0.159 inch of shim bank travel.

At the completion of these experiments, all core poison rods were replaced in the tie tubes to permit the tie tube arrangement to be changed.

VI. CRITICAL EXPERIMENTS - MODIFIED CORE CONFIGURATION

The initial core configuration, based upon the design studies, had a tie-tube complement consisting of 81 René-41 tubes and 40 Hastelloy R-235 tubes. It was intended that necessary small adjustments in the core reactivity would be made by variations in the proportion of René and Hastelloy tubes. The foregoing measurements had indicated that the shutdown margin was less than had been intended; criticality had been attained at a shim rod bank position of 38.5 inches instead of the expected 35 inches. The decision was made to replace all Hastelloy tie tubes by René tubes.

1. Activation Foil Traverse - A

The tie tube exchange was performed. At the same time, 89 aluminum strips containing uranium fission foils were installed in the core. Additional stainless steel poison ribbons were also added; this made the total poison ribbon loading 806, distributed nominally 9 per unit cell.

Two No. 14 copper flux wires were placed in the core; one was covered with a brass tube to discriminate recoil activities from neutron-induced activity. Several aluminum wires were distributed inside the core to serve as fission recoil catchers.

A Westinghouse Type 6377 compensated ion chamber⁷ was positioned beside the reactor duct inside a large shield made of a cadmium-covered boral box filled with paraffin. The shield was intended to isolate the chamber from all the environment except the reactor itself. This assembly was mounted against the outside of the reactor duct opposite cells R-19 and 20. The bottom of the shield was 29 inches above the lower (aft) flange of the duct; the lower end of the ion chamber was 7 inches above the bottom of the shield. This arrangement was devised to obtain a low power calibration for this chamber to provide a starting point for calibrating instruments in Nevada.

The measured shutdown multiplication for this configuration was 8.2. The system was taken to critical at a power corresponding to an ion chamber current of 2.0×10^{-7} ampere and operated at that level until integrated power was about 82 watt-hours. The average critical shim rod bank position was 22.672.

From the time of first reaching the scheduled power, but prior to optimum leveling, the position of the regulating shim rod was observed as an aid to evaluating the significance of the delayed photoneutron groups. The data are summarized in Table VIII. Based upon the observations above, it was concluded that the prolonged photoneutron effects are quite small; therefore, a 10-minute wait to assure power stability would appear to be adequate. (See Appendix III.)

During the operation at power, the observed gamma fluxes as seen by remote area monitor units were 1.6 R/hr at 13.5 feet from the core axis and 0.7 R/hr at 15.5 feet from the core axis. Thirty minutes after shutdown, gamma radiation levels were 30 mR/hr at 5 feet from the side of the reactor duct, 100 mR/hr at 3 inches from the side of the reactor duct, and 100 mR/hr at the support grid. The neutron dose rate levels as observed by a portable survey instrument were equal in magnitude to the gamma field.

The fission foil traverses were removed for analysis. The data are listed in Table IX. A typical traverse is shown in Fig. 19.

The axial power map derived from the foil traverse of Fig. 19 is shown in Fig. 20. Radial plots derived from this series of traverses are shown in Figs. 21, 22, and 23.

Flux wires were removed for analysis. The flux wire traverse of tube P-7-186 is shown in Fig. 24. There was insufficient activity in the fission recoil catchers to be of any value.

Absolute fission determinations of selected foils indicated that the fission rate during the irradiation was 1.10×10^{12} fissions/sec, which corresponds to 33.7 watts. (This is based upon the assumed energy yield of 191.1 MeV per fission. See reference 3, page 106.)

The correlation plot between the Westinghouse ion chamber and the BF_3 ion chambers is shown in Fig. 25.⁸ It was determined that the nonlinearity at the upper end of the range was a property of the BF_3 ion chambers. The Westinghouse ion chamber and its shield were removed from the reactor.

The fission probe drive system was re-installed on the reactor for examinations of the more heavily poisoned configuration. A "Centronics" fission probe⁹ was also installed 45 inches down into tie tube R-13a, as a secondary normalizing detector.

2. Transient Measurements — 806 Poison Ribbons

A series of power transients was performed to determine the differential worth of the shim rod bank near the critical position at this stage of poisoning. Power was regulated by shim rod 4. Experimental conditions are summarized below:

<u>Power 1×10^{-9} ampere:</u>	Average shim bank position	22.692
	Position shim rod 4	24.726
<u>Power 3×10^{-9} ampere:</u>	Average shim bank position	22.664
	Position shim rod 4	24.393
<u>Transient No. 1:</u>	Average shim bank position	22.341
<u>Transient No. 1 Shim Rod Swing:</u>	$\Delta \bar{x} = 0.323$	
<u>Transient No. 2:</u>	Average shim bank position	22.136
<u>Transient No. 2 Shim Rod Swing:</u>	$\Delta \bar{x} = 0.528$	

The transient data taken from the power traces are tabulated in Table X. For this set of measurements the subcritical correction was taken to be 0.5 cent.. The corrected differential worth for the shim rod bank at the position range listed above is taken to be

$$\Delta\rho/\Delta x = 39.0 \text{ cents/inch} \pm 10\%.$$

This value is somewhat inferior to those from subsequent measurements because the procedure described in Appendix III had not yet been completely developed.

3. Fission Counter Traverses 6 and 7

The reactor was taken to critical at an ion chamber current of 2×10^{-7} ampere (36 watts) with an average shim bank position of 22.638. Fission detector traverse No. 6 was performed. The system was shut down, the fission probes were rearranged, and traverse No. 7 was performed at the same power with a critical bank position of 22.647. The data from the traverses are listed in Table XI; a typical traverse is shown in Fig. 26, the derived power map is shown in Fig. 27.

The BF_3 ion chamber voltages were increased to 600 V. This had the effect of greatly reducing the nonlinearity as correlated with the Westinghouse chamber, which was shown in Fig. 25.

4. Transient Measurements — 448 Poison Ribbons

Three poison ribbons were removed from cells R-1, 6, 11, 16, 21, and 26; four ribbons were removed from all other unit cells. Total remaining core poison loading was then 448. The shutdown multiplication was 9.1.

A series of transients was performed to determine the differential worth of the shim rod bank near the critical position at this stage of poisoning. Power was regulated by shim rod 9. Experimental conditions are summarized below:

<u>Power 1×10^{-9} ampere:</u>	Average shim bank position	29.256
	Position shim rod 9	32.052
<u>Power 3×10^{-9} ampere:</u>	Average shim bank position	29.237
	Position of shim rod 9 when measuring subcriticality correction	31.691
<u>Transient No. 1:</u>	Average shim bank position	29.000

Transient No. 1 Shim Rod Swing: $\Delta\bar{x} = 0.237$

<u>Transient No. 2:</u>	Average shim bank position	28.846
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Transient No. 2 Shim Rod Swing: $\Delta\bar{x} = 0.391$

The transient data taken from the power traces are tabulated in Table XII. For this set of measurements the subcritical correction was taken to be 0.8 cent. The corrected differential worth for the shim rod bank at the position range listed above is taken to be

$$\Delta\rho/\Delta x = 54.3 \text{ cents/inch} \pm 6\%.$$

5. Fission Counter Traverse 8

All poison ribbons were withdrawn from the core except 37 scattered ribbons which hung in the tubes and could not be removed at that time. The shutdown multiplication for this system was 10.3. The fission probes were reconnected in the same arrangement as for traverse No. 7. The "Centronics" fission probe was removed from the core, and a General Electric fission probe¹⁰ was inserted 45 inches into tube R-14-142 to be used instead.

The reactor was taken to critical at a power level of 2×10^{-7} ampere (about 22 watts) with a critical shim bank position of 35.900. Traverse No. 8 was performed. The data are listed in Table XIII.

6. Activation Foil Traverse - B

The residual poison ribbons were removed from the core. A second set of uranium fission foils was installed in the reactor. Their arrangement was almost identical to the ones in Set A. The system was taken to critical at a power level of 2×10^{-7} ampere until an integrated power of about 62 watt-hours was attained. The critical shim bank position was 36.335. The foil traverse data are listed in Table XIV. Absolute fission determinations of selected foils indicated that the fission rate during the irradiation was 7.29×10^{11} fissions/sec which corresponds to 22.3 watts.

Additional study was made of regulating rod position correlated with elapsed time. The data are summarized in Table XV. A typical traverse is shown in Fig. 28, for the same tube column as was shown for activation traverse A. The derived power map is shown in Fig. 29; derived radial power maps are shown for three locations in Figs. 30-32.

7. Transient Studies - No Core Poison

A transient series was performed to determine the differential shim rod bank worth near the critical position for a clean core. Power was regulated by shim rod 4. Experimental conditions are summarized below:

<u>Power 1×10^{-9} ampere:</u>	Average shim bank position	36.279
	Position of shim rod 4 (transient 1)	38.868
	Position of shim rod 4 (transient 2)	39.866

<u>Power 3×10^{-9} ampere:</u>	Average shim bank position	36.267
	Position of shim rod 4 when measuring subcriticality correction (transient 1)	38.540
	Position of shim rod 4 when measuring subcriticality correction (transient 2)	39.595

<u>Transient No. 1:</u>	Average shim bank position	36.042
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<u>Transient No. 1 Shim Rod Swing:</u>	$\Delta \bar{x} = 0.225$
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<u>Transient No. 2:</u>	Average shim bank position	35.930
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<u>Transient No. 2 Shim Rod Swing:</u>	$\Delta \bar{x} = 0.337$
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The transient data taken from the power traces are tabulated in Table XVI. For this set of measurements the subcritical corrections were 0.9 and 0.7 cent. The corrected differential worth for the shim rod bank at the position range listed above is taken to be

$$\Delta \rho / \Delta x = 64.1 \text{ cents/inch} \pm 6\%.$$

8. Fission Counter Traverses 9-11

Three additional fission counter traverses were performed with this same core configuration. The power level was 2×10^{-7} ampere (22 watts) with a critical shim bank position of 36.240. The power was regulated by use of shim 4. The traverse data are listed in Table XIII. A typical traverse is

shown in Fig. 33; the derived power map is shown in Fig. 34. A correlation was made between the motion of shim 4 and the cluster of counters during the traverse. These data are shown in Table XVII. Note that the indicated shim rod motion also takes into account the requirements for attaining a steady power level. The results are taken to mean that the cluster of fission probes has a reactivity worth of less than 0.05 inch of shim rod travel (<0.25 cent). The fission probe drive unit was removed from the reactor.

9. Critical Shim Rod Configuration for Heavily Poisoned Core

Ten boron steel poison ribbons were installed in cells R-1, 6, 11, 16, 21, and 26. Thirteen ribbons were installed in all other cells. The total loading was then 1165 poison ribbons. The shutdown multiplication for this poison loading was 7.0. The reactor was taken to critical at a power level of 3×10^{-9} ampere. The critical shim bank position was 9.194. The reactor was shut down and all poison ribbons were removed.

10. Activation Foil Traverse - C

A series of threshold detector foil traverses was installed in the reactor. Ten copper flux wire traverses were also positioned in the core. The reactor was taken to critical at a power level of 2×10^{-7} ampere until about 135 watt-hours of irradiation had been accumulated. The critical shim rod bank position was 36.177. The foil traverse data are listed in Table XVIII. The flux wire data are listed in Table XIX-a through -j.

During this irradiation run a more detailed study was made of regulating rod position with time. The data are shown in Table XX.

11. Measurements of Vernier Worth

A set of measurements was performed to determine the worth of the swing of both vernier rods through the range of travel to be used during the high power tests. At the beginning, the verniers were positioned at 40.413. The reactor was taken to critical at a power level of 3×10^{-9} ampere with a critical shim bank position of 34.583. The system was shut down; the verniers were withdrawn to 5.912; and the system was returned to critical at the same power level. The critical shim position was then 36.266. The swing of 34.501 inches of both vernier rods had the same reactivity worth as a swing of 1.683 inches in the shim rod bank. Based upon the transient data above, the worth of a single vernier rod should be 54 cents.

12. Measurements of Reactivity Worth of Gold Foils

A method of core reactivity adjustment which had been considered, in addition to the tie tube exchange, was plating the tie tubes with a thin deposit of gold. Although this alternative was not necessary, several experiments were performed to obtain a measure of the effect of gold plating upon the critical rod positions as a check on the multigroup diffusion calculations.

The gold plating was simulated by use of gold foils with dimensions $0.001 \times 0.440 \times 30.375$ inches, sandwiched between aluminum strips 0.063 inch thick. The units were installed inside core tie tubes so that the gold foils extended 30.375 inches into the fueled region of the reactor, beginning at the interface with the front reflector. The average gold foil weight was 4.162 ± 0.01 grams; the purity was 99.95%.

Prior to installing the gold foils, the shutdown multiplication was 12.7. Sixty gold foils were installed in the R-ring of unit cells, one foil per tie tube. The shutdown multiplication was then 12.6. The reactor was taken critical at a power level of 3×10^{-9} ampere. The critical shim bank position was 35.963. This gold foil loading was equivalent in worth to a shim rod bank shift of 0.303 inch, or 19 cents in reactivity.

The gold loading was increased to 94 foils, one in each tie tube except K, L-4, M-1-12, and P-1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24. The system was returned to critical at the same power as before. The critical shim bank position was 35.401. This foil loading was equivalent in worth of a shim rod bank shift of 0.865 inch, or 55 cents of reactivity.

13. Tory II-C Experiments for Operational Safety

The final series of experiments was a group of measurements intended to provide safety indices for various operations planned during the tests in Nevada. (The multiplications listed are the observed leakage multiplication adjusted by a factor of 2.0, derived from the estimated leakage probability. Rod positions cited are inches of penetration measured from the outer surface of the cell plates.)

a. The first set of measurements was to determine the multiplication for several degrees of shutdown:

<u>Configuration</u>	<u>Multiplication</u>
1. Shim and vernier rod positions: 40.5	39.9
2. Same, with stack of paraffin blocks beside the reactor duct	38.9

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Conclusion: No significant body tampering would be expected for

$$M \leq 40.$$

3. Shim and vernier rod positions: 40.5	16.5
6 B ₄ ¹⁰ C safety rods in L-ring: 45.0	
4. Shim and vernier rod positions: 40.5	
B ₄ ¹⁰ C safety rods in L-ring: 45.0	
12 transportation poison rods in tie tubes N-2,3,5,6,8,9,11,12,14,15,17,18	8.5
5. Shim and vernier rod positions: 40.5	
12 transportation poison rods in tie tubes N-2,3,5,6,8,9,11,12,14,15,17,18	10.8

Conclusion: Either configuration 4 or configuration 5 affords adequate shutdown margin for safe working conditions in the vicinity of the reactor.

b. The next series of measurements was used to determine how many shim and vernier rods could be withdrawn from the core without achieving criticality. The starting configuration was a4 above.

<u>Configuration</u>	<u>Multiplication</u>
1. a4 above, except vernier 1 withdrawn to 5.5	8.7
2. a4 above, except verniers 1 and 2 withdrawn to 5.5	9.1
3. a4 above, except verniers both to 5.5 shims 1, 2, and 3 to 5.5	9.7
4. a4 above, except verniers both to 5.5 and shims 1-6 to 5.5	11.2
5. a4 above, except verniers both to 5.5 and shims 1-9 to 5.5	13.0
6. a4 above, except all shims and verniers at 5.5	15.5

Conclusion: Starting from configuration a4, all hafnium elements may be withdrawn without attaining criticality.

c. The following series of measurements was used to determine where criticality occurs starting from configuration a3 above, first for sequential withdrawal of actuator groups and secondly for ganged withdrawal of actuators.

<u>Configuration</u>	<u>Multiplication</u>
1. a3 above, except shims 1-3 to 5.5	21.6
2. a3 above, except shims 1-6 to 5.5	38.1
3. a3 above, except shims 1-9 to 5.5	94.7
4. a3 above, except shims 1-9 to 5.5 and shims 10-12 to 28.4	critical (3×10^{-9} ampere)
5. a3 above, except shims 1-9 and both verniers at 5.5 and shims 10-12 to 37.5	critical (3×10^{-9} ampere)
6. Six safeties at 45, one vernier at 5.5, one vernier at 29.0, and shim bank at 21.33	critical (3×10^{-9} ampere)

Conclusion: When using the safety rods for added shutdown, withdrawal of all hafnium elements is not possible without attaining criticality; however, a great degree of freedom exists for exercising rod actuators. Only one actuator group of three shim rods is required to maintain a subcritical condition.

d. The following set of measurements was made to determine whether a subcritical condition would prevail if one shim rod actuator group should be fully withdrawn starting from configuration a1 above. (Two different groups were tested because of the slight differences in arrangement of the groups of three shim rods.)

<u>Configuration</u>	<u>Multiplication</u>
1. a1 above, except shims 1-3 to 5.5	212
2. a1 above, except shims 2-4 to 5.5	268

Conclusion: When shutdown due to full insertion of all hafnium rods, withdrawal of a single shim rod actuator group will produce a very high multiplication, but will not cause attainment of criticality. This situation was not a design

objective, just a fortunate circumstance. Note that the shutdown position used in the above series was 40.5. In the actual high power tests the shutdown position will probably be about 40.0, so at 40.5 inches the reactor is more subcritical by 0.5 inch of shim bank travel (about 32 cents). This does not alter the conclusion above; the system is expected to be subcritical, but with a higher multiplication.

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Table I. Summary of reactor data.

<u>Core (Active):</u>	
Length	51.03 inches (av)
Equivalent diameter	47.46 inches (av)
Volume	52.2 ft ³
Void fraction	0.479
<u>Fuel:</u>	
Material	UO ₂ (93.2% enriched in U ²³⁵)
Mass in core	63.5 kg
Mass of U ²³⁵	52.1 kg
Molar ratio BeO/U ²³⁵ in fueled region	362 (av)
Maximum UO ₂ concentration	6.85%
Minimum UO ₂ concentration	1.08%
<u>Moderator:</u>	
Material	BeO
Density	98% of theoretical 3.008 g/cm ³
Weight of active core	2087 kg (4603 lb)
<u>Reflector:</u>	
Side — thickness	2.98 inches (av)
material	BeO; nickel shims
Aft — thickness	2.37 inches (av)
material	BeO
Forward — thickness	9.67 inches (av)
material	BeO
<u>Reflected Core</u>	
Overall ceramic length	63.08 inches
Overall diameter	53.42 inches
Volume	82.0 ft ³
Weight	4617 kg (10,181 lb)
Total number of ceramic tubes	464,379
Total number of fueled tubes	293,412

Table II. Summary of measurements during core poison removal.

Configuration	Corrected multiplication
1. All Hf elements inserted, 107 poison rods in place.	3.19
2. Twelve shims withdrawn, 107 poison rods in place.	3.63
3. Even numbered shims inserted, odd numbered shims withdrawn, 107 poison rods in place.	3.33
4. Same as 3 except poison rods removed from L-ring.	3.58
5. Same as 3, except poison rods removed from L- and N-rings.	5.07
6. Same as 3, except poison rods removed from L-, N-, and P-rings.	6.57

Table II. Summary of measurements during core poison removal. (Cont'd.)

Configuration	Corrected multiplication
7. Same as 3, except poison rods removed from L-, N-, and P-rings and 44 rods were removed from R-ring.	13.8
8. All shims inserted, poison rods out of L-, N-, and P-rings and 44 rods out of R-ring.	8.83
9. All actuated rods inserted, all 96 core poison rods removed.	11.4
10. Same as 9, except actuated K safety rod withdrawn.	12.2
11. All shim rods inserted, all safeties withdrawn.	26.4

Table III. Shim rod withdrawal during initial approach to critical.

Shim bank average position (inches insertion)	Corrected multiplication
44.424	42.0
43.423	49.1
42.414	59.1
41.421	77.0
40.431	112.5
39.420	226.1
38.944	460
38.534	Critical at 1.33×10^{-9} ampere

Table IV. Power dependence of "critical" rod position hot core.

Power (amperes) ion chamber No. 1	Position shim 12
6.2×10^{-8}	39.98
1.25×10^{-8}	40.08
4.6×10^{-9}	40.34
1.3×10^{-9}	40.77

Table V. Fission detector traverses 1-5 — initial core configuration.

Traverse (final pass)	Probe	Tube	r/R (R = 23.68 in.)	Norm factor	$\int R d\epsilon$	$\int \frac{R_{14}}{R d\epsilon}$	$\int \frac{\rho R_{14}}{\rho R d\epsilon}$	$\frac{R_7}{X/L}$ = .178	$\frac{R_9}{X/L}$ = .208	$\frac{R_{13}}{X/L}$ = .488	$\frac{R_{14}}{X/L}$ = .550	$\frac{R_{15}}{X/L}$ = .610	$\frac{\rho R_7}{X/L}$ = .178	$\frac{\rho R_9}{X/L}$ = .208	$\frac{\rho R_{13}}{X/L}$ = .488	$\frac{\rho R_{14}}{X/L}$ = .550	$\frac{\rho R_{15}}{X/L}$ = .610	Class	Location ^a	
8/1/63	1	R28(198)	.912	.9524	.5758	1.7709	.04695	1.5420	.3329	.3008	.9728	1.0197	1.0434	.04876	.04406	.06907	.07240	.07408	3	—
	4	R27(104)	.916	.4782	.5651	1.7774	.04456	1.6004	.3334	.3058	.9671	1.0045	1.0051	.04884	.04480	.06866	.07132	.07136	4	—
	8	R24(78)	.895	.7710	.5564	1.7956	.04376	1.6209	.3170	.2929	.9327	.9990	.9954	.04644	.04292	.06622	.07093	.07067	4	—
	11	R24(221)	.945	.9009	.5347	1.7814	.04506	1.5010	.3115	.2881	.9085	.9525	.9597	.04956	.04584	.06450	.06763	.06814	6	—
	12	R25(76)	.866	.9830	.6227	1.7911	.04531	1.6148	.3556	.3336	1.0580	1.1154	1.1183	.04797	.04500	.06941	.07317	.07336	1	—
	13	R25(36)	.889	.7790	.5827	1.7540	.04388	1.5281	.3353	.3067	.9909	1.0221	1.0390	.04913	.04493	.06500	.06705	.06816	5	—
8/1/63	1	R25(233)	.995	.9524	.6239	1.7446	.04332	1.5228	.3757	.3567	1.0621	1.0885	1.1074	.05067	.04811	.06436	.06596	.06711	1	Λ
	4	M10(185)	.343	.4782	1.3897	1.5462	.03913	1.4057	.6027	.6162	1.9722	2.1488	2.5211	.03593	.03451	.05049	.05501	.06454	1	—
	8	R24(233)	.955	.7710	.5401	1.7529	.04402	1.5269	.3102	.2789	.9169	.9467	.9578	.04936	.04438	.06510	.06721	.06800	5	—
	9	M11(246)	.499	1.1737	1.1503	1.5771	.04278	1.3696	.5370	.5397	1.7015	1.8141	2.0712	.04468	.04490	.05496	.05860	.06690	6	—
	11	P20(146)	.715	.9009	.8376	1.7178	.04442	1.5515	.4697	.4338	1.4014	1.4388	1.4859	.04970	.04234	.06713	.06892	.07118	1	—
	12	R28(115)	.850	.9830	.6709	1.7488	.04820	1.4752	.3939	.3545	1.1393	1.1733	1.1897	.05314	.04783	.06904	.07110	.07210	3	—
13	R28(42)	.850	.7790	.6426	1.7712	.04615	1.4946	.3685	.3420	1.1070	1.1382	1.1472	.04971	.04613	.06709	.06897	.06952	3	—	
8/2/63	1	R24(297)	.969	.9524	.6062	1.7767	.04909	1.5576	.3371	.3397	1.0353	1.0770	1.0698	.05363	.05405	.07351	.07646	.07595	4	—
	8	M11(148)	.446	.7710	1.1855	1.5545	.03827	1.3340	.5348	.5369	1.6771	1.8428	2.1538	.04113	.04129	.04645	.05105	.05966	6	—
	9	R27(104)	.913	1.1737	.5781	1.7763	.04557	1.5998	.3220	.3095	.9755	1.0268	1.0428	.04718	.04534	.06926	.07290	.07404	4	—
	11	L6(219)	.280	.9009	1.5268	1.5999	.04159	1.3918	.6859	.7387	2.1992	2.4426	2.7609	.04157	.04476	.05212	.05789	.06543	6	—
	12	P22(177)	.760	.9830	.8305	1.7809	.04960	1.5448	.4524	.4568	1.3682	1.4791	1.5099	.05189	.05239	.07088	.07662	.07821	3	—
	13	N16(76)	.565	.7790	1.1466	1.7129	.04985	1.4931	.5724	.5753	1.7998	1.9640	2.0614	.05157	.05184	.06821	.07444	.07813	3	—
8/5/63	1	M11(35)	.335	1.0650	1.3180	1.5675	.03744	1.4126	.5778	.6116	1.8525	2.0658	2.4325	.03790	.03425	.04742	.05289	.06227	2	—
	4	R24(233)	.955	.5682	.5041	1.7897	.04117	1.5558	.2763	.2714	.8550	.9022	.9210	.04396	.04317	.06070	.06405	.06539	5	—
	8	N16(22)	.544	.6667	1.1747	1.6706	.04284	1.4795	.5709	.6035	1.7613	1.9625	2.1354	.04749	.04285	.05689	.06339	.06897	1	—
	9	P19(202)	.697	1.3605	.7897	1.7105	.04005	1.4940	.4245	.4182	1.2818	1.3507	1.4236	.04491	.04082	.05679	.05983	.06307	5	—
	11	R25(213)	.955	1.0373	.5462	1.7458	.04621	1.4653	.3127	.3099	.9271	.9536	.9611	.04975	.04931	.06582	.06771	.06824	3	—
	13	R26(71)	.990	.9216	.6053	1.7392	.04246	1.5025	.3586	.3720	1.0115	1.0527	1.0750	.04838	.05018	.06130	.06379	.06514	5	V
8/5/63	1	N17(245)	.623	1.0650	1.0206	1.7309	.04434	1.5101	.5341	.5470	1.6529	1.7666	1.8684	.05212	.04551	.06265	.06695	.07081	2	—
	4	R24(353)	.992	.5682	.5833	1.7735	.04499	1.5480	.3490	.3427	1.0045	1.0345	1.0277	.04709	.04623	.06087	.06269	.06228	4	Λ
	8	L6(115)	.230	.6667	1.5382	1.5716	.04069	1.4079	.6971	.7337	2.1492	2.4173	2.6999	.03940	.04109	.05094	.05729	.06399	3	—
	9	R26(6)	.921	1.3605	.6371	1.7769	.05211	1.5424	.3675	.3523	1.0888	1.1321	1.1491	.05384	.05161	.07730	.08038	.08159	6	—
	11	K(196)	.067	1.0373	1.7551	1.6953	.04317	1.5093	.8811	.9007	2.7309	2.9754	3.1703	.04934	.04314	.05981	.06516	.06943	5	—
	12	R28(257)	.958	1.2484	.5616	1.8102	.04757	1.5174	.3256	.3181	.9778	1.0167	1.0228	.05181	.05060	.06424	.07218	.07262	6	—
	13	L6(21)	.132	.9216	1.6839	1.6753	.04288	1.4410	.8394	.8745	2.6223	2.8212	3.0259	.04701	.04897	.05743	.06178	.06268	3	—

^a Unperturbed = —, thin reflector = Λ, thick reflector = V.

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Table VI. Power dependence of "critical" rod position — initial core configuration.

Power (amperes) ion chamber No. 1	Position shim 4
1.2×10^{-9}	42.937
3×10^{-9}	42.471
6×10^{-9}	42.323
1×10^{-8}	42.240
1×10^{-7}	42.154

Table VII. Shutdown multiplications at design rod positions — initial core configuration.

Configuration	Multiplication
a) B ¹⁰ safety rods 45.00 Vernier rods 5.41 Shim rods 40.06	23.5
b) Same as a), except shims 1-3 at 5.5	35.5
c) Same as b), except shims 1-6 at 5.5	103
d) Same as c), except shims 7-9 at 27.87	Critical (6×10^{-9} ampere)
e) Same as b), except shims 1-3, 7-9 at 5.5, shims 4-6 at 26.24	Critical (6×10^{-9} ampere)

Table VIII. Time dependence in position of regulating rod.

Time after attaining power, min	Position shim 12
5	25.066
35	25.074
65	25.078
95	25.053
125	25.049

Table IX. Summary of data — activation foil traverse A.

Traverse	Chan-		r/R	Norm	$\int R d\epsilon$	$\int R_{14} d\epsilon$	$\int \rho R d\epsilon$	$\int \rho R_{14} d\epsilon$	R_7	R_9	R_{13}	R_{14}	R_{15}	ρR_7	ρR_9	ρR_{13}	ρR_{14}	ρR_{15}	Class	Location ^a
8/26/63	nel	Tube	(R = 23.68 in.)	factor					X/L = .178	X/L = .208	X/L = .488	X/L = .550	X/L = .610	X/L = .178	X/L = .208	X/L = .488	X/L = .550	X/L = .610		
10 Foil Run A Set 1	2	K(19)	.0884	1.0000	.5541	1.8551	.01367	1.6462	.2537	.2871	1.0002	1.0279	1.0232	.01421	.01375	.02190	.02251	.02241	2	—
	3	K(161)	.0343	"	.5758	1.8764	.01472	1.6075	.2618	.3008	1.0062	1.0804	1.0178	.01466	.01685	.02204	.02366	.02229	6	O
	4	L1(186)	.1865	"	.5386	1.8602	.01396	1.7006	.2385	.2748	.9630	1.0019	.9698	.01335	.01317	.02282	.02375	.02299	2	—
	5	L3(135)	.2032	"	.5430	1.8028	.01405	1.6516	.2358	.2663	1.0063	.9789	.9525	.01321	.01276	.02385	.02320	.02257	5	O
	6	M3(206)	.3761	"	.4357	1.8924	.01314	1.6067	.1633	.1812	.7952	.8246	.8192	.01160	.01287	.02036	.02111	.02097	6	Δ
	7	M5(184)	.3800	"	.4447	1.9204	.01296	1.6875	.1742	.1952	.8145	.8541	.8287	.01237	.01183	.02085	.02186	.02121	5	—
	8	M9(63)	.3998	"	.4359	1.9091	.01379	1.6721	.1634	.1844	.7995	.8322	.8006	.01160	.01309	.02215	.02305	.02218	6	X
	9	M9(183)	.3840	"	.4425	1.9211	.01287	1.6911	.1733	.1887	.8085	.8500	.8276	.01230	.01143	.02070	.02176	.02119	5	—
	10	M10(60)	.3721	"	.4404	1.9370	.01284	1.7005	.1779	.1926	.8190	.8531	.8326	.01263	.01167	.02097	.02184	.02131	2	—
	11	M10(70)	.3523	"	.4535	1.9831	.01276	1.8038	.1755	.1977	.8489	.8993	.8597	.01151	.01107	.02173	.02302	.02201	1	—
	12	M10(47)	.3009	"	.4864	1.8576	.01268	1.6883	.1873	.2155	.8914	.9035	.8971	.01135	.01117	.02113	.02141	.02126	1	—
	13	M12(164)	.3932	"	.4290	1.9384	.01358	1.6962	.1612	.1803	.7990	.8316	.8249	.01144	.01280	.02213	.02304	.02285	3	X
	14	N3(224)	.5898	"	.3277	1.7573	.01376	1.4650	.1634	.1758	.5728	.5758	.5954	.01473	.01583	.02005	.02015	.02084	3	—
10 Foil Run A Set 2	2	N7(38)	.6717	1.0000	.2857	1.7994	.01349	1.5632	.1410	.1480	.5063	.5142	.5087	.01376	.01333	.02076	.02108	.02086	2	Δ
	3	N8(64)	.5767	"	.3380	1.8364	.01349	1.6100	.1663	.1790	.6059	.6207	.6056	.01499	.01376	.02121	.02172	.02119	1	O
	4	N9(29)	.6241	"	.3109	1.8211	.01347	1.5926	.1551	.1695	.5581	.5661	.5563	.01514	.01410	.02115	.02146	.02108	1	—
	5	N12(23)	.5793	"	.3416	1.7860	.01426	1.4978	.1562	.1767	.5996	.6102	.6058	.01408	.01592	.02099	.02136	.02120	6	Δ
	6	P11(133)	.7205	"	.2516	1.8218	.01398	1.5698	.1348	.1416	.4462	.4583	.4455	.01427	.01499	.02137	.02195	.02134	6	Δ
	7	P18(193)	.7007	"	.2570	1.8284	.01301	1.6001	.1378	.1398	.4568	.4699	.4637	.01458	.01365	.02024	.02082	.02054	1	—
	8	P20(96)	.7535	"	.2315	1.7853	.01389	1.5416	.1213	.1277	.4038	.4134	.4082	.01391	.01465	.02092	.02141	.02115	6	Δ
	9	P23(183)	.7548	"	.2318	1.8077	.01339	1.6213	.1245	.1296	.4094	.4190	.4092	.01428	.01371	.02121	.02170	.02120	4	—
	10	R13(57)	.8168	"	.2003	1.8101	.01372	1.6016	.1130	.1185	.3512	.3625	.3584	.01524	.01473	.02128	.02197	.02172	2	—
	11	R13(339)	.9831	"	.1655	1.8224	.01423	1.5049	.09765	.1042	.2898	.3015	.2944	.01554	.01658	.02058	.02141	.02090	3	Δ
	12	R29(334)	.9870	"	.1685	1.8268	.01375	1.5891	.09833	.09691	.2968	.3078	.2955	.01564	.01542	.02107	.02186	.02098	4	Δ
20 Foil Run A	2	K(79)	.0633	1.0000	.5542	1.8479	.01416	1.5840	.2491	.2861	.9863	1.0241	1.0048	.01395	.01602	.02160	.02243	.02201	6	Δ
	3	K(242)	.0884	"	.5662	1.8477	.01395	1.6421	.2639	.2949	1.0183	1.0462	1.0328	.01478	.01413	.02230	.02291	.02262	5	—
	4	M9(173)	.3906	"	.4337	1.9336	.01372	1.6934	.1651	.1799	.8056	.8386	.8296	.01172	.01277	.02231	.02323	.02298	6	X
	5	P17(108)	.8630	"	.1790	1.8359	.01320	1.6335	.1013	.1059	.3167	.3287	.3247	.01367	.0143	.02077	.02156	.02130	2	—
	6	R21(54)	.9791	"	.1804	1.7993	.01479	1.5587	.1047	.1102	.3176	.3246	.3196	.01666	.01753	.02255	.02305	.02269	1	V

^a Unperturbed = —, near tie tube = O, near thermocouple group = Δ , near shim = X, thin reflector = Δ , thick reflector = V.

Table X. Transient data for core loaded with 806 poison ribbons.

t, sec ^a	Doubling time, sec	Observed period, sec	Asymptotic period correction ^b	Asymptotic period, sec	Reactivity swing, cents
Transient No. 1					
56.7	47.9	69.1	0.8%	69.7	12.7
76	48.5	70.0	0.4%	70.4	12.6
93	49.1	70.8	--	70.8	12.5
105	49.6	71.5	--	71.5	12.4
117	48.8	70.4	--	70.4	12.6

Corrected differential worth 39.4 cents/inch

Transient No. 2					
12.2	22.0	31.7	4.0%	33.0	20.9
22.5	22.8	32.9	1.8%	33.5	20.7
26.4	22.8	32.9	1.4%	33.4	20.7
32.2	23.5	33.9	0.9%	34.2	20.4

Corrected differential worth 38.7 cents/inch

^a Elapsed time after rod motion stopped.^b See Appendix III.

Table XI. Fission detector traverses 6 and 7 — 806 poison ribbons in core.

Traverse (final pass)	Probe	Tube	r/R ($R =$ 23.68 in.)	Norm factor	$\int R d\epsilon$	$\int R_{14} d\epsilon$	$\int \rho R d\epsilon$	$\int \rho R_{14} d\epsilon$	R_7 X/L =.178	R_9 X/L =.208	R_{13} X/L =.488	R_{14} X/L =.550	R_{15} X/L =.610	ρR_7 X/L =.178	ρR_9 X/L =.208	ρR_{13} X/L =.488	ρR_{14} X/L =.550	ρR_{15} X/L =.610	Class	Location ^a
6 8/19/63	1	M12(177)	.359	1.464	1.3376	1.8986	.03769	1.7250	.5394	.5797	2.3774	2.5396	2.4897	.03539	.03246	.06086	.06501	.06374	1	—
	2	R28(257)	.950	.8439	.4892	1.8038	.04171	1.5024	.3021	.2750	.8603	.8825	.8501	.04806	.04735	.06108	.06266	.06036	6	—
	3	R25(76)	.863	.6653	.5664	1.8282	.04151	1.6367	.3389	.3231	1.0067	1.0355	1.0152	.04571	.04359	.06604	.06793	.0660	1	—
	4	L6(219)	.277	.4500	1.3698	1.8245	.03766	1.5727	.6227	.6643	2.3717	2.4992	2.4570	.03374	.04257	.05621	.05923	.05823	6	—
	5	K(214)	.061	.8432	1.5159	1.8299	.03812	1.5938	.6002	.6693	2.5211	2.7739	2.8194	.03361	.03748	.05521	.06075	.06174	6	—
	7	P23(178)	.710	.8834	.7254	1.8270	.03874	1.6385	.4294	.4108	1.2458	1.3253	1.2760	.04543	.04009	.05968	.06348	.06112	4	—
	8	N16(22)	.541	.5640	.8907	1.7997	.03271	1.5830	.4519	.4541	1.4898	1.6030	1.6276	.03760	.03224	.04812	.05178	.05257	1	—
	9	P20(67)	.660	1.149	.8505	1.8190	.04001	1.5854	.4994	.4859	1.4632	1.5470	1.5189	.04874	.04378	.05999	.06343	.06228	1	—
	10	R28(42)	.839	.7764	.6046	1.8685	.04377	1.5640	.3639	.3360	1.0846	1.1298	1.0865	.04909	.04533	.06573	.06846	.06584	3	—
	11	M11(187)	.454	.8157	1.1440	1.8466	.03833	1.6478	.5323	.5581	2.0024	2.1126	2.0453	.04093	.03661	.05987	.06317	.06115	5	—
	13	N17(1)	.420	.6998	1.2429	1.8550	.03919	1.6295	.5587	.5937	2.2025	2.3056	2.2617	.04304	.03895	.06101	.06387	.06265	1	—
7 8/19/63	1	N16(76)	.565	1.464	.5683	1.8770	.02200	1.6970	.2711	.2843	1.0022	1.0666	1.0529	.02255	.02018	.03508	.03733	.03685	4	—
	2	R28(266)	.955	.8439	.5296	1.8112	.04352	1.5648	.3025	.3088	.9387	.9592	.9513	.04812	.04913	.06665	.06810	.06755	5	—
	3	R25(233)	.995	.6653	.5957	1.8058	.04167	1.5645	.3512	.3805	1.0552	1.0757	1.0830	.04738	.05133	.06395	.06518	.06563	1	Λ
	4	L6(41)	.140	.4500	1.5761	1.7886	.04047	1.5257	.7520	.8499	2.7125	2.8191	2.8433	.04211	.04787	.05940	.06174	.06227	3	—
	5	K(196)	.0673	.8432	1.9972	1.7847	.04809	1.6231	.6925	.7788	3.2511	3.5643	3.7159	.03878	.03730	.07120	.07806	.08138	5	—
	6	R25(213)	.955	.7911	.5371	1.8551	.04579	1.5451	.3063	.3239	.9420	.9964	.9729	.04873	.05153	.06688	.07074	.06907	3	—
	7	R24(221)	.945	.8834	.5502	1.8633	.04688	1.5528	.3299	.3238	.9391	1.0253	.9877	.05249	.05151	.06668	.07279	.07013	6	—
	8	M11(148)	.446	.5640	1.2144	1.7780	.03983	1.5016	.5156	.5492	2.0869	2.1592	2.2511	.03965	.04224	.05781	.05981	.06236	6	—
	9	R26(71)	.990	1.149	No data,	bad connection.													5	V
	10	R25(122)	.897	.7764	.2041	1.8588	.01627	1.6560	.1125	.1148	.3562	.3795	.3705	.01648	.01682	.02529	.02694	.02630	5	—
	11	M10(185)	.343	.8157	1.2799	1.8294	.03638	1.6477	.5742	.6321	2.2634	2.3414	2.3464	.03767	.03540	.05794	.05994	.06007	1	—
	13	P22(177)	.760	.6998	.7402	1.8329	.04458	1.5763	.4307	.4231	1.3221	1.3567	1.3246	.04940	.04852	.06849	.07028	.06862	3	—

^a Unperturbed = —, thin reflector = Λ, thick reflector = V.

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Table XII. Transient data for core loaded with 448 poison ribbons.

$t,^a$ sec	Doubling time, sec	Observed period, sec	Asymptotic period correction ^b	Asymptotic period, sec	Reactivity swing, cents
<u>Transient No. 1</u>					
62	50.3	72.6	0.8%	73.0	12.2
91	50.3	72.6	0.4%	73.0	12.2
113	50.6	73.0	--	73.0	12.2
130	51.2	73.8	--	73.8	12.1
143	51.9	74.9	--	74.9	12.0
154	52.5	75.8	--	75.8	11.9
213	53.8	77.6	--	77.6	11.7
Corrected differential worth 54.4 cents/inch					
<u>Transient No. 2</u>					
26	22.7	32.8	1.4%	33.3	20.8
32.6	23.5	33.9	0.9%	34.2	20.4
39.2	23.5	33.9	0.6%	34.1	20.5
45	23.8	34.4	0.4%	34.6	20.3
71	24.5	35.4	--	35.4	20.0
73.5	24.2	34.9	--	34.9	20.2
Corrected differential worth 54.2 cents/inch					

^a Elapsed time after rod motion stopped.^b See Appendix III.

Table XIII. Fission detector traverses 8-11 — no poison in core.

Traverse (final pass)	Probe	Tube	r/R ($\frac{R-23}{68}$ in)	Norm factor	$\int R d\epsilon$	$\int R_{14} d\epsilon$	$\int \rho R d\epsilon$	$\int \rho R_{14} d\epsilon$	R_7 X/L 178	R_9 X/L 208	R_{13} X/L 488	R_{14} X/L 550	R_{15} X/L 610	ρR_7 X/L 178	ρR_9 X/L 208	ρR_{13} X/L 488	ρR_{14} X/L 550	ρR_{15} X/L 610	Class	Location ^a
8 8/23/63	1	N16(76)	565	1 2312	1 1120	1 7694	04272	1 6121	5238	5369	1 7211	1 9676	2 0745	04385	03812	06024	06886	07261	4	—
	2	R28(266)	955	7576	5461	1 7714	04452	1 5427	3149	3001	9113	9647	9830	05010	04775	06470	06868	06979	5	—
	3	R25(233)	995	6242	6331	1 7973	04386	1 5721	3620	3792	1 0741	1 1379	1 1507	04883	05116	06509	06896	06973	1	Δ
	4	L6(41)	140	4047	1 6000	1 7069	04042	1 4796	7402	7885	2 3946	2 7310	2 9495	04145	04116	05244	05981	06459	3	—
	5	K(196)	0673	4621	1 7677	1 6845	04231	1 5411	6338	6735	2 4434	2 9776	3 3653	03550	03226	05351	06521	07370	5	—
	6	R25(213)	955	7463	5527	1 8085	04656	1 5241	3140	3084	9287	9995	1 0060	04995	04907	06593	07097	07143	3	—
	7	R24(221)	945	7413	5546	1 7872	04667	1 5082	3219	2958	9129	9913	9853	05122	04707	06481	07038	06996	6	—
	8	M11(148)	446	3850	1 1722	1 6597	03787	1 4232	4654	5048	1 6120	1 9455	2 2329	03579	03882	04465	05389	06185	6	—
	10	R25(122)	897	2 1322	2131	1 7638	01686	1 5832	1206	1111	3614	3759	3812	01767	01627	02566	02669	02707	5	—
	11	M10(185)	343	7949	1 3112	1 6712	03695	1 5180	5609	6217	1 8603	2 1913	2 5380	03680	03482	04762	05610	06497	1	—
	13	P22(177)	760	6423	7903	1 7817	04709	1 5489	4453	4239	1 2942	1 4080	1 4355	05108	04862	06704	07293	07436	3	—
9 8/28/63	1	P20(67)	660	1 2312	07549	1 7871	003489	1 5853	03960	03754	1248	1349	1384	00389	00338	00512	00553	00567	1	—
	2	R28(42)	839	7576	04976	1 7821	003537	1 5068	02713	02575	08451	08869	1 09016	00366	00347	00508	00533	00542	3	—
	3	R28(257)	950	6242	05085	1 8130	004273	1 5316	02900	02623	08751	09219	09182	00461	00417	00621	00655	00652	6	—
	4	R27(230)	987	4047	04498	1 7264	003137	1 5002	02553	02567	07568	07765	07992	00344	00346	00459	00471	00484	5	Δ
	5	L6(219)	277	4621	11393	1 6494	003023	1 4734	03982	04322	1578	1879	2207	00241	00262	00374	00445	00523	6	—
	6	R25(233)	995	7463	046707	1 7931	003233	1 5699	02722	02713	08028	08375	08269	00367	00366	00486	00508	00501	1	—
	7	N16(22)	541	7413	09141	1 7088	003327	1 5167	04355	04375	1422	1562	1680	00362	00311	00459	00505	00543	1	—
	8	K(214)	061	3850	12623	1 6427	003164	1 4352	05319	05745	1911	2074	2258	00299	00322	00419	00454	00494	6	—
	9	P23(178)	710	1 1696	06973	1 7461	003695	1 5784	03785	03646	1153	1218	1247	00400	00356	00552	00583	00597	4	—
	10	M11(187)	454	2 1322	03774	1 6601	001245	1 5043	01587	01614	05402	06265	07396	00122	00106	00162	00187	00221	5	—
	11	R25(76)	863	7949	05019	1 7471	003649	1 5762	03009	02552	08619	08768	09165	00406	00344	00565	00575	00601	1	—
	13	N17(1)	420	6423	11257	1 6652	003514	1 4777	04992	05208	1635	1875	2163	00384	00342	00453	00519	00599	1	—
10 8/29/63	1	P20(169)	773	1 1507	05943	1 7702	003678	1 6020	03189	02923	09904	1052	1104	00396	00335	00555	00589	00618	1	—
	2	R28(47)	826	7267	05288	1 7574	003576	1 5747	02934	02689	08903	09292	09432	00396	00334	00540	00564	00572	5	—
	3	R28(275)	959	6803	04666	1 7992	003930	1 5166	02629	02442	07941	08395	08244	00418	00389	00564	00596	00585	6	—
	4	R27(149)	937	4095	03934	1 8485	003181	1 6235	02224	02089	06547	07273	07080	00354	00332	00465	00516	00503	1	—
	5	L6(166)	232	2935	1571	1 6166	004031	1 4937	05607	05734	2169	2540	3085	00340	00297	00514	00602	00731	4	—
	6	R25(233)	992	7231	04793	1 7686	003319	1 5479	02700	02778	08349	08477	08661	00364	00375	00506	00514	00525	1	Δ
	7	N15(194)	617	6493	09130	1 7380	004096	1 4684	04771	04745	1447	1587	1667	00466	00463	00549	00601	00632	3	—
	8	K(240)	095	2669	1459	1 6553	003534	1 4962	06146	06534	2180	2415	2706	00344	00313	00477	00529	00593	5	—
	9	P23(240)	764	1 1655	06150	1 7540	003625	1 5303	03411	03201	1012	1071	1100	00424	00367	00524	00555	00570	5	—
	10	M11(59)	351	7252	1215	1 6471	003423	1 4962	04819	05175	1711	2001	2359	00316	00290	00438	00512	00604	5	—
	11	R24(145)	934	8333	04208	1 7703	003543	1 4928	02448	02208	06952	07450	07471	00389	00351	00494	00529	00530	6	—
	13	N18(194)	913	7072	08811	1 7014	003208	1 5094	04332	04267	1382	1499	1620	00360	00303	00447	00484	00523	4	—
11 8/29/63	3	R27(257)	1 008	6803	05248	1 7598	003642	1 5366	03137	03141	08662	09235	09317	00423	00424	00525	00560	00565	4	Δ
	4	R27(30)	852	4095	04114	1 7563	003104	1 5273	02288	02186	06955	07226	07203	00309	00295	00456	00474	00473	6	—
	5	K(238)	095	2935	1373	1 6920	003360	1 5137	04492	04862	1966	2322	02659	00252	00272	00431	00509	00582	6	—
	6	R25(233)	992	7231	04857	1 7741	003360	1 5540	02842	02732	08073	08617	08761	00383	00369	00489	00522	00531	1	Δ
	7	N16(29)	546	6493	09787	1 7367	003720	1 4758	04722	04720	1509	1700	1827	00393	00393	00488	00549	00590	3	—
	8	K(240)	095	2669	1235	1 7037	002982	1 5452	04911	05098	1881	2104	2334	00275	00244	00412	00461	00511	5	—
	9	P19(21)	588	1 1655	08669	1 7602	003656	1 5816	04374	04355	1368	1526	1577	00394	00335	00525	00578	00598	2	—
	10	M12(115)	317	7252	1236	1 6833	003486	1 5277	05027	05285	1738	2081	2405	00330	00296	00445	00536	00616	2	—
	11	R24(34)	792	8333	04916	1 7787	003054	1 6034	02775	02802	08170	08744	08889	00345	00298	00458	00490	00498	1	—
	13	M10(136)	327	7072	1049	1 6700	003062	1 4650	04469	04648	1462	1752	2029	00293	00305	00374	00449	00519	3	—

^a Unperturbed — thin reflector Δ thick reflector V
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Table XIV. Summary of data — activation foil traverse B.

Traverse	Channel	Tube	r/R (R = 23.68 in.)	Norm factor	$\int R d\epsilon$	$\int R_{14} d\epsilon$	$\int \rho R d\epsilon$	$\int \rho R_{14} d\epsilon$	R_7 X/L = .178	R_9 X/L = .208	R_{13} X/L = .488	R_{14} X/L = .550	R_{15} X/L = .610	ρR_7 X/L = .178	ρR_9 X/L = .208	ρR_{13} X/L = .488	ρR_{14} X/L = .550	ρR_{15} X/L = .610	Class	Location ^a
10 foil Run B Set 1	2	K(19)	.0884	1.0000	.5841	1.7288	.01429	1.5481	.2627	.2904	.9041	1.0098	1.0942	.01471	.01391	.01980	.02211	.02396	2	—
	3	K(161)	.0343	"	.5939	1.7386	.01503	1.5048	.2651	.2999	.9402	1.0326	1.1204	.01485	.01679	.02059	.02261	.02454	6	O
	4	L1(186)	.1865	"	.5552	1.7864	.01430	1.6433	.2428	.2715	.8547	.9918	1.0442	.01360	.01300	.02026	.02351	.02475	2	—
	5	L3(135)	.2032	"	.5489	1.7008	.01414	1.5643	.2427	.2668	.8232	.9336	1.0476	.01359	.01278	.01951	.02213	.02483	5	O
	6	M3(206)	.3761	"	.4352	1.6138	.01298	1.3849	.1738	.1891	.5860	.7023	.8585	.01234	.01343	.01500	.01798	.02198	6	Δ
	7	M5(184)	.3800	"	.4333	1.6139	.01253	1.4289	.1789	.1934	.6214	.6993	.8325	.01270	.01172	.01591	.01790	.02131	5	—
	8	M9(63)	.3998	"	.4190	1.5780	.01315	1.3924	.1648	.1771	.5540	.6612	.8598	.01170	.01258	.01535	.01831	.02382	6	X
	9	M9(183)	.3840	"	.4398	1.6116	.01268	1.4316	.1701	.1887	.6184	.7088	.8758	.01208	.01143	.01583	.01815	.02242	5	—
	10	M10(60)	.3721	"	.4430	1.6768	.01282	1.4829	.1798	.1991	.6294	.7428	.8803	.01277	.01207	.01611	.01902	.02254	2	—
	11	M10(70)	.3523	"	.4428	1.6858	.01240	1.5414	.1743	.1918	.5525	.7465	.9055	.01144	.01074	.01414	.01911	.02318	1	—
	12	M10(47)	.3009	"	.4749	1.6736	.01235	1.5256	.1990	.2143	.6688	.7947	.9464	.01206	.01110	.01585	.01884	.02243	1	—
	13	M12(164)	.3932	"	.4224	1.6990	.01236	1.4989	.1699	.1829	.5778	.7177	.8730	.01207	.01299	.01600	.01988	.02418	3	X
	14	N3(224)	.5898	"	.3464	1.8099	.01434	1.5304	.1643	.1791	.5541	.6270	.6380	.01480	.01613	.01939	.02194	.02233	3	—
10 foil Run B Set 2	2	N7(38)	.6717	1.0000	.3039	1.7872	.01419	1.5693	.1530	.1585	.4925	.5432	.5542	.01493	.01428	.02019	.02227	.02272	2	Δ
	3	N8(64)	.5767	"	.3502	1.7462	.01387	1.5434	.1701	.1839	.5677	.6116	.6531	.01533	.01414	.01987	.02141	.02286	1	O
	4	N9(29)	.6241	"	.3317	1.7660	.01423	1.5598	.1641	.1710	.5296	.5858	.6348	.01601	.01423	.02007	.02220	.02406	1	—
	5	N12(23)	.5793	"	.3632	1.7217	.01499	1.4598	.1625	.1761	.5634	.6254	.6678	.01464	.01587	.01972	.02189	.02337	6	Δ
	6	P11(133)	.7205	"	.2731	1.7649	.01499	1.5409	.1405	.1438	.4565	.4821	.4981	.01486	.01521	.02187	.02309	.02386	6	Δ
	7	P18(193)	.7007	"	.2827	1.7987	.01418	1.5881	.1454	.1506	.4744	.5085	.5270	.01538	.01470	.02102	.02253	.02335	1	—
	8	P20(96)	.7535	"	.2502	1.8117	.01487	1.5791	.1273	.1366	.4243	.4532	.4519	.01460	.01567	.02198	.02348	.02341	6	Δ
	9	P23(183)	.7548	"	.2520	1.7996	.01443	1.6286	.1330	.1312	.4299	.4536	.4508	.01525	.01388	.02227	.02350	.02335	4	—
	10	R13(57)	.8168	"	.2139	1.8800	.01449	1.6814	.1168	.1192	.3733	.4021	.3948	.01576	.01482	.02262	.02437	.02393	2	—
	11	R13(339)	.9831	"	.1797	1.8224	.01519	1.5309	.09872	.1018	.3062	.3274	.3227	.01571	.01620	.02174	.02325	.02291	3	Λ
	12	R29(334)	.9870	"	.1868	1.8197	.01514	1.5938	.1010	.1075	.3171	.3399	.3357	.01607	.01710	.02251	.02413	.02384	4	Λ
20 foil Run B	2	K(79)	.0633	1.0000	.5812	1.7513	.01465	1.5213	.2560	.2794	.8986	1.0178	1.0609	.01434	.01564	.01968	.02229	.02323	6	Δ
	3	K(242)	.0884	"	.5877	1.7230	.01434	1.5460	.2601	.2870	.9227	1.0126	1.0455	.01457	.01375	.02021	.02218	.02290	5	—
	4	M9(173)	.3906	"	.4291	1.6143	.01345	1.4268	.1655	.1817	.5690	.6927	.8941	.01175	.01290	.01576	.01919	.02477	6	X
	5	P17(108)	.8630	"	.2000	1.8000	.01462	1.6156	.1068	.1103	.3368	.3603	.3668	.01441	.01488	.02210	.02362	.02406	2	—
	6	R21(54)	.9791	"	.2031	1.7743	.01647	1.5534	.1106	.1142	.3600	.3603	.3631	.01759	.01816	.02556	.02558	.02578	1	V

^a Unperturbed = —, near tie tube = O, near thermocouple group = Δ, near shim = X, thin reflector = Λ, thick reflector = V.

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Table XV. Time dependence in position of regulating rod.

Time after attaining power, min	Position shim 4
0	37.782
3	37.896
4	37.939
9	37.967
14	37.983
19	37.978
24	37.983
29	37.983
34	37.983
144	37.997

Table XVI. Transient data for clean core.

t, ^a sec	Doubling time, sec	Observed period, sec	Asymptotic period correction ^b	Asymptotic period, sec	Reactivity swing, cents
Transient No. 1					
96.3	43.2	62.3	--	63.1	13.6
113	43.8	63.2	--	63.2	13.6
129	44.1	63.6	--	63.6	13.5
141	43.8	63.2	--	63.2	13.6
151	44.1	63.6	--	63.6	13.5
200	46.1	63.3	--	63.3	13.6
213	46.1	63.3	--	63.3	13.6
Corrected differential worth 64.4 cents/inch					
Transient No. 2					
30.3	22.6	32.6	1.1	33.0	20.9
37.7	22.9	33.1	0.7	33.3	20.8
43.5	22.9	33.1	0.5	33.2	20.8
50.3	23.2	33.5	--	33.5	20.7
80.1	24.2	33.3	--	33.3	20.8
Corrected differential worth 63.8 cents/inch					

^a Elapsed time after rod motion stopped.

^b See Appendix III.

Table XVII. Correlation of motions of shim rod 4 and the fission counters.

Time after attaining power, min	Position shim 4	Position, fission probes
1	35.845	62.00
2	35.920	58.00
3	35.975	54.00
5	35.991	50.00
7	36.013	46.00
9	36.005	42.00
37	36.069	1.00

Table XVIII. Summary of data — activation run C.

X/L	U ²³⁵ foils		U ²³⁸ foils				Thorium foils	
	P9(28)	P13(38)	P9(57)	P13(5)	L6(36)	N5(225)	R11(108)	P1(215)
.043	.7379 ^a	.6702	.0881	.0814	-----	.1584	.0591	.0626
.131	1.0616	.9624	.2179	.1991	.3277	.2918	.1952	.1478
.146	.9431	.8450	.2540	.2355	.3687	.3095	.1667	.1359
.177	.5922	.5509	.3329	.3210	.4656	.3922	.2296	.2026
.207	.5950	.5552	.3837	.3539	.5515	.4514	.2398	.2657
.305	.9818	.9301	.5553	.5135	.7996	.7229	.4141	.2553
.488	1.8369	1.7724	.7531	.7370	1.1602	.9826	.6081	.3392
.549	1.9606	1.8619	.7688	.7823	1.3076	1.0436	.5910	.3860
.610	2.0182	1.8762	.7995	.7339	1.3509	1.1686	.5775	.3181
.671	1.8045	1.7932	.7947	.7413	1.3672	1.1594	.5489	.2819
.701	1.7439	1.7335	.7691	.6692	1.3554	1.1316	.5673	.4067
.732	1.6529	1.6410	.6280	.6496	1.2956	1.1400	.5163	.3304
.762	1.5253	1.5100	.6590	.5805	1.2345	1.0114	.4797	.3224
.793	1.3977	1.3229	.6078	.5498	1.0999	.9542	.4168	.1485
.832	1.2359	1.1948	.5387	.4797	.8963	.8369	.3650	.2491
.854	1.0886	1.0331	.4512	.4161	.8268	.7286	.3445	.2934
.884	.9663	1.0051	.3885	.3510	.6761	.6250	.2710	.2635
.915	.7737	.7991	.2916	.2812	.5242	.4603	.2258	.1974
.945	.6469	.6492	.1828	.1799	.3522	.2872	.1486	.2180
.976	.3818	.3860	.0995	.0930	.1813	.1714	.0761	.0265

^a Data are listed as relative activation per unit foil weight.
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Table XIX-a. Flux wire traverse — tube K-196.

Position	Relative activity ^a	Position	Relative activity
62.5	14840	17.5	12090
61.5	17990	16.5	11580
60.5	19770	15.5	11370
59.5	22210	14.5	10740
58.5	24490	13.5	10350
57.5	26370	12.5	11270
56.5	28010	11.5	11410
55.5	29590	10.5	10920
54.5	30710	9.5	10720
53.5	34110	8.5	10060
52.5	34560	7.5	8960
51.5	36760	6.5	7750
50.5	37440	5.5	7760
49.5	38100	4.5	4970
48.5	39000	3.5	2950
47.5	38790	2.5	1979
46.5	39690	1.5	1881
45.5	39610	0.5	1825
44.5	39570		
43.5	40660		
42.5	38960		
41.5	39660		
40.5	38550		
39.5	38220		
38.5	37130		
37.5	36940		
36.5	34500		
35.5	34090		
34.5	32460		
33.5	31990		
32.5	31090		
31.5	28520		
30.5	26700		
29.5	26290		
28.5	26720		
27.5	25380		
26.5	25430		
25.5	22110		
24.5	20910		
23.5	19690		
22.5	18240		
21.5	16500		
20.5	15310		
19.5	14690		
18.5	13460		

^a All relative activities in Tables XIX-a through -j have a common base.

Table XIX-b. Flux wire traverse — tube M-10-185.

Position	Relative activity	Position	Relative activity
62.5	4441	14.5	9719
61.5	7310	13.5	8606
60.5	10566	12.5	8301
59.5	11451	11.5	7592
58.5	12956	10.5	7550
57.5	15729	9.5	8634
56.5	18166	8.5	7934
55.5	18745	7.5	8602
54.5	20844	6.5	7876
53.5	24437	5.5	7859
52.5	24010	4.5	7139
51.5	24722	3.5	6444
50.5	26743	2.5	5896
49.5	28049	1.5	4250
48.5	29053	0.5	2853
47.5	30292		
46.5	31249		
45.5	31248		
44.5	33572		
43.5	33017		
42.5	32678		
41.5	32938		
40.5	32579		
39.5	32399		
38.5	31669		
37.5	30320		
36.5	28900		
35.5	28354		
34.5	26297		
33.5	25825		
32.5	23955		
31.5	23465		
30.5	21285		
29.5	21013		
28.5	21448		
27.5	21019		
26.5	19442		
25.5	18874		
24.5	18228		
23.5	17582		
22.5	16297		
21.5	15499		
20.5	14942		
19.5	13933		
18.5	13032		
17.5	12482		
16.5	11055		
15.5	10552		

Table XIX-c. Flux wire traverse — tube N-6-210.

Position	Relative activity	Position	Relative activity
63.5	3957	15.5	8355
62.5	6379	14.5	7851
61.5	8531	13.5	7423
60.5	10358	12.5	7113
59.5	10932	11.5	6617
58.5	12804	10.5	7521
57.5	13769	9.8	8446
56.5	15576	8.5	9138
55.5	16284	7.5	9036
54.5	17941	6.5	8159
53.5	19895	5.5	7809
52.5	19528	4.5	6718
51.5	21587	3.5	5579
50.5	22561	2.5	3821
49.5	23438	1.5	3736
48.5	23472	0.5	1777
47.5	24275		
46.5	25494		
45.5	26489		
44.5	26741		
43.5	26690		
42.5	26169		
41.5	26590		
40.5	27244		
39.5	26531		
38.5	25458		
37.5	24736		
36.5	23567		
35.5	24239		
34.5	23215		
33.5	23414		
32.5	20712		
31.5	20302		
30.5	19743		
29.5	19829		
28.5	19889		
27.5	17868		
26.5	17875		
25.5	16984		
24.5	15995		
23.5	15434		
22.5	14150		
21.5	14220		
20.5	12704		
19.5	12045		
18.5	10134		
17.5	10855		
16.5	9472		

Table XIX-d. Flux wire traverse — tube P-7-186.

Position	Relative activity	Position	Relative activity
61.90	5480	13.90	5484
60.90	7208	12.90	4560
59.90	8500	11.90	4046
58.90	9396	10.90	4370
57.90	10549	9.90	5237
56.90	12694	8.90	5619
55.90	13454	7.90	6491
54.90	14356	6.90	5916
53.90	15934	5.90	5934
52.90	17467	4.90	5618
51.90	18444	3.90	4916
50.90	18899	2.90	4247
49.90	19532	1.90	2531
48.90	19369	0.90	2017
47.90	21022		
46.90	21712		
45.90	21980		
44.90	21688		
43.90	22814		
42.90	22348		
41.90	22087		
40.90	22892		
39.90	22292		
38.90	22736		
37.90	20662		
36.90	21116		
35.90	20142		
34.90	19336		
33.90	18472		
32.90	19271		
31.90	18577		
30.90	16851		
29.90	15975		
28.90	16639		
27.90	16099		
26.90	15097		
25.90	14186		
24.90	13261		
23.90	12135		
22.90	11730		
21.90	10450		
20.90	10217		
19.90	8860		
18.90	8374		
17.90	7692		
16.90	7559		
15.90	6336		
14.90	5506		

Table XIX-e. Flux wire traverse — tube P-8-242.

Position	Relative activity	Position	Relative activity
61.65	3449	13.65	9103
60.65	5279	12.65	7205
59.65	6878	11.65	7486
58.65	7816	10.65	7792
57.65	8624	9.65	8304
56.65	10266	8.65	8641
55.65	11587	7.65	9447
54.65	13214	6.65	9535
53.65	13656	5.65	10181
52.65	14184	4.65	9468
51.65	15319	3.65	8196
50.65	16160	2.65	7855
49.65	17609	1.65	5926
48.65	18319	0.65	5114
47.65	17942		
46.65	19839		
45.65	20098		
44.65	20507		
43.65	21308		
42.65	22162		
41.65	21526		
40.65	21564		
39.65	21662		
38.65	22273		
37.65	21870		
36.65	21879		
35.65	20464		
34.65	21154		
33.65	21505		
32.65	20808		
31.65	19549		
30.65	19242		
29.65	17525		
28.65	18112		
27.65	19222		
26.65	17196		
25.65	17400		
24.65	16488		
23.65	15607		
22.65	14524		
21.65	14330		
20.65	13469		
19.65	12887		
18.65	11652		
17.65	11118		
16.65	10768		
15.65	9765		
14.65	9772		

Table XIX-f. Flux wire traverse — tube P-20-146.

Position	Relative activity	Position	Relative activity
62.5	3459	14.5	6915
61.5	4909	13.5	6390
60.5	5677	12.5	6302
59.5	5691	11.5	5844
58.5	7660	10.5	5813
57.5	9040	9.5	6444
56.5	9221	8.5	7821
55.5	10970	7.5	8247
54.5	12000	6.5	7935
53.5	12150	5.5	8355
52.5	13970	4.5	7614
51.5	14050	3.5	7548
50.5	14730	2.5	6485
49.5	15480	1.5	6288
48.5	17000	0.5	4880
47.5	16370		
46.5	17060		
45.5	18170		
44.5	18150		
43.5	18510		
42.5	18510		
41.5	18850		
40.5	18620		
39.5	19600		
38.5	18750		
37.5	18600		
36.5	17700		
35.5	19040		
34.5	18810		
33.5	18850		
32.5	17960		
31.5	16820		
30.5	16230		
29.5	16560		
28.5	16060		
27.5	15840		
26.5	15150		
25.5	14750		
24.5	13810		
23.5	13370		
22.5	12206		
21.5	11060		
20.5	10920		
19.5	9767		
18.5	9044		
17.5	8934		
16.5	8097		
15.5	7523		

Table XIX-g. Flux wire traverse - tube R-8-165.

Position	Relative activity	Position	Relative activity
62.56	3317	14.56	4431
61.56	3846	13.56	4353
60.56	4647	12.56	3991
59.56	5194	11.56	4035
58.56	6033	10.56	5025
57.56	6613	9.56	5742
56.56	6918	8.56	6387
55.56	7566	7.56	6041
54.56	8134	6.56	6108
53.56	9082	5.56	5762
52.56	8873	4.56	5164
51.56	9243	3.56	4348
50.56	9958	2.56	3213
49.56	10431	1.56	2535
48.56	10696	0.56	1353
47.56	11376	-0.44	19
46.56	11808		
45.56	12084		
44.56	12694		
43.56	12293		
42.56	12270		
41.56	12842		
40.56	12861		
39.56	13131		
38.56	12543		
37.56	12413		
36.56	12380		
35.56	12276		
34.56	12249		
33.56	11908		
32.56	11923		
31.56	10723		
30.56	10556		
29.56	11101		
28.56	10597		
27.56	10389		
26.56	10080		
25.56	9195		
24.56	9146		
23.56	8452		
22.56	7959		
21.56	7364		
20.56	6804		
19.56	6573		
18.56	5821		
17.56	5563		
16.56	4861		
15.56	4940		

Table XIX-h. Flux wire traverse - tube R-24-233.

Position	Relative activity	Position	Relative activity
62.56	2484	14.56	4734
61.56	3637	13.56	4308
60.56	4075	12.56	4087
59.56	4314	11.56	4131
58.56	5046	10.56	4118
57.56	5566	9.56	5238
56.56	6142	8.56	6058
55.56	6829	7.56	5954
54.56	7208	6.56	5910
53.56	7919	5.56	6044
52.56	8509	4.56	5182
51.56	9478	3.56	4675
50.56	9642	2.56	3855
49.56	9844	1.56	3158
48.56	10587	0.56	3485
47.56	10670	-0.44	1695
46.56	11174		
45.56	11248		
44.56	11602		
43.56	11473		
42.56	12220		
41.56	11890		
40.56	12501		
39.56	12234		
38.56	12396		
37.56	12730		
36.56	12179		
35.56	12174		
34.56	12591		
33.56	12018		
32.56	11705		
31.56	11187		
30.56	10722		
29.56	10738		
28.56	10770		
27.56	10585		
26.56	10192		
25.56	9522		
24.56	9138		
23.56	8519		
22.56	7872		
21.56	7717		
20.56	7569		
19.56	6296		
18.56	6177		
17.56	5801		
16.56	5458		
15.56	5058		

Table XIX-i. Flux wire traverse — tube R-26-54.

Position	Relative activity	Position	Relative activity
62.87	3822	14.87	5010
61.87	4545	13.87	4649
60.87	4339	12.87	4560
59.87	5980	11.87	4675
58.87	6345	10.87	5530
57.87	7432	9.87	5779
56.87	7819	8.87	6179
55.87	8595	7.87	5877
54.87	9367	6.87	5665
53.87	9767	5.87	5054
52.87	10400	4.87	4535
51.87	10890	3.87	3437
50.87	11205	2.87	2575
49.87	11813	1.87	1702
48.87	12395	0.89	984
47.87	12483		
46.87	12895		
45.87	13352		
44.87	13106		
43.87	13327		
42.87	13762		
41.87	13869		
40.87	14080		
39.87	13730		
38.87	13928		
37.87	13692		
36.87	13658		
35.87	13557		
34.87	12777		
33.87	13398		
32.87	13004		
31.87	11697		
30.87	11563		
29.87	11831		
28.87	11464		
27.87	11054		
26.87	10518		
25.87	10179		
24.87	9208		
23.87	9052		
22.87	8690		
21.87	8070		
20.87	7648		
19.87	7219		
18.87	6519		
17.87	6010		
16.87	5610		
15.87	5399		

Table XIX-j. Flux wire traverse — tube R-28-42.

Position	Relative activity	Position	Relative activity
62.12	4022	14.12	5295
61.12	4784	13.12	4654
60.12	5430	12.12	4311
59.12	5995	11.12	4411
58.12	6685	10.12	5255
57.12	7565	9.12	6306
56.12	8748	8.12	6694
55.12	9739	7.12	6774
54.12	10922	6.12	6722
53.12	11118	5.12	6428
52.12	11713	4.12	5468
51.12	12275	3.12	4839
50.12	13201	2.12	4006
49.12	13335	1.12	2817
48.12	14009	0.12	1227
47.12	14433	-0.88	-470
46.12	15060		
45.12	15282		
44.12	15714		
43.12	16181		
42.12	16077		
41.12	16471		
40.12	16280		
39.12	16242		
38.12	15581		
37.12	16059		
36.12	16487		
35.12	15816		
34.12	15735		
33.12	15732		
32.12	15045		
31.12	14637		
30.12	13016		
29.12	12837		
28.12	12559		
27.12	12030		
26.12	11609		
25.12	11108		
24.12	10640		
23.12	9781		
22.12	9533		
21.12	9379		
20.12	8012		
19.12	7603		
18.12	6787		
17.12	6524		
16.12	5503		
15.12	5434		

Table XX. Regulating rod position variation with running time.

Time after attaining power, min.	Position shim 12	
0	35.714	Leveling power
1	35.873	
2	35.894	
3	35.961	
4	35.961	
5	35.984	
6	35.984	
7	35.982	
8	35.976	
9	35.974	
13	35.989	
18	35.995	
23	35.997	
28	36.004	
33	35.995	
63	35.992	
93	35.997	
123	35.997	
153	35.992	
183	35.996	
213	35.995	
243	35.990	
273	35.982

Fig. 1. Overall view of the reactor arrangement for the cold critical experiments

COLD EXPERIMENT

F - 1000 CFM FILTERS.
 P - PITOT TUBE-MEASURE AIR FLOW.
 D₁ - DAMPER.-SET AIR FLOW AT 1000 CFM PER FILTER.
 S - TUBE & SHUT OFF VALVE FOR AIR SAMPLING.
 B - 3000 CFM CENTRIFUGAL BLOWER.
 H - 54 KW HEATER-OFF.
 D₂ - DAMPER WIDE OPEN FOR 3000 CFM DISCHARGE TO ROOM.
 ("HD" DUCT NOT INSTALLED FOR COLD EXPERIMENT)

AIR SYSTEM-CRITICAL EXPERIMENT

HEAT EXPERIMENT

HD - DUCTING INSTALLED FOR CLOSED LOOP.
 D₂ - DAMPER SET FOR 1000-1500 CFM FLOW.
 H - HEATER TURNED ON TO SUPPLY 250°F AIR.
 TC - THERMO-COUPLES FOR TEMP. MEASUREMENT.
 TC1-MONITORS INCOMING AIR & CONTROLS HEATER FOR 250°F AIR DURING HEATING.
 TC2-MONITORS DISCHARGE AIR.
 TC3,4,5,6,&7- CORE TEMP. AT VARIOUS LOCATIONS.
 TC5-CONTROLS HEATER AT 200°F CORE TEMP.
 ENTIRE LOOP INSULATED.
 APPROX. 16 HRS. TO REACH CORE TEMP.

GLL-632-251

Fig. 2. Schematic diagram of the reactor ventilation system.

- + SAFETY RODS
- ⊗ SHIM RODS
- SPACES FOR ADDITIONAL SHIM RODS
- ⊛ VERNIER RODS

GLL-623-16365A

Fig. 3. Cross-sectional view of the core.

Fig. 6. Relation of control actuators to top of reactor.

Fig. 7. View from below the control unit showing the typical arrangement of the control rods.

Fig. 8. View of insulating cover over the top of reactor.

Fig. 9. Reactor prepared for heating experiment. The heater can be seen in the center rear, supported on a stand.

Fig. 10. Details of fission probes.

Fig. 11. Fission probe drive unit, side view.

Fig. 12. View of fission probe driveplate from the position of the reactor core.

GLB-634-2426A

Fig. 13. Major components of automatic data-collecting system.

GLB-636-3982

Fig. 14. View of auxiliary rod actuators mounted above the control unit baseplate.

Fig. 15. Graph of inverse multiplication versus number of rods removed. The upper curve shows measurements with all hafnium rods inserted.

Fig. 16. Initial approach to critical.

Fig. 17. Traverse of tube R-24-233. From fission detector traverses 1-5.

Fig. 18. Power map corresponding to the flux traverse of Fig. 17.

Fig. 19. Traverse of tube R-13-57. From activation foil traverse A.

Fig. 20. Power map corresponding to the flux traverse of Fig. 19.

Fig. 21. Radial variation of relative specific power - 84 inches from core baseplate.

Fig. 22. Radial variation of relative specific power - 74 inches from core baseplate.

Fig. 23. Radial variation of relative specific power - 64 inches from core baseplate.

Fig. 24. Copper flux wire traverse - tube P-7-186.

Fig. 25. Correlation of ion chamber data.

Fig. 26. Traverse of tube L-6-219. From fission detector traverses 6 and 7.

Fig. 27. Power map corresponding to the flux traverse of Fig. 26.

Fig. 28. Traverse of tube R-13-57. From activation foil traverse B.

Fig. 29. Power map corresponding to the flux traverse of Fig. 28.

Fig. 30. Radial variation of relative specific power - 84 inches from core baseplate.

Fig. 31. Radial variation of relative specific power - 74 inches from core baseplate.

Fig. 32. Radial variation of relative specific power - 64 inches from core baseplate.

Fig. 33. Traverse of tube N-15-194. From fission detector traverses 7-11.

Fig. 34. Power map corresponding to the flux traverse of Fig. 33.

APPENDIX I. ACTIVITIES DURING CORE ASSEMBLY OPERATIONS

Prior to the actual critical experiments, numerous measurements were performed during various stages of core assembly during the period of March 25 through July 8, 1963.

The emission rates from each of the 91 unit cells were measured using a 60-inch moderated BF_3 chamber, which had a counting efficiency factor of 18.4% for a distributed source. The emission rates from the individual unit cells are tabulated in Table I-1. The tabulated values take no account of self-shielding within the unit cells and assume that their neutron spectrum is identical to that of a Po-Be source. The uncertainty due to counter statistics is $\pm 1\%$. Based upon the totals from the individual unit cells, the total built-in (α, n) source in the reactor is taken to be 3.09×10^6 n/sec.

During the actual core assembly operations, the leakage neutron emission was monitored continuously. From the emission rates observed at various stages of assembly, one could define an "observed multiplication" by

$$M_{\text{obs}} = \frac{\text{Emission Rate from Assembled Unit}}{\text{Emission Rate from Constituent Parts}},$$

where all rates were corrected to the geometry of the counter. The interpretation of the observed multiplication in terms of "actual multiplication" is discussed in Appendix II. For these measurements the counter geometry was assumed constant. In actual fact the geometry would be expected to change as the dimensions of the core and the leakage probability changed. Neglect of this point would cause the multiplication to be underestimated. Selected values of the observed multiplication are listed in Table I-2. The final entry in the table is the starting system for the critical experiments.

Table I-1. Neutron emission rates from Tory II-C unit cells.

Unit cell	Emission rate $\times 10^{-4}$, n/sec	Unit cell	Emission rate $\times 10^{-4}$, n/sec
K ^a	1.47	P-10	3.48
L-1	1.72	P-11	3.22
L-2	1.62	P-12	3.67
L-3	1.66	P-13	3.89
L-4	1.77	P-14	3.29
L-5	1.76	P-15	3.38
L-6	1.68	P-16	3.37
M-1	2.08	P-17	4.31
M-2	1.76	P-18	3.34
M-3	1.93	P-19	3.14
M-4	1.80	P-20	3.64
M-5	1.96	P-21	4.07
M-6	1.79	P-22	3.51
M-7	1.87	P-23	3.16
M-8	1.99	P-24	3.53
M-9	1.98	R-1	2.92
M-10	1.89	R-2	4.66
M-11	1.87	R-3	5.45
M-12	1.69	R-4	5.40
N-1	2.69	R-5	4.82
N-2	2.62	R-6	2.50
N-3	2.47	R-7	4.67
N-4	2.99	R-8	5.02
N-5	2.25	R-9	5.17
N-6	2.51	R-10	4.99
N-7	2.75	R-11	2.69
N-8	2.37	R-12	4.85
N-9	2.41	R-13	5.25
N-10	2.79	R-14	5.85
N-11	2.41	R-15	5.11
N-12	2.21	R-16	2.72
N-13	2.88	R-17	4.63
N-14	2.45	R-18	5.36
N-15	2.30	R-19	5.32
N-16	2.89	R-20	7.44
N-17	2.25	R-21	2.35
N-18	2.80	R-22	4.82
P-1	4.04	R-23	5.56
P-2	3.05	R-24	5.89
P-3	3.08	R-25	5.47
P-4	3.67	R-26	3.05
P-5	4.32	R-27	4.04
P-6	3.79	R-28	5.69
P-7	3.07	R-29	5.40
P-8	3.45	R-30	5.03
P-9	4.66		

^a Each unit cell except K and L-1 contained a B₄C transportation poison rod; all R unit cells contained two poison rods.

Table I-2. Observed multiplication at various stages of assembly.

Configuration	M _{obs}
Cells, K, L-1	1.00
All unit cells assembled	1.02
All drill rods removed	1.29
Core after squeezing and shaking	1.30
Side support assembly installed	1.40
Reactor duct in place	1.60 ^a
All tie tubes installed	1.60

^a The apparent large increase in multiplication at this point was partially due to surrounding the external counter by the lower portion of the reactor duct.

APPENDIX II. METHOD OF ADJUSTING LEAKAGE MULTIPLICATIONS

When measuring the multiplication of a system by use of external leakage detectors, the observed multiplication is a leakage multiplication which is related to the "actual" multiplication through the leakage probability of the system. For purposes of core evaluation it was necessary to deduce a relation between the "observed multiplication" and the "actual multiplication."

The total core source value was taken to be

$$S = \sum_{i=1}^{91} C_i \quad (\text{II-1})$$

where C_i is the emission rate for individual unit cell.

The emission rate from the assembled core, C_T , is

$$C_T = SMP_L \quad (\text{II-2})$$

where M is the actual core multiplication and P_L is the core leakage probability.

The observed leakage multiplication, M' , is given by

$$M' = \frac{SMP_L}{S} = MP_L \quad (\text{II-3})$$

Transforming by use of the relationship

$$M = \frac{1}{1 - k}, \quad (\text{II-4})$$

$$\frac{1}{1 - k'} = \frac{P_L}{1 - k} \quad (\text{II-5})$$

or

$$P_L = \frac{1 - k}{1 - k'}. \quad (\text{II-6})$$

But the leakage probability is also defined by

$$P_L = 1 - \frac{k}{k_\infty}. \quad (\text{II-7})$$

Eliminating P_L and solving for k ,

$$k = \frac{k'k_\infty}{k' + k_\infty - 1}. \quad (\text{II-8})$$

By (II-4) the multiplication factor corresponding to the observed M' is 0.38. Then if we know k_{∞} we can deduce a corrected value of k by (II-8).

One difficulty in this procedure is that k_{∞} would be expected to have one value when the system is fully poisoned and a somewhat larger value when the poison was removed. Reasonable values for k_{∞} would be 1.2 for a fully poisoned system and 1.8 for an unpoisoned system.

For operational purposes we chose to use the value of 1.8 for calculations, then arbitrarily multiplied by a safety factor of 1.3, in the following way:

By (II-8)

$$k = \frac{0.38(1.8)}{0.38 + 1.8 - 1} = 0.58.$$

From (II-4) the "actual" multiplication is

$$M = 2.4,$$

and

$$M = \frac{2.4}{1.61} M' = 1.5 M'. \quad (\text{II-9})$$

Since the above does not take into account any variations of k_{∞} during poison removal, multiplying by the safety factor produces

$$M = 1.5(1.3) M' = 2.0 M'. \quad (\text{II-10})$$

Calculating back shows that this is equivalent to assuming $k_{\infty} \approx 1.4$ over the sequence of poison removal.

Based upon subsequent values derived from various observed multiplications, it is believed that this method over-estimated the actual multiplications somewhat; however, for operational purposes this approach was found to be quite practical.

APPENDIX III. CALIBRATION OF SHIM RODS BY POSITIVE PERIOD METHOD

One of the major requirements in the cold critical experiments was the determination of the worth of the shim rod bank. Achievement of this objective was somewhat more complicated than had been expected.

By far the greatest difficulty was caused by the presence of "built-in" sources. The homogeneous character of the fuel elements contributed a steady beryllium (α, n) source with a magnitude of 3.09×10^6 n/sec (Appendix I). In addition, the production of photoneutrons within the moderator material was an additional source which was power dependent. The presence of these sources tended to obscure the point of criticality, and also imposed the requirement that one begin transients at a fairly high power level to have assurance of starting near to critical.

A second difficulty was the operational requirement that the power level not exceed about 50 watts. This limitation conflicted with the previous one and acted to minimize the range of power available for positive period transients.

A third limitation was due to the nature of the control system, which permitted movement of only one shim rod at a time, with a reactivity addition rate of about $0.25/\text{min}$.

A procedure was devised to cope with the above difficulties after a number of preliminary transients had been performed. The low power critical point was defined to correspond operationally to an ion chamber current of 3×10^{-9} ampere (about 0.5 watt). The procedure for a typical measurement was as follows:

1. The reactor was taken to critical at 3×10^{-9} ampere. The shim bank was adjusted so that all the rod positions were very nearly identical. Waiting time to assure steady power was 10 minutes.

2. The amount of shim bank movement to produce the transient was selected. The reactor was made quite subcritical by insertion of one shim rod. The remainder of the shim bank was withdrawn the chosen increment. The system was returned to a steady state at a power corresponding to 1×10^{-9} ampere by withdrawal of the single deeply-inserted shim rod. There was a 10-minute waiting period to verify a steady power level. The position of the regulating rod was noted.

3. The power was raised to 3×10^{-9} ampere by use of the shim rod used for regulating, and conditions were returned to the steady state. There was

again a 10-minute waiting period to verify a constant power level. The regulating rod position was again noted. At the higher power, the regulating rod was withdrawn slightly more than at the lower power.

4. The positive period was initiated by withdrawing the regulating rod to the position of the remainder of the shims. The power was allowed to increase to a level corresponding to 2×10^{-7} ampere (about 22 watts) before returning to subcritical conditions.

The sequence of operations above is illustrated graphically in Fig. III-1. Four rods are used in the sketch to illustrate the arrangement of the shim rod bank. The numbers in the sketch correspond to the conditions listed above.

For proper interpretation of the transient data two corrections may be required. They are (1) a correction to account for the fact that a stable period might not yet have been attained, and (2) a correction for the slight degree of subcriticality at the start of the transient due to the presence of the source.

The correction for nonasymptotic period was deduced from calculations of the same transients by use of AIREK,¹¹ a reactor kinetics computer program. The magnitude of this correction typically did not exceed 2%.

The correction for subcriticality was deduced by use of the information shown in Fig. III-1 and the well-known expression for a reactor in a steady state with a source present.¹²

$$n = \frac{\ell s}{1 - k_{\text{eff}}} \approx \frac{\ell s}{\rho} \quad (\text{III-1})$$

For condition (2) in the figure there are ρ_1 and n_1 , and for condition (3) there are ρ_2 and n_2 . Substituting into Eq. (III-1) in each case and subtracting yields

$$\Delta\rho = \frac{2}{3} \frac{s\ell}{n_1} = \frac{2}{3} \rho_1. \quad (\text{III-2})$$

$$\text{Then since } \rho_1 = \rho_2 + \Delta\rho, \quad (\text{III-3})$$

$$\rho_2 = \frac{1}{3} \rho_1 = \frac{\Delta\rho}{2}. \quad (\text{III-4})$$

The incremental worth of the shim rod bank deduced from the period measurement must then be corrected by adding ρ_2 . Actual evaluation of $\Delta\rho$ must be

done starting from an uncorrected value of the differential shim bank worth. Improved values can be obtained by iteration. This correction was typically of the magnitude of 1 cent of reactivity.

Fig. III-1. Sequence of operations for shim rod bank calibration.

APPENDIX IV. CHRONOLOGICAL OUTLINE OF THE TORY II-C CRITICAL EXPERIMENTS.

- 7/9 Experiments begun.
- 7/18 Transportation poison rod withdrawal begun.
- 7/19 Initial approach to criticality: $\bar{x} = 38.534$. *
- 7/23 Fiber glass insulation placed around reactor: $\bar{x} = 38.566$ at 80°F.
- 7/25 Hot critical experiment: $\bar{x} = 38.103$ at 209°F; $\Delta x / \Delta T = -3.9 \times 10^{-3}$ in./°F.
- 7/26 Recheck of cold crit position: $\bar{x} = 38.603$.
- 8/1 Probe traverses 1 and 2: $\bar{x} = 38.58$.
- 8/2 Probe traverse 3: $\bar{x} = 38.58$.
- 8/5 Probe traverses 4 and 5: $\bar{x} = 38.58$.
- 8/6 Evaluated shutdown multiplication of various operational shim positions utilizing the NTS operational safety system. Installed four optional shims: $\bar{x} = 35.232$.
- 8/8 Installed 266 boron-loaded, stainless steel strips: $\bar{x} = 34.762$. Evaluated worth of transition cartridge thermocouple leads.
- 8/9 Replaced all R-235 tie tubes by Rene-41. Increased loading of boron-steel ribbons to 806.
- 8/15 Activation run A with above conditions: $\bar{x} = 22.672$. Ran for 146 minutes at 36 watts. Irradiated 89 foil-bearing ribbons, seven flux-mapping wires and two emulsion packages.
- 8/19 Rod bumps with poisoned core: $\Delta \rho / \Delta x = 39.9$ in., $\bar{x} = 22.664$. Probe traverse 6: $\bar{x} = 22.638$. Traverse 7: $\bar{x} = 22.646$.
- 8/22 Decreased loading of poison ribbons to 448: $\bar{x} = 29.237$, $\Delta \rho / \Delta x = 53.6\text{¢}/\text{in.}$
- 8/23 Probe traverse 8: $\bar{x} = 35.900$. Thirty-seven boron-steel ribbons left in core.
- 8/26 All poison ribbons removed. Activation run B ≈ 35 watts for 149 minutes: $\bar{x} = 36.335$. Irradiated 89 foil-bearing ribbons and three nuclear emulsions.
- 8/27,28 Rod bump series: $\bar{x} = 36.267$, $\Delta \rho / \Delta x = 63.8\text{¢}/\text{in.}$
- 8/28 Probe traverse 9: $\bar{x} = 36.239$
- 8/29 Probe traverse 10: $\bar{x} = 36.240$. Traverse 11: $\bar{x} = 36.243$.

* $\bar{x}$ is the average critical shim bank in inches measured from the outside of the front cell plates. Core temperature at 72°F and both vernier rods full out unless otherwise specified.

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- 9/4 Core heavily poisoned with 1165 boron-steel ribbons: $\bar{x} = 9.194$.
- 9/5 Poison ribbons removed, activation run C: $\bar{x} = 36.177$. Irradiated eight foil-bearing ribbons and ten copper wires. Evaluated vernier rod worth; both rods are worth 1.683 inches of shim bank movement.
- 9/6 Experiment with 60 gold foils in peripheral tie tubes: $\Delta \bar{x} = 0.303$. With a total of 95 foils, $\Delta \bar{x} = 0.865$ inch.
- 9/9,10 Multiplication measurements for handling and operational safety. Experiments concluded.

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