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THE INITIAL CRITICAL AND ZERO POWER TESTING OF THE HWCTR

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THE INITIAL CRITICAL AND ZERO POWER TESTING OF THE HWCTR

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ABSTRACT

The initial lattice of the Heavy Water Components Test Reactor (HWCTR) was assembled and was made critical without incident. The reactivity worth of the control system and the reactivity effects of temperature were measured in a series of zero power tests. The axial and radial flux distributions were measured for several control rod complements. The results of the complete set of tests demonstrated that the operating behavior of the reactor could be predicted with consistency, and provided the basis for proceeding to full power, nuclear operation.

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THE INITIAL CRITICAL AND ZERO POWER TESTING OF THE HWCTR

INTRODUCTION

The Heavy Water Components Test Reactor (HWCTR) is a high temperature, pressure vessel reactor, cooled and moderated with D_2O. It was designed and constructed specifically to test candidate power reactor fuel elements at operating conditions and exposures similar to those expected in a full-sized D_2O power reactor. The fuel development program was part of the Du Pont program to advance the technology of D_2O power reactors. Operation of the HWCTR was terminated on December 1, 1964, following a decision by the AEC to redirect the heavy water program toward organic cooled reactors. The HWCTR facility has been placed in a standby condition.

Construction of the HWCTR was begun in 1958 and completed early in 1962. A series of zero power tests was conducted to attain the initial critical and to measure basic lattice parameters before attaining full power conditions. Parameters of special interest that were investigated included the excess lattice reactivity, the reactivity margin of control, the maximum possible rate of reactivity addition, the radial and axial flux distributions, and the reactivity effects of temperature. The results of this study are presented in this report.

SUMMARY

The initial core of the HWCTR driver fuel (zirconium-enriched uranium) was assembled and was made critical under carefully controlled conditions on March 3, 1962. No fuel was present in the test lattice positions. Following the complete withdrawal of the fast-acting safety rods, the reactivity added by the withdrawal of control rods to attain criticality was 0.08 K. After thorough appraisal, natural uranium test fuel was charged, the complete initial core was made critical, and zero power measurements were made with this loading.

The worth of the control rod system measured by the pile-period technique was:

Lattice	Moderator Temperature, °C	Worth of One Rod, K	Worth of 12 Rods, K
Driver fuel only	20	0.020	0.234
	240	0.023	0.276
Driver and test fuel	20	0.017	0.200
	240	0.020	0.240

The worth of the six safety rods was 0.09 K in the driver and test fuel lattice at 20°C.

The maximum moderator temperature (250°C) at which the driver and test lattice could be operated was imposed by the worth of the safety rod system, which, in accordance with AEC Technical Specifications, must exceed by 0.01 K the reactivity gained in reducing the moderator temperature from the operating value to 20°C.

The radial and axial flux distributions were measured in several lattice arrangements. The results were used to develop both a radial and an axial computational model. During power operation, the axial flux distributions must be obtained solely by computations, in lieu of in-core instrumentation.

The maximum rate at which reactivity could be introduced by the withdrawal of a single control rod was 2.6×10^{-4} K/sec at 20°C and 3.1×10^{-4} K/sec at 240°C.

DISCUSSION

FACILITY DESCRIPTION

A detailed description of the HWCTR facility is given in reference 1. Only a brief description of the reactor and its associated equipment will be given here.

The reactor and principal auxiliary equipment are housed in a building designed to confine steam and radioactivity that might be released by accidental rupture of the reactor system. The containment building is constructed of carbon steel and stressed, reinforced concrete. The building is 70 feet in diameter and 125 feet high, with half of the building above grade. The containment building is shown in Figure 1.

An isometric drawing of the reactor vessel is shown in Figure 2. The vessel is approximately 30 feet high. The reactor core is in the lower third of the vessel. Core components are charged or removed through the top of the vessel. Control rods and safety rods are driven by motors and gear assemblies mounted above the reactor head. Primary D_2O coolant, circulated through two identical systems, enters the vessel above the fuel, passes down through the fuel coolant annuli, and enters the bulk moderator region. The D_2O leaves the vessel through two nozzles near the top of the fuel, and passes through two steam generators before returning to the reactor.

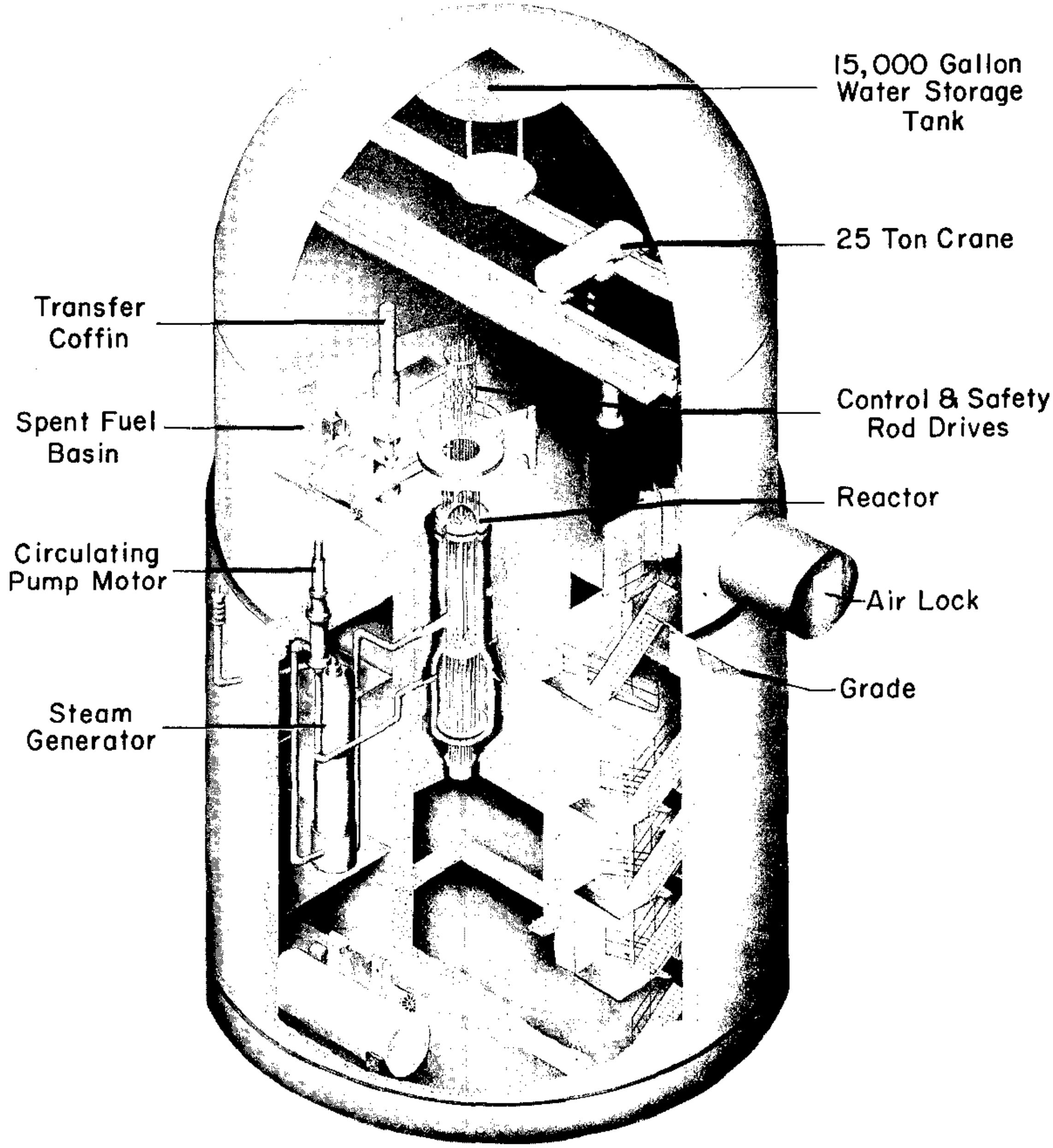


FIG. 1 HWCTR CONTAINMENT BUILDING

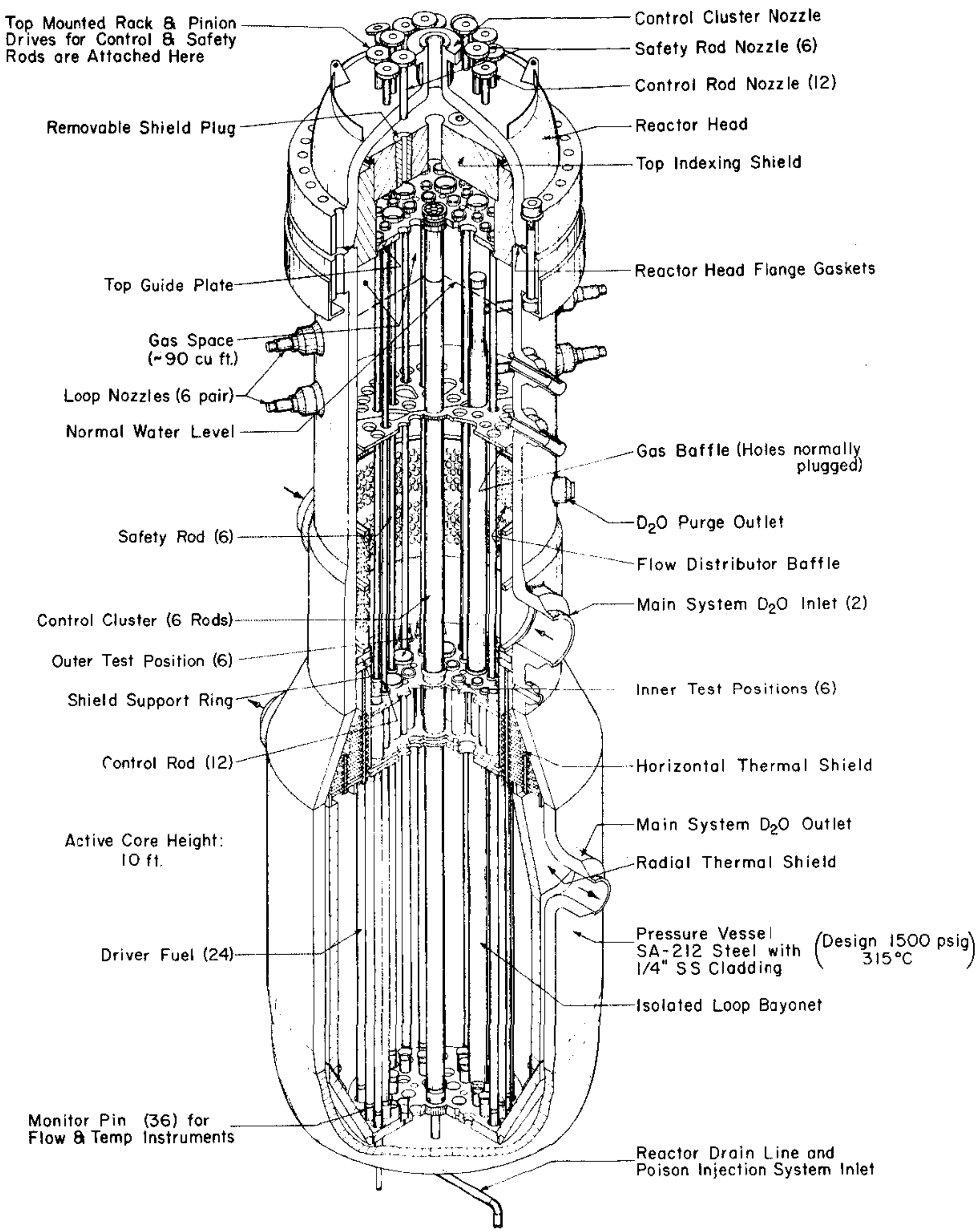
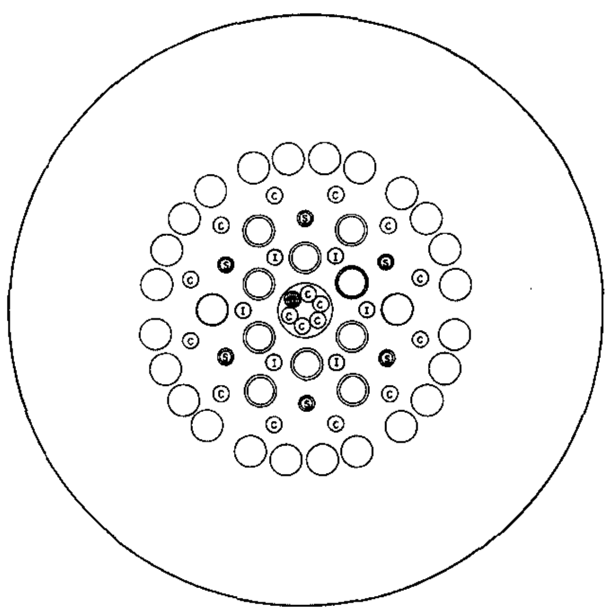


FIG. 2 REACTOR VESSEL AND COMPONENTS ARRANGEMENT

A cross section of the reactor core is shown in Figure 3. The driver fuel elements, in six groups of four elements each, surround the test region. The driver fuel provides the necessary lattice reactivity for operation at full power and temperature. There are 12 test fuel positions inside the driver ring, arranged on a seven-inch triangular spacing. Isolated pressure tubes occupy two of the test positions, and serve to separate their fuel coolant from the main system moderator. Each pressure tube is connected to a separate flow loop having its own pumps and heat removal system. The isolated pressure tubes contained D_2O only during the low power tests.

Twelve control rods and six safety rods are arranged in concentric rings inside the driver fuel. A cluster of six control rods occupies the core center. The control and safety rods are tubes of boronated stainless steel having an outside diameter of 1.25 inches and an inside diameter of 1.00 inch. The natural boron content is 1.0 wt %. The control rods are driven in or out at a maximum speed of 2.5 feet per minute. The safety rods are driven out at a speed of 2.5 feet per minute, and can be rapidly inserted from their full out position to 90% insertion in less than two seconds, following a scram signal.



○ Driver Position (24) ⓒ Control Rod (18)

○ Normal Test Position (10) ⓢ Safety Rod (6)

○ Isolated Loop Bayonet (2) ⓘ Instrument Position (6)

FIG. 3 LATTICE ARRANGEMENT

The initial driver and typical test fuel assemblies are shown in Figure 4. The driver fuel tube is Zircaloy clad and contains a ^{235}U loading of 108 g/ft, alloyed with zirconium. The fuel was fabricated by Nuclear Metals, Inc. The target elements, or burnable poison components, consist of a column of foot-long pairs of boronated stainless steel plates arranged in the shape of a cross.

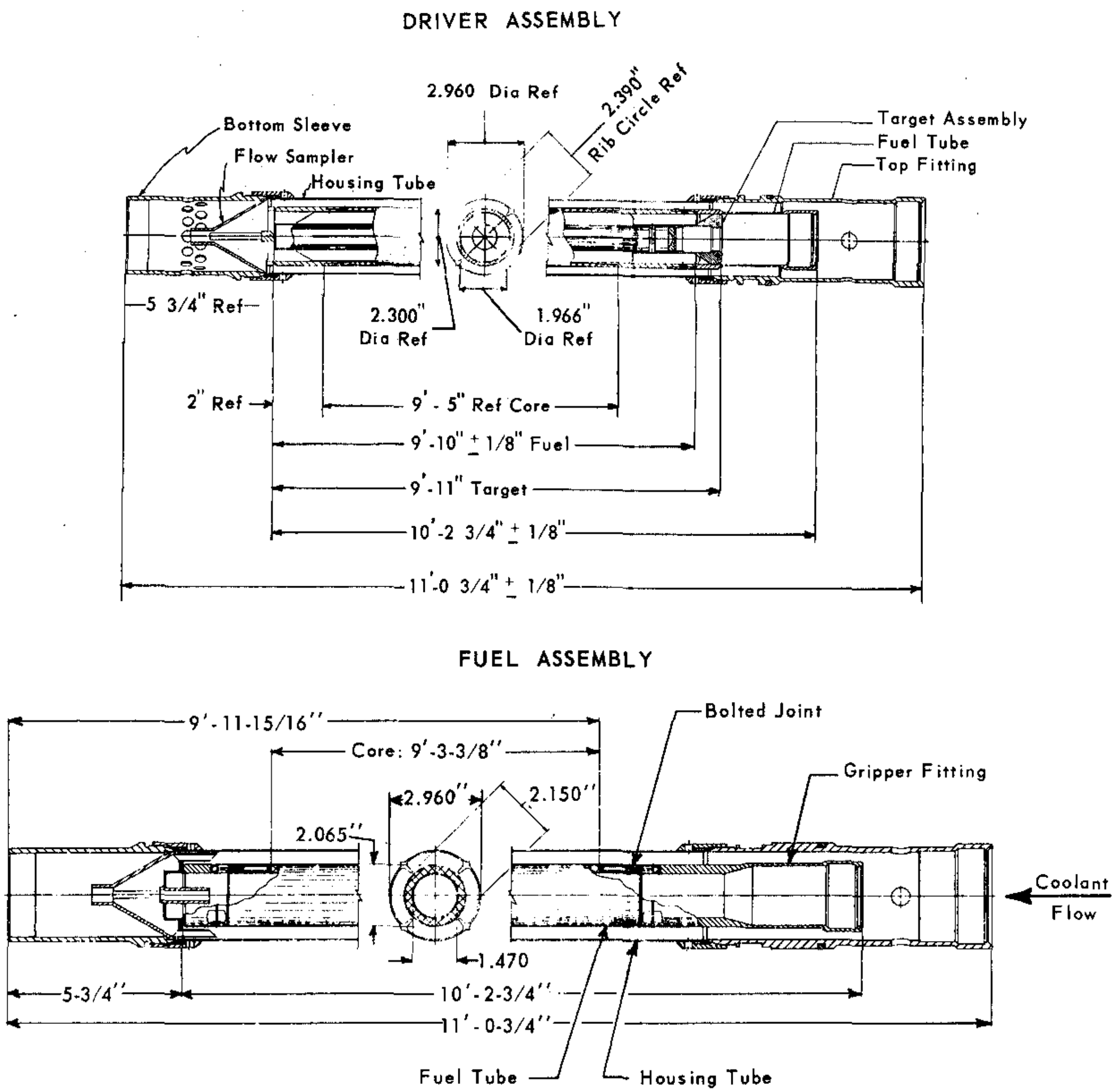


FIG. 4 DRIVER AND TEST FUEL ASSEMBLIES

The test elements used during part of the low power tests were natural uranium tubes clad in Zircaloy. These elements were not of power operation quality, but provided a satisfactory test region lattice for the zero power tests.

Normal operating conditions for the HWCTR are achieved at a reactor power of approximately 50 MW and a moderator temperature of 250°C. Pressurization is provided by a helium gas system, including a small volume of helium in the top of the vessel. Energy is removed from the system by boiling H_2O on the shell side of two vertical U-tube steam generators. The steam is vented to the atmosphere.

During the tests described in this report, reactor power did not exceed 10 KW. Some tests were conducted at elevated temperature. In those instances, energy was added to the system by operating the main system pumps at full D_2O flow, with no coolant H_2O in the steam generators.

MATERIAL CONTENT OF CORE COMPONENTS

An important part of the prestartup preparations consisted of determining the material content of core components such as fuel, target elements, control rods, and safety rods. A summary of these analyses is given below.

Driver Fuel and Target Elements

The ^{235}U content of the driver fuel was measured by the vendor, Nuclear Metals, Inc. (NMI), and by SRP personnel operating the Nuclear Test Gage (NTG).[2] The results of these measurements are given in Table I for both the initial driver charge (M-1) and the second driver charge (M-2). Only the M-1 drivers were used in the physics tests described in this report.

No direct comparison can be made between the total amount of ^{235}U in any element and the specific loading of the element, in g/ft. A tube that is above average in total ^{235}U content, for example, may be below average in the specific loading. These differences can be attributed to differences in fuel core length between tubes and to errors inherent in each method of measurement. The total spread in ^{235}U content was not so large as to introduce a significant reactivity uncertainty or to create a power-limiting "hot spot".

The boron content of the target blades was determined from neutron transmission measurements. The average natural boron content of the 510 target blades was 0.34 wt %, corresponding to 0.61 g/ft of natural boron. Good agreement was obtained between the results of chemical analyses and neutron transmission measurements made on a selected few samples. The target blades used to make up an assembly for a given driver element were taken randomly from the group. Each driver element contained 20 target blades, so that differences in reactivity worth among the assembled target elements were minor.

TABLE I

^{235}U Content of HWCTR Driver Elements

Lattice Position No.	M-1 Set Tube No.	M-1 Set NMI g ^{235}U	M-1 Set NTG Data Avg ^{235}U, g/ft	M-1 Set NTG Data Max Variation along Tube,* g/ft	M-2 Set Tube No.	M-2 Set NMI g ^{235}U	M-2 Set NTG Data Avg ^{235}U, g/ft	M-2 Set NTG Data Max Variation along Tube,* g/ft
1	8	941	109.5	1.4	29	966	110.9	1.8
2	20	956	108.7	1.2	41	948	107.6	1.2
3	15	957	109.0	1.6	7	949	108.5	2.3
4	42	958	108.7	1.2	6	947	109.1	1.8
5	44	955	108.6	1.2	13	967	110.4	2.6
6	40	952	108.0	1.2	37	953	107.7	1.5
7	46	972	109.2	1.3	3	943	108.9	1.1
8	34	955	108.0	0.9	52	957	109.1	2.5
9	36	947	108.2	1.4	43	960	110.0	1.5
10	35	939	108.0	1.1	38	949	108.0	1.0
11	48	954	107.7	1.0	25	954	108.2	2.1
12	31	953	108.1	1.7	26	966	109.6	2.4
13	33	964	108.9	1.7	30	966	110.9	1.6
14	24	941	108.6	1.8	27	946	107.7	1.9
15	22	950	109.6	1.8	16	952	108.5	1.9
16	10	954	109.0	1.7	12	956	109.5	1.8
17	47	952	108.2	1.4	4	947	110.2	1.5
18	53	950	108.5	1.7	39	951	107.6	1.0
19	55	955	108.6	1.3	18	948	108.9	1.9
20	54	950	108.9	1.8	32	943	109.0	2.2
21	56	927	107.5	1.7	14	955	110.0	1.9
22	49	955	107.3	1.0	1	960	107.9	1.6
23	51	949	107.6	1.6	5	949	108.2	1.9
24	50	946	108.2	1.2	17	963	109.7	1.7
	Avg →	951	108.4	1.4	Avg →	954	109.0	1.8

*Maximum variation is equal to the difference between the highest reading and the lowest reading along the tube.

Control Rods and Safety Rods

The average natural boron content of the control rods and safety rods was 1.06 wt % as determined from chemical analyses, and 0.97 wt % as determined by neutron transmission measurements. The reactivity worth of a HWCTR control rod was measured to be 95% the worth of a standard rod used in a HWCTR mockup experiment that was conducted in the Process Development Pile (PDP).[3] The standard rod contained 1.42 wt % natural boron, as determined both by chemical analyses and neutron transmission measurements.

INITIAL CRITICAL

Special attention was given to the manner in which fuel components were added to the reactor core and to the method of attaining the initial critical. Reliance was placed on information obtained from HWCTR mockup studies conducted in the PDP.[3] As described in the previous section, the material content of each fuel and control rod component was known, and was consistent with the design values set after the PDP tests. Nevertheless, the assembly of the dry core, the raising of the moderator in the shutdown core, and the attaining of the initial critical were all accompanied by continuous monitoring of changes in the neutron flux in the core. The conservative assumption was made that criticality could be achieved after any step in the startup sequence.

Loading the Reactor Core

The sequence of events to accomplish the assembly of the reactor core provided for the loading of all control rods, safety rods, and driver fuel to the dry vessel, followed by the filling of the vessel with D_2O. The moderator and safety rods were to be raised slowly together, assuring that the reactor would never approach criticality without the safety rods removed. It was anticipated that large decreases in count rate on the nuclear instruments would occur as the neutron sources and instrument chambers became covered by D_2O. Real changes in neutron flux multiplication would be masked by changes resulting from the geometry effects. To obtain a measure of the anticipated geometry effects, count rate data were obtained from the nuclear instruments as the D_2O was drained from the reactor core containing control rods and sources, but no fuel.

TABLE II

Nuclear Instruments

Instruments	No. of Systems	Probe Location	Operating Range
Temporary BF_3 (Boron-lined ion chambers)	2	In-core	Shutdown to 1 KW
BF_3	1	(a)	Shutdown to 5 KW
Fission Counter	1	(a)	Shutdown to 1 MW
High Level Monitor	3	(a)	100 watts to full power
Log-Period	2	(a)	100 watts to full power
Galvanometer	1	(a)	100 watts to full power

(a) Sleeve external to reactor.

The nuclear instruments used throughout the zero power test period are listed in Table II. The BF_3 instruments and the fission counters were used (1) to monitor increases in multiplication during the approach to criticality, and (2) to conduct the low-flux power rise. The remaining instruments became operable at a power of approximately 100 watts and were used for all higher powers. There was sufficient overlap between the low level and high level instruments to ensure safe operation when power was raised through the instruments transition region.

Changes in count rate of each nuclear instrument versus changes in core D_2O height are shown in Figure 5. The leakage neutron flux measured by the two external startup instruments increased by a factor of about 5000 as D_2O was drained from the core. The increase in flux at the two internal BF_3 chambers was less than a factor of 10, but occurred very abruptly as each chamber was uncovered by the D_2O.

Driver fuel elements were charged to the dry core. Small increases in count rate were observed on the two external startup systems. The external BF_3 count rate increased 40% and the fission counter 18%. No change in count rate was observed on the two internal BF_3 instruments. No test fuel was charged at this time.

Attaining Criticality

The moderator level in the reactor core was raised in small increments, with count rate data obtained after each increment. The block valves in the two main circulation systems were locked closed to prevent the sudden addition of a large amount of D_2O to the core. The six safety rods were raised in increments, with the tips of the rods maintained above the D_2O level. The responses of the nuclear instruments with the increases in D_2O level are shown in Figures 6, 7, and 8. Count rate data obtained when no fuel was present are also shown.

The removal of control rods was begun after the D_2O level was above the top shield. The six cluster rods were fully removed, resulting in the addition of about 0.025 K. The twelve ring control rods were removed in increments in a banked configuration with count rate data obtained after each increment. A stable period was attained with all 12 ring control rods about one-third withdrawn. The power rise was terminated at a power of a few hundred watts. The initial criticality of the HWCTR was attained at 11:31 PM on March 3, 1962. The axial position of the 12 ring control rods was 650 veeder units.*

*A fully inserted control rod has the axial position of 1000 veeder units, and a fully removed rod, zero veeder units. The total rod travel is 114 inches.

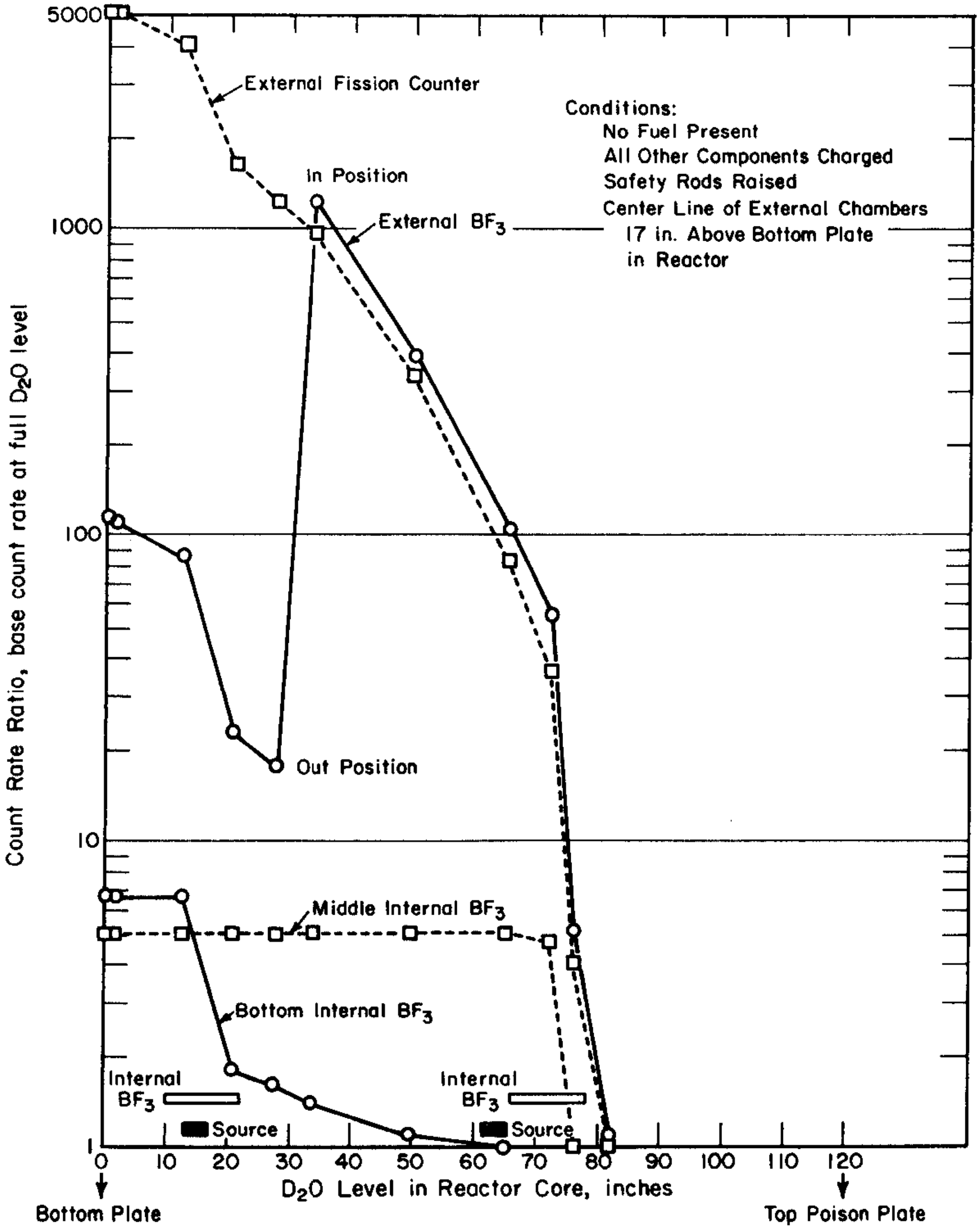


FIG. 5 COUNT RATE RATIO VS. D_2O LEVEL IN REACTOR CORE

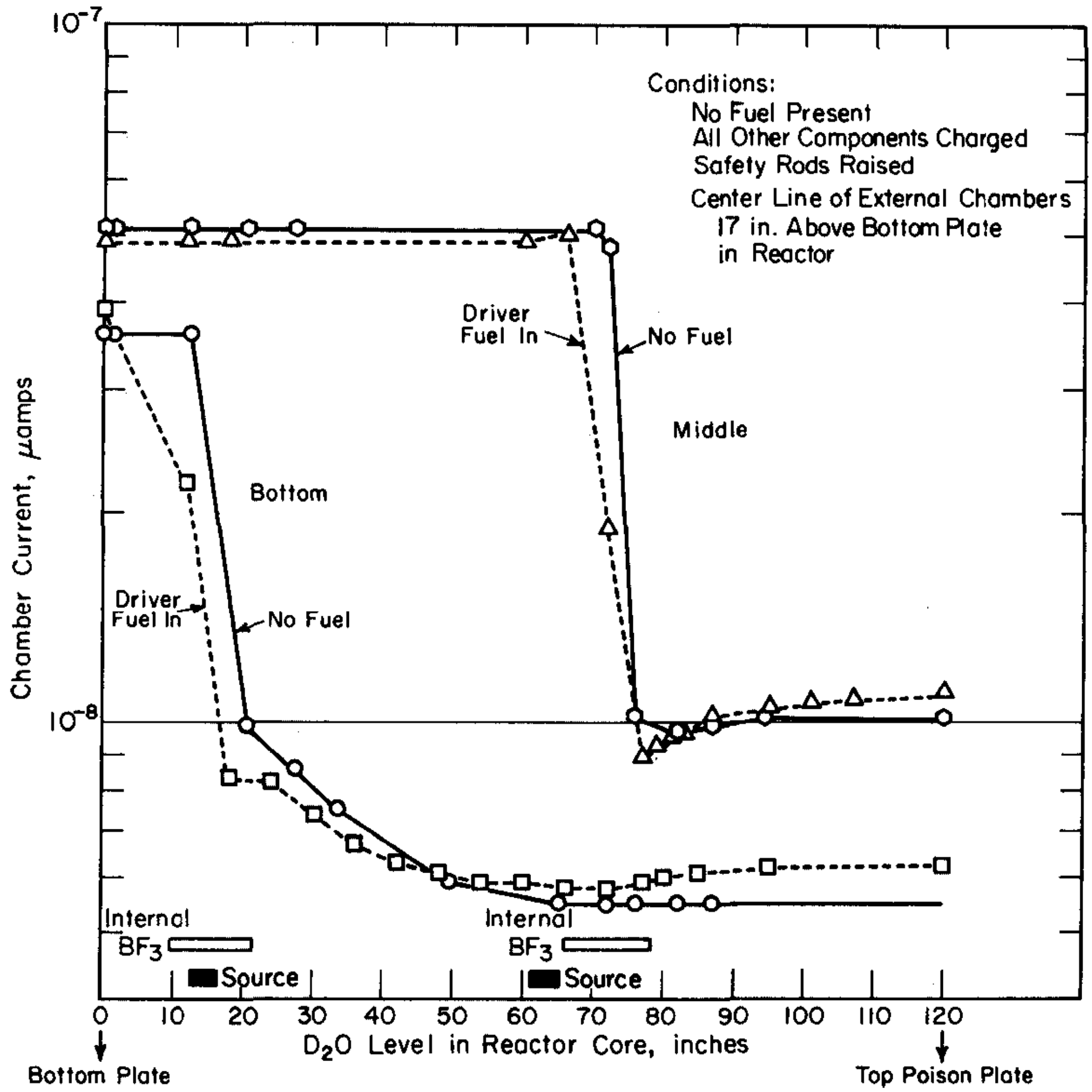


FIG. 6 INTERNAL BF_3 CHAMBER CURRENT VS. D_2O LEVEL IN REACTOR CORE

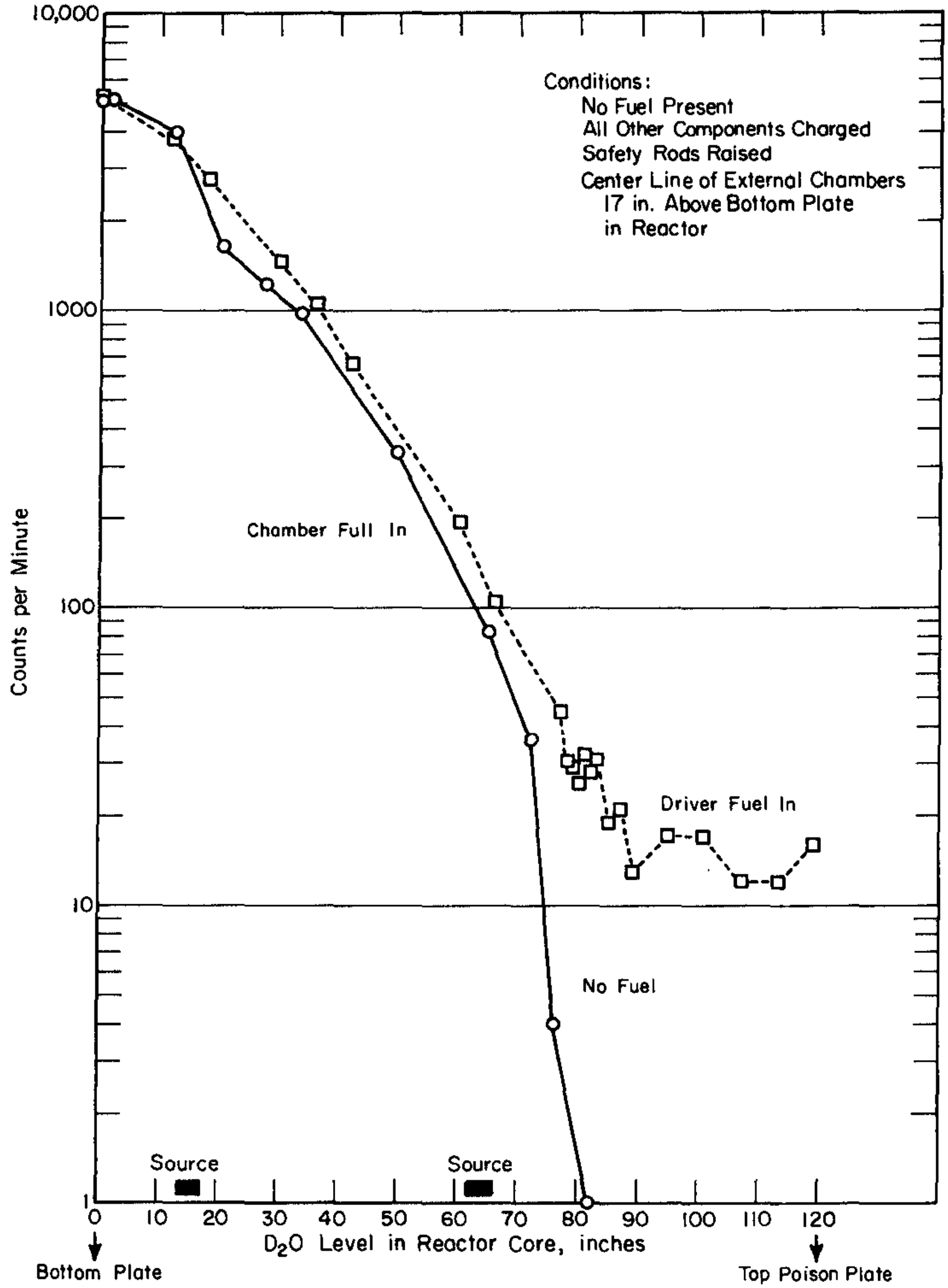


FIG. 7 EXTERNAL FISSION COUNTER COUNT RATE VS. D_2O LEVEL IN REACTOR CORE

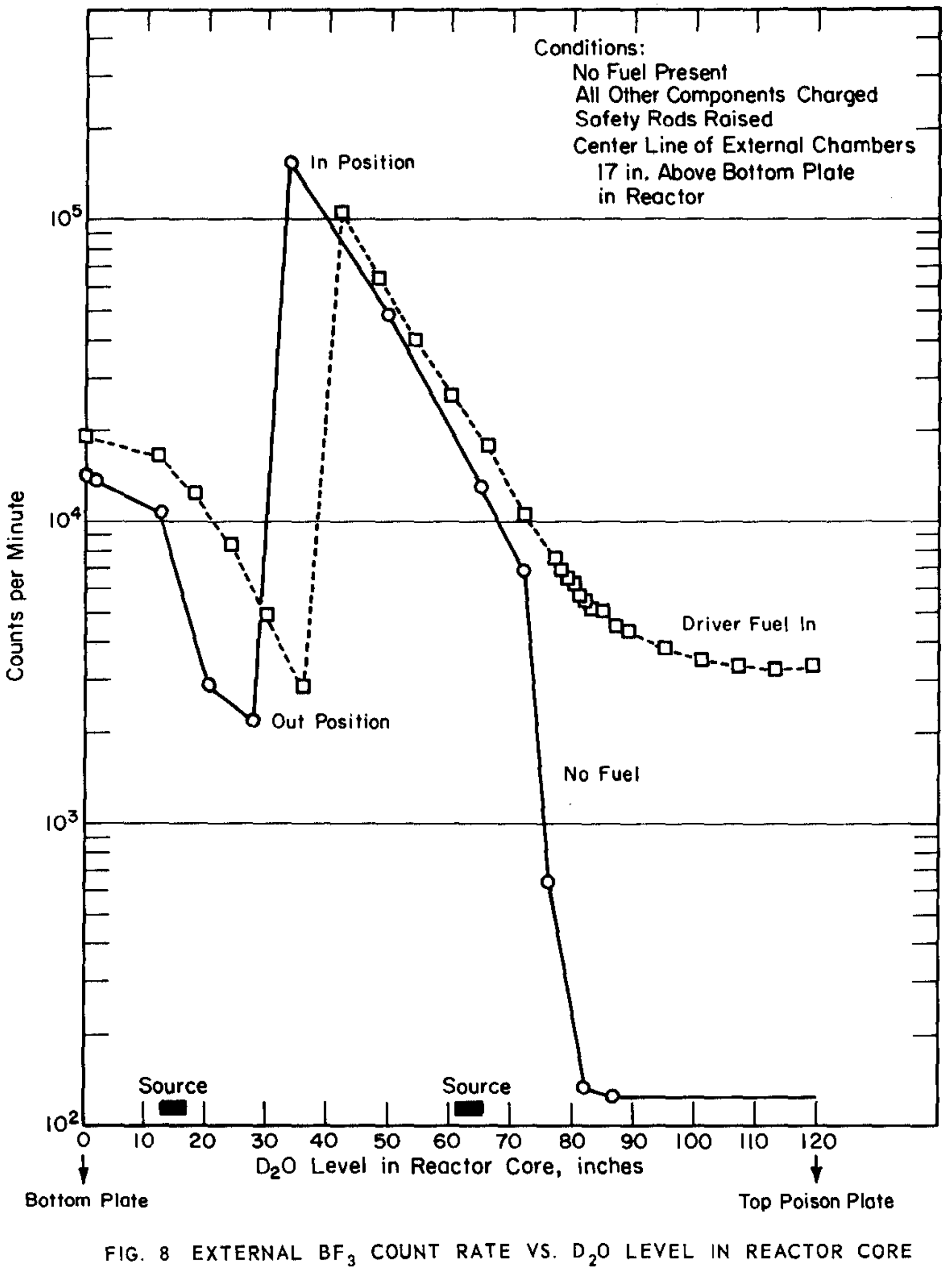


FIG. 8 EXTERNAL BF_3 COUNT RATE VS. D_2O LEVEL IN REACTOR CORE

After criticality was attained, a test was conducted to determine if the in-core sections of the control rods and safety rods were properly connected or "latched" to the upper racks and extensions, which operate the axial position indicators. Two safety rods were found delatched, i.e., the rods were fully inserted in the reactor. The reactor was shut down, the two safety rods were latched, and criticality was again attained.

The banked ring control rod positions at the second criticality was 733 veeder units. The reactivity added in raising the 12 ring control rods from 1000 to 733 veeder units was about 0.055 K. Thus, the reactivity added in cluster and ring control rods to attain criticality was about 0.08 K. The "margin of control" of the HWCTR is defined as the amount by which the reactor is subcritical at 20°C with the safety rods fully removed and all control rods fully inserted. In this case, the margin of control was 0.08 K. The minimum satisfactory margin conservatively set for the initial critical was 0.04 K.

Natural uranium fuel elements were charged to ten of the test lattice positions, excluding the pressure tubes. The reactor was made critical at 793 veeder units of ring control rod at 20°C. The margin of control in this lattice was 0.045 K.

Soon after the zero power tests began, a reactivity-hydraulic relationship was discovered. The reactivity of the lattice was influenced by changes in system pressure and by operation of pumps. Investigation showed that helium gas bubbles were entrained in the reactor core when the main system pumps were operating. A description of this problem and the system modifications made to eliminate it are given in reference 4. Reactivity data presented in this report were obtained after the problem was eliminated.

REACTIVITY WORTH OF CONTROL SYSTEM

Ring Control Rods

Several tests were conducted to measure the worth of the ring control rods, and the negative reactivity effects resulting from raising the moderator temperature. Duplicate tests were conducted in a lattice containing driver fuel, then driver fuel and test fuel.

The banked, critical ring control rod configuration was measured at several moderator temperatures during a temperature ascension to 240°C. Heat was added to the reactor system by operating the main system pumps at full flow, with no heat removal capacity in the secondary system. The control rod positions as a function of moderator temperature are shown in Figure 9.

Measurements of the worth of a single control rod were made at a moderator temperature of 240°C. The technique used was to determine by period measurements the reactivity introduced when ring control rod No. 1 was removed several veeder units at each of several axial positions. To minimize radial flux tilts, ring control rod No. 7, which is directly opposite rod No. 1, was set at the same axial position as rod No. 1 prior to the period measurement. The remaining ten rods were all set at the banked rod configuration required to maintain criticality. Figure 10 shows the banked rod configuration at each position of rods 1 and 7 where a reactivity data point was obtained.

The reactivity-period relationship used in the measurements is shown in Figure 11. The delayed neutron groups include fissions from ^{235}U and ^{238}U, and photoneutrons from the (γ,n) reaction with the deuterium.

The excess reactivity measured at each rod withdrawal was divided by the total rod withdrawal in veeder units (v.u.) to obtain the reactivity per unit axial distance, or K/v.u. A plot of K/v.u. versus the average position of rod No. 1 during the rod withdrawal is shown in Figure 12. The area under each curve is proportional to the total rod worth. The rod worths measured by this method are given in Table III.

TABLE III

Rod Worths at 240°C Moderator Temperature

Lattice	Reactivity, K	
	Single Rod	12 Rods
Driver fuel only	0.023	0.276
Driver and test fuel	0.020	0.240

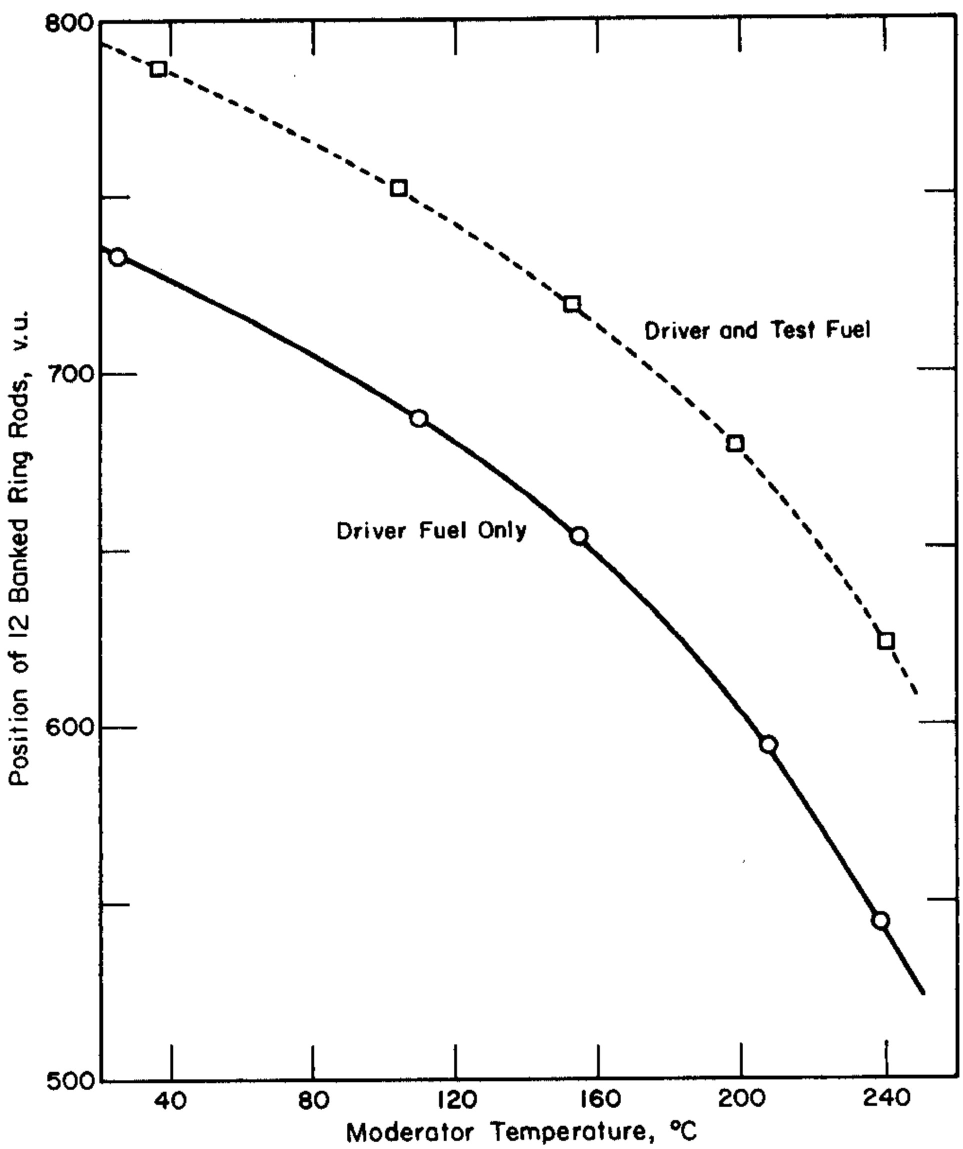


FIG. 9 AXIAL POSITION OF RING CONTROL RODS VS. MODERATOR TEMPERATURE

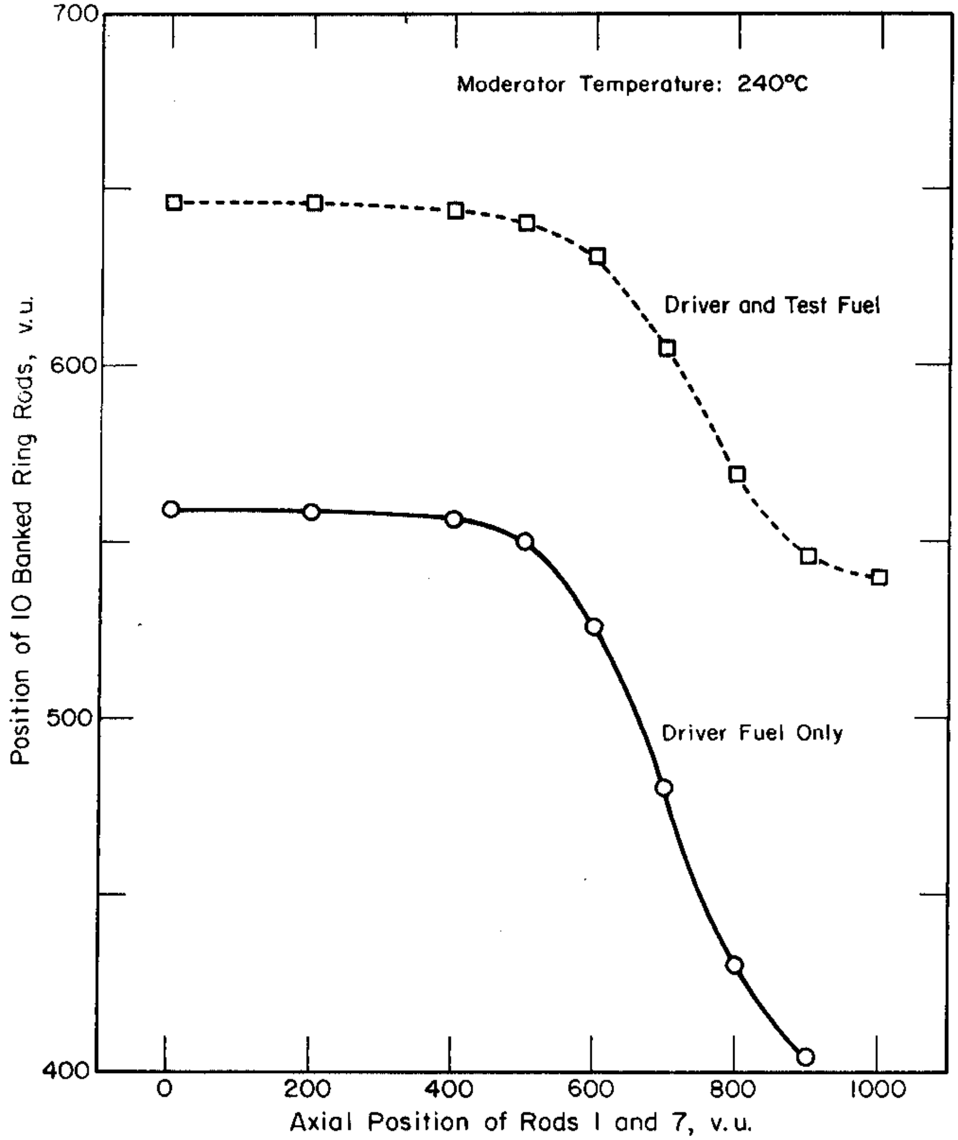


FIG. 10 AXIAL POSITION OF 10 RING CONTROL RODS VS. AXIAL POSITION OF RODS 1 AND 7

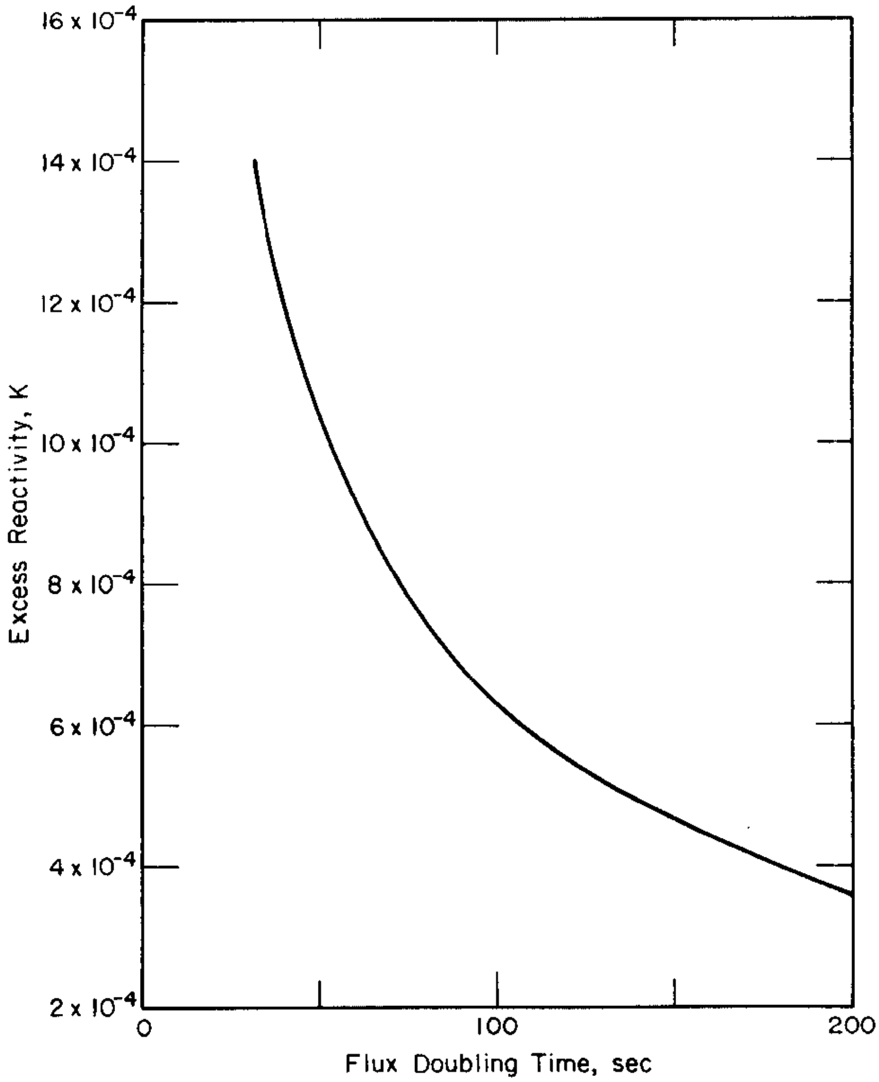


FIG. 11 EXCESS REACTIVITY VS. FLUX DOUBLING TIME

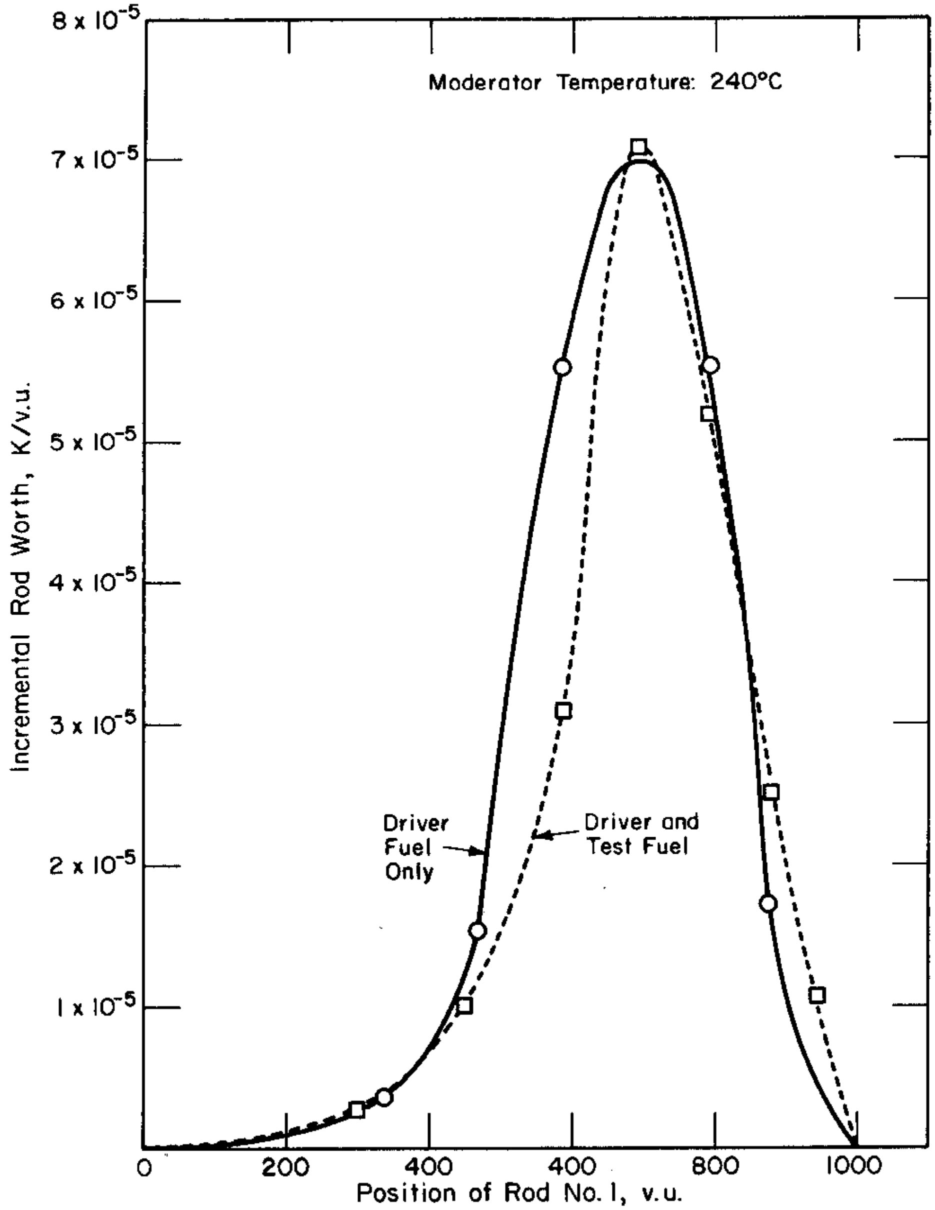


FIG. 12 INCREMENTAL ROD WORTH VS. POSITION OF ROD No. 1

The worth of the control system as a function of moderator temperature was obtained from the measured values given above and from calculated changes in the migration area, M^2. Measurements of HWCTR rod worths made in a pressurized exponential facility[5] showed that the changes in temperature had little effect on the incremental rod buckling. Thus, the change in rod worth to the lattice should follow the change in M^2. The calculated values for the worth of the 12 ring control rods as a function of temperature are shown in Figure 13. The rod worth values at 20°C moderator temperature are given in Table IV.

TABLE IV

Rod Worths at 20°C Moderator Temperature

Lattice	Reactivity, K Single Rod	12 Rods
Driver fuel only	0.020	0.234
Driver and test fuel	0.017	0.200

The maximum drive speed of a control rod is 2.5 ft/min or 4.4 v.u./sec. If the control rod tip were in the axial region of maximum reactivity worth, the reactivity introduced at 240°C would be 7×10^{-5} K/v.u. of rod motion, as shown in Figure 12. The rate of reactivity addition would be 3.1×10^{-4} K/sec. The corresponding rate at 20°C is 2.6×10^{-4} K/sec.

Safety Rods

The six safety rods are identical in composition with the control rods, and are arranged on a circle with a diameter seven inches less than the ring control rods. The effectiveness of the safety rods is dependent on the number of other rods present in the lattice. The lattice condition at which it is most meaningful to evaluate the safety rod worth is with the critical rod configuration at full operating temperature and with a moderator temperature of 20°C. This condition simulates the abnormal sequence of events in which the reactor is scrammed from full operating temperature and the safety rods drop in, but the control rods do not drive in. HWCTR operating standards require that the negative reactivity introduced by the safety rods be sufficient to hold the reactor subcritical by at least 0.01 K when the system temperature reaches 20°C. Computations made using the PDQ-3 routine[6] showed that the worth of the six safety rods, with the control rod complement just described, was approximately 5-1/2 ring rods, or 0.09 K at 20°C moderator temperature. Thus, to

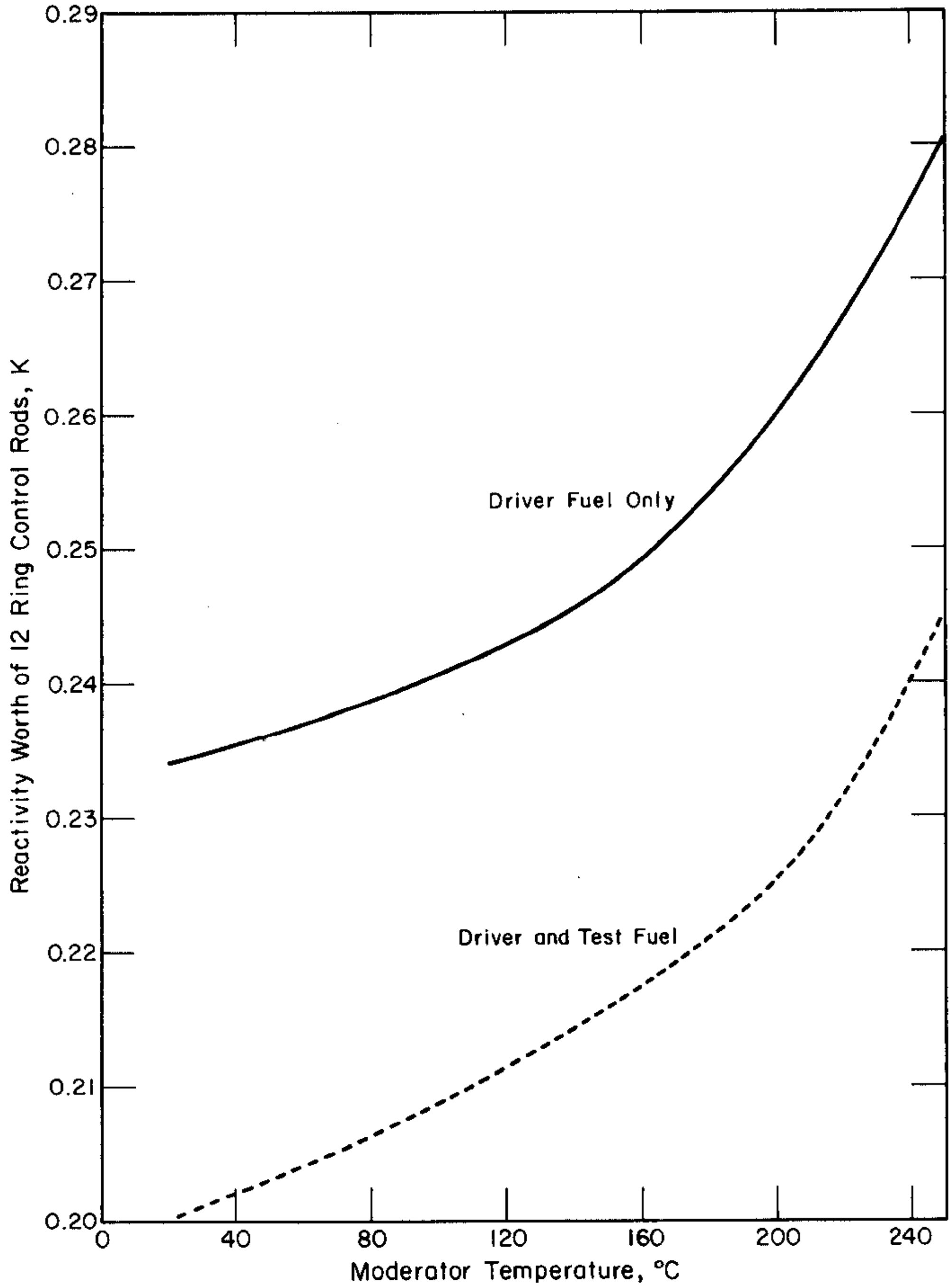


FIG. 13 REACTIVITY WORTH OF 12 RING CONTROL RODS VS. MODERATOR TEMPERATURE

maintain the required margin of 0.01 K, the reactivity regained when the system cools down from the operating temperature to 20°C must not exceed 0.08 K. The value of 0.08 K in temperature reactivity effects set the upper limit on the allowable operating temperature for the lattice containing driver and test fuel.

Two methods were used to determine the maximum allowable operating temperature. In the first, a fractional rod worth curve was prepared, for use with the banked control rod data. In the second method, control rod complements of fully inserted rods were compared at hot and ambient temperature conditions.

The fractional rod worth curve was prepared from calculations made using the PDQ-2 routine,[7] and from data obtained in period measurements. The curve is presented in Figure 14. The rod worth fraction that may be used to raise the moderator temperature from 20°C to the limiting temperature is equal to the ratio of 0.08 K/0.20 K, or 0.40. Figure 14 shows that rod removal from 793 v.u. (20°C) to 610 v.u. is equivalent to the rod worth fraction of 0.40. Figure 9 shows that the moderator temperature was 250°C at a rod position of 610 v.u. Thus, the limiting moderator temperature is 250°C.

The difference in the number of fully inserted control rods between the 20°C and 250°C moderator temperature was approximately 5 rods. The effective worth of the six safety rods was approximately 5-1/2 rods. A margin of 0.01 K, approximately 1/2 rod, is required by HWCTR operating standards. Thus, the limiting moderator temperature for the driver and test lattice is 250°C, as determined also by the second method.

The limiting temperature for the driver only lattice was not evaluated in detail, but was shown to be higher than 250°C. The effectiveness of the safety rods in the lattice with driver fuel only is larger than in the combined driver and test fuel lattice.

Calculations show that a small increase in the limiting moderator temperature occurs with fuel depletion. The reactivity required to conduct the temperature ascension increases with fuel depletion, but the worth of the safety rods also increases, at a slightly higher rate.

The worth of the six safety rods in the shutdown lattice could not be measured directly and was not evaluated in detail. The safety rod worth was less than the 0.09 K value given for the specific lattice conditions described earlier. Estimates made from a brief study show that the reactivity added by the removal of the six safety rods prior to a nuclear startup was 0.06 to 0.07 K. Thus, a reactor charge with a measured margin of control of 0.04 K has a K_{eff} value of 0.90 K, or less, in the completely shutdown condition.

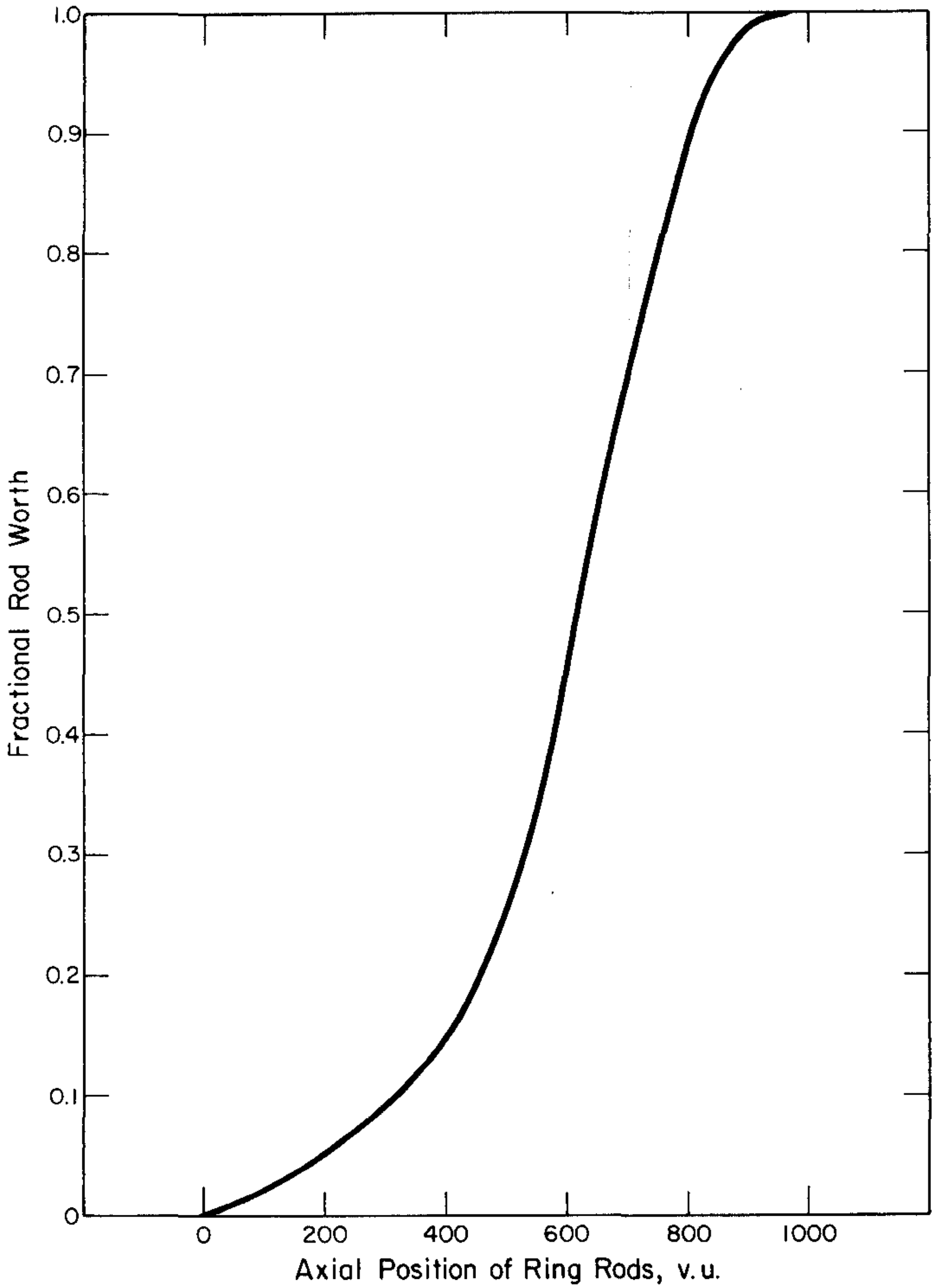


FIG. 14 FRACTIONAL ROD WORTH VS. AXIAL POSITION OF RING RODS
Driver and Test Fuel

Center Cluster Control Rods

The measured worth of the center cluster control rods was less than the calculated value and less than the value obtained in the PDP mockup tests.[3] Insertion of the cluster rods required that the banked ring control rods be removed from 793 v.u. to 746 v.u. The rod worth curve in Figure 14 shows that the 47 veeder units of rod motion is equal to 0.02 K. Calculations showed the worth of the cluster rods to be 0.025 to 0.030 K. The PDP mockup tests showed the worth of the cluster rods to be 0.030 to 0.035 K.

The cluster control rods serve only to provide additional shutdown margin and were not used to control the reactor during operation at full power. A conservative value of 0.020 K was used for the cluster rod worth in margin of control calculations. The corresponding value used for the driver only lattice was 0.025 K. The reference moderator temperature in margin of control calculations was 20°C.

TEMPERATURE COEFFICIENT OF REACTIVITY

A measure of the increase in neutron leakage from the reactor with moderator temperature increases may be obtained by combining the banked rod data shown in Figure 9, the total rod worths at each temperature from Figure 13, and the fractional rod worths from Figure 14. Of more practical interest, however, is the moderator temperature effect related to the kinetic response of the reactor. An outstanding safety feature of the HWCTR is its large, negative moderator temperature coefficient. Two general effects contribute to the coefficient - the increase in neutron leakage and the increase in rod worth with increasing moderator temperature. The most direct method of obtaining a measure of the coefficients from the data obtained is to combine the banked control rod data of Figure 9 with the fractional rod worth curve of Figure 14, and to fix the total rod worth value at the 20°C value of 0.20 K. The rates of change of the reactivity differences obtained in this manner are equal to the temperature coefficients, which are temperature dependent. The results are shown in Figure 15.

The temperature coefficient at the normal operating temperature of 250°C was -7×10^{-4} K/°C.

FLUX DISTRIBUTIONS

The radial and axial flux distributions were measured for several control rod configurations by irradiating copper wires. Ten-foot lengths of copper wire were inserted in each fuel element, and the reactor was operated at a power of a few kilowatts. The activity of

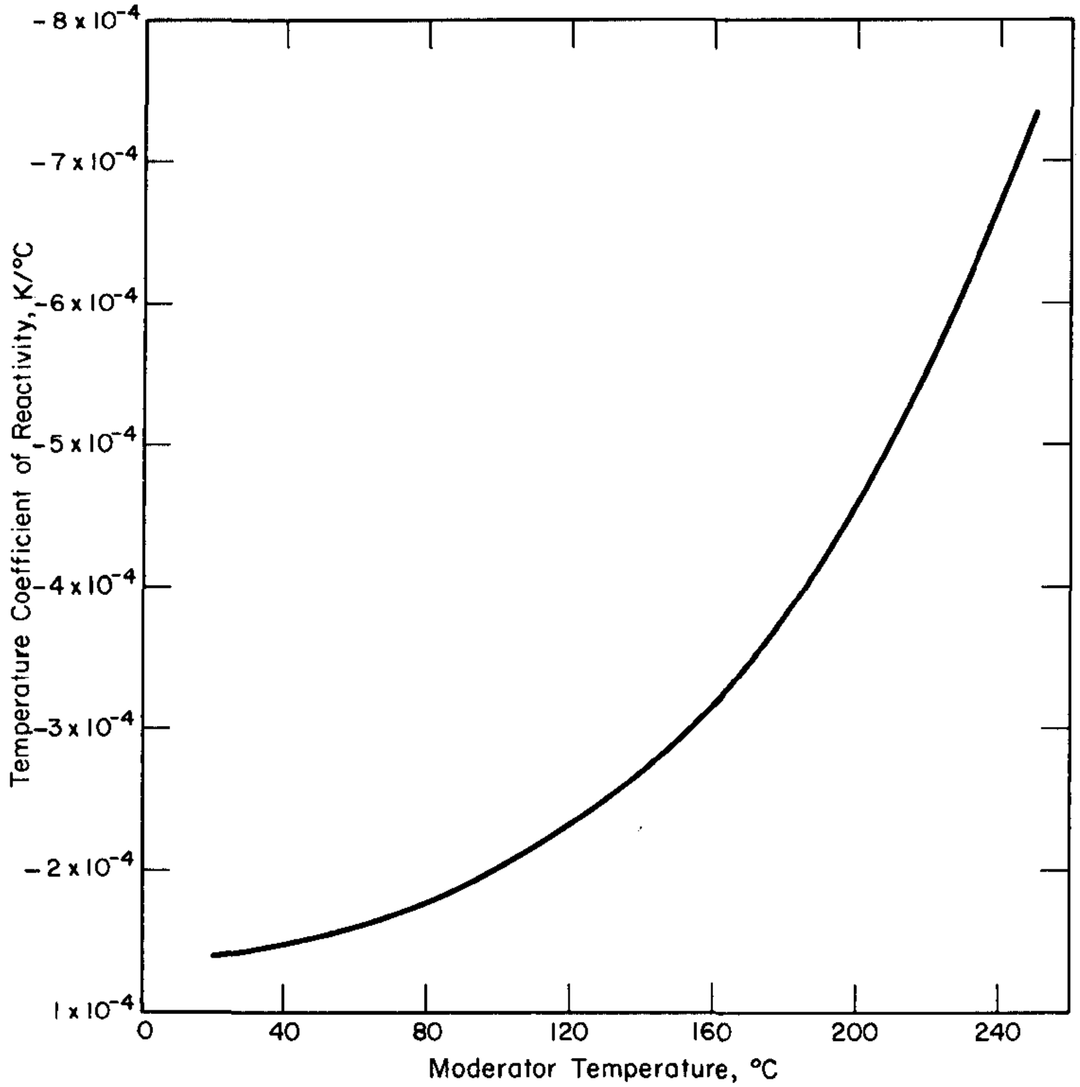


FIG. 15 TEMPERATURE COEFFICIENT OF REACTIVITY VS. MODERATOR TEMPERATURE

each wire was measured by a moving scintillation probe. The recorder trace was a profile of the axial flux distribution, and the area under the trace was proportional to the integrated radial flux at the fuel element.

Radial Flux

The results of the radial flux measurements are shown in Figure 16 through 24. The values given at each fuel position represent the average, relative flux in the fuel tube. Calculated disadvantage factors were used to convert the wire flux value to fuel tube flux, a correction of only 3%.

Figure 16 shows the relative flux distribution with all ring control rods positioned at 793 veeder units and all cluster rods removed. Some asymmetries in radial flux are apparent. Fuel elements 180° apart do not necessarily have the same flux value. The maximum driver element flux was 8% above the average driver flux. The average test element flux was 66% above the average driver flux.

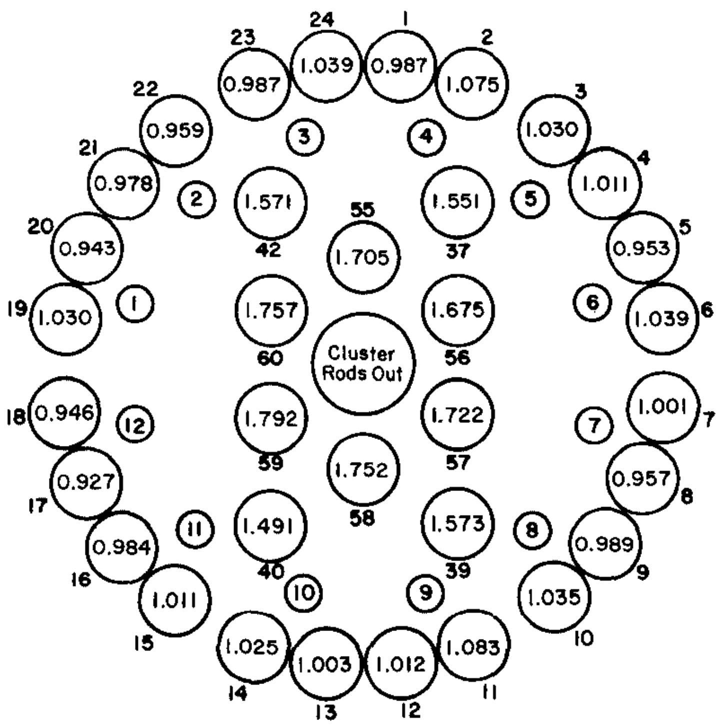
Figure 17 shows the results of the wire irradiation run made with the odd numbered ring control rods set at 1000 v.u., and the even numbered rods set at 662 v.u.

Figure 18 shows that the average flux in the inner test fuel was reduced 30% by the complete insertion of the center cluster rods.

The flux peak resulting from the complete removal of a ring control rod is shown in Figure 19. The maximum driver flux was 1.21, compared to a value of 1.08 measured when all ring control rods were banked.

The severe radial flux tilt that is shown in Figure 20 demonstrates that opposing rod pairs must be set at the same axial position. The high side of the tilt was centered in driver group 21, 22, 23, and 24, with the low side in the corresponding four drivers on the opposite side of the lattice. The only difference in the axial position of opposite control rod pairs that could create the tilt is in ring rods 2 and 8. Rod 8 was fully inserted, but rod 2 was inserted only to 700 v.u. Other opposing rod pairs were either at the same axial position or were oriented at right angles to the line of the tilt.

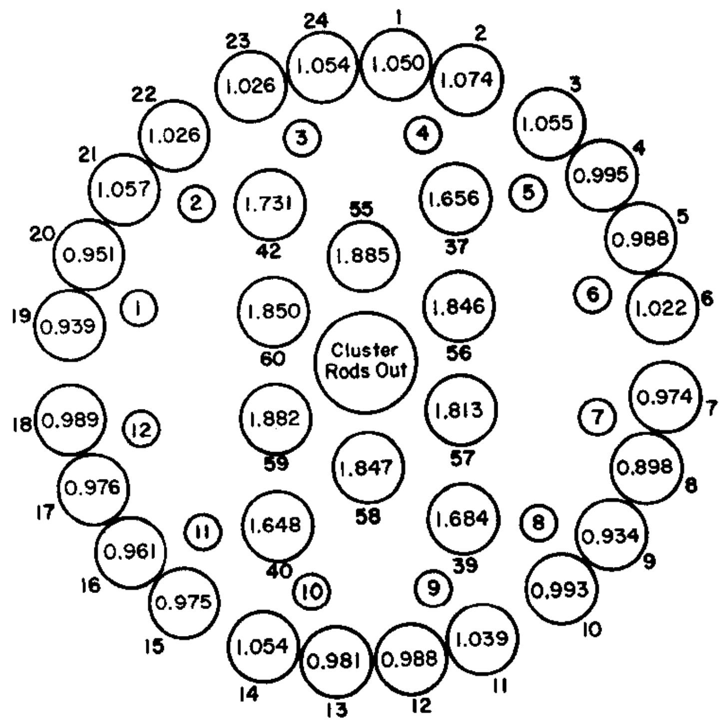
In the final wire irradiation run made at ambient temperature, the reactor was taken critical on only two control rods, rods 1 and 2, which were removed to 437 v.u. As shown in Figure 21, the flux in the driver fuel on the high side of the tilt was almost 2-1/2 times the flux on the low side of the tilt.



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.083
Avg. Outer Test	1.547
Avg. Inner Test	1.734
Avg. Test	1.659
Temperature, °C	24°C

Ring Control Rods
Banked-793 v.u.

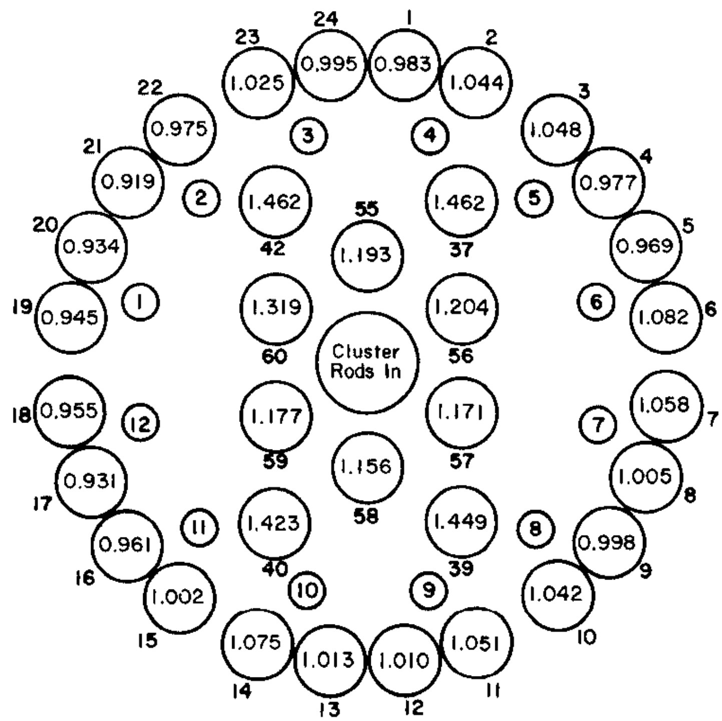
FIG. 16 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.074
Avg. Outer Test	1.680
Avg. Inner Test	1.854
Avg. Test	1.784
Temperature, °C	24°C

Ring Control Rods
Odd Numbers - 1000 v.u.
Even Numbers - 662 v.u.

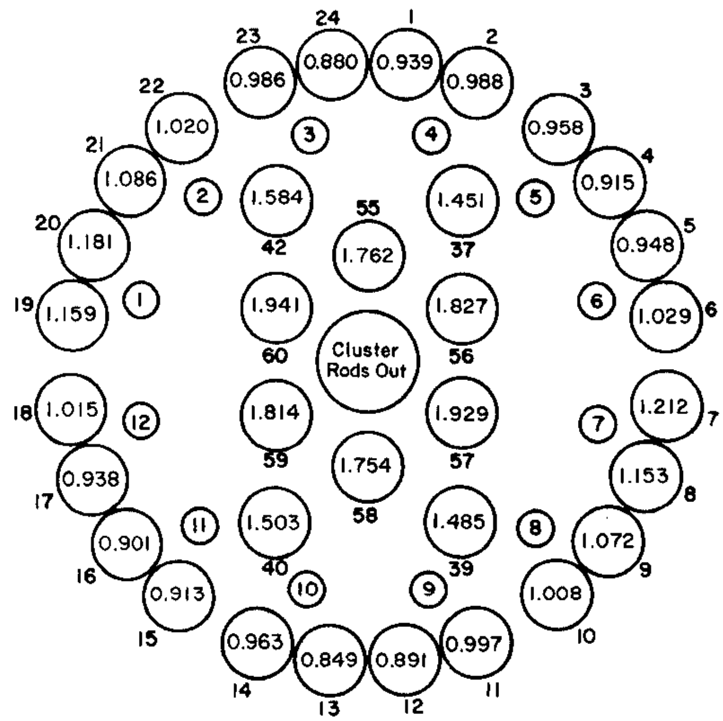
FIG. 17 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.082
Avg. Outer Test	1.449
Avg. Inner Test	1.203
Avg. Test	1.302
Temperature, °C	24°C

Ring Control Rods
Banked-746 v.u.

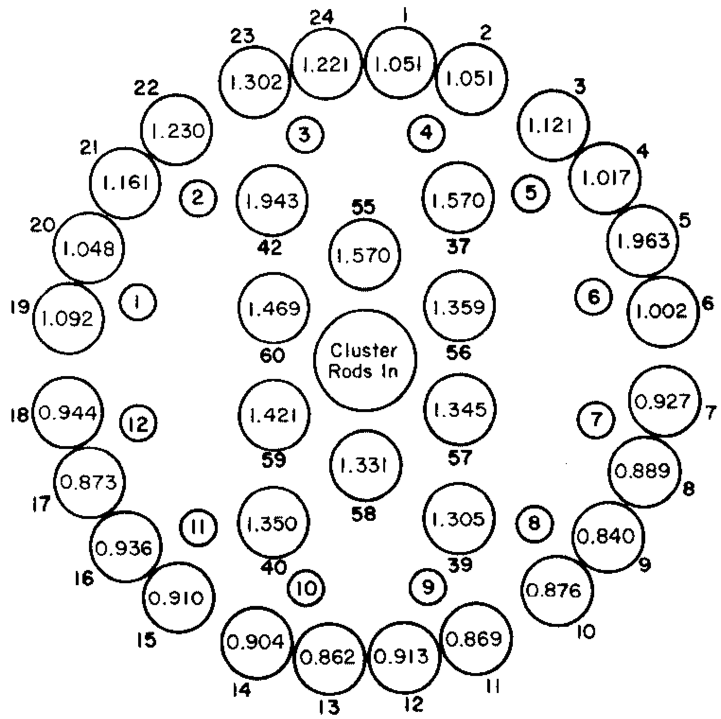
FIG. 18 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.212
Avg. Outer Test	1.506
Avg. Inner Test	1.838
Avg. Test	1.705
Temperature, °C	24°C

Ring Control Rods
1 and 7 Out
4 and 10-808 v.u.
All Others-1000 v.u.

FIG. 19 MEASURED RADIAL FLUX DISTRIBUTION

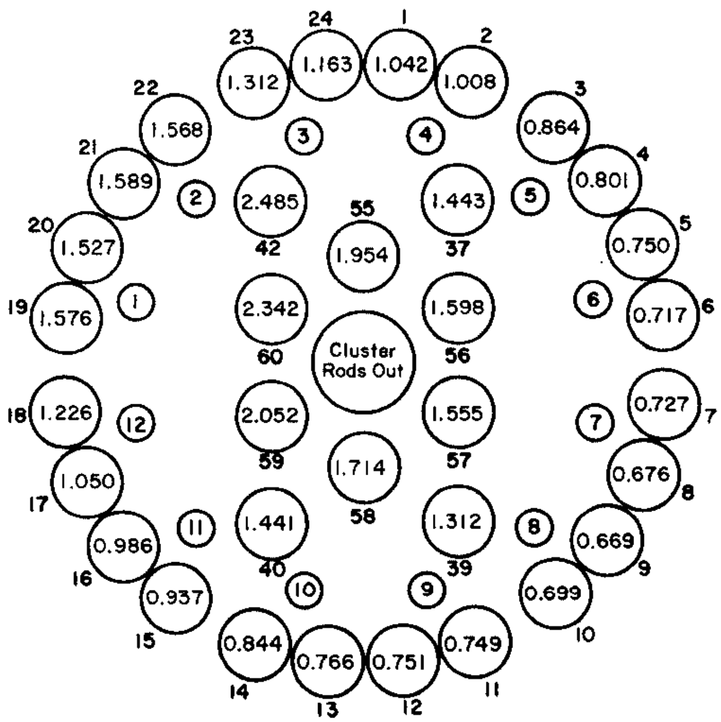


Avg. Driver	1.000
Max. Driver / Avg. Driver	1.302
Avg. Outer Test	1.542
Avg. Inner Test	1.416
Avg. Test	1.466
Temperature, °C	24°C

Ring Control Rods

1	2	3	4	5	6
637	700	637	1000	637	750
7	8	9	10	11	12
637	1000	637	850	637	1000

FIG. 20 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.589
Avg. Outer Test	1.670
Avg. Inner Test	1.869
Avg. Test	1.790
Temperature, °C	24°C

Ring Control Rods
1 and 2 - 437 v.u.
All other Rods - 1000 v.u.

FIG. 21 MEASURED RADIAL FLUX DISTRIBUTION

Three wire irradiation runs were made near the anticipated operating temperature of 240°C. The results of these three runs are shown in Figures 22, 23, and 24. The most important results of these measurements were that the highest driver flux was only 5% above the average, and that the average test flux was 68% above the average driver flux when the 12 ring control rods were banked. A similar test flux value was measured at 24°C (Figure 16).

Computational models were developed to permit the calculation of radial and axial flux distributions. The XY version of PDQ-3[6] was used for the radial model, and the RZ version of PDQ-2[7] was used for the axial model. The core configurations in the two models are shown in Figures 25 and 26.

In the radial model, fuel elements and control rods were represented as square cells surrounded by moderator. Input parameters for the cells in the PDQ-3 routine were obtained from MUFT IV[8] calculations and calculations using the P_3 approximation to transport theory. A constant axial buckling was assigned.

Only two comparisons of calculated and measured flux distributions were made. The measured data were already described in Figures 16 and 17. The calculated distributions are shown in Figures 27 and 28. In the first comparison, input parameters for the control rods and center cluster housing were adjusted to yield a test to driver flux ratio in agreement with the measured flux ratio. The calculated driver flux distribution was symmetrical about two axes, so that four driver positions shared a single relative flux value. In the second calculated distribution, driver elements 180° apart had the same relative flux value.

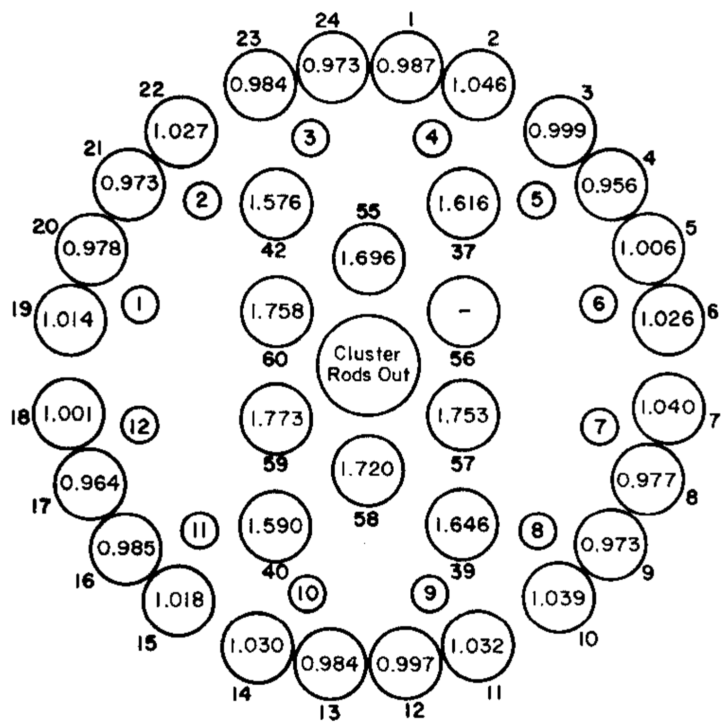
No satisfactory method was developed for obtaining PDQ-3 input parameters for partially inserted control rods, different from the banked rod position. No comparison of measured and calculated radial flux distributions was made for most of the rod configurations shown in Figures 16 through 24. During power operation of the HWCTR, the ring control rods were all set at the same axial position. Application of the radial model was used in these instances to predict the operating conditions of test fuel elements of new design.

Axial Flux

The axial computational model was developed to permit the calculation of axial flux distributions as a function of control rod position. Because the HWCTR contained no in-core flux monitors, the determination of maximum operating conditions was made directly from calculated axial flux distribution. (The total power of each fuel element was measured from flow and ΔT instruments.) The fuel and control rod regions of the axial model, shown in Figure 26, were composed of concentric cylinders in the two-dimensional geometry. The lower boundary of the control rod regions could be set at any elevation, to simulate partial insertions of banked rods. The input parameters for the control rod region were determined empirically from the results of the wire irradiations at low power. A comparison of the calculated and measured axial flux profiles is shown in Figures 29 and 30.

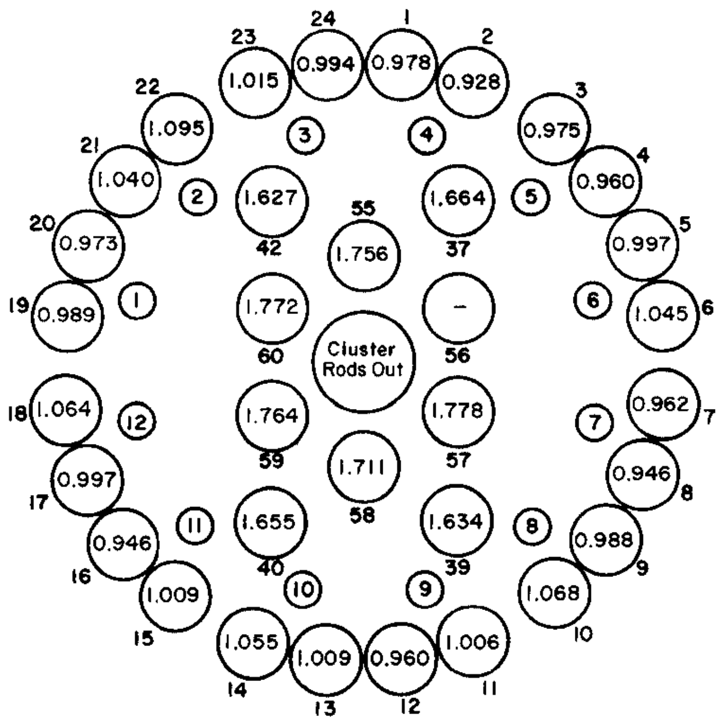
The calculation of axial flux profiles with fuel exposure was made using the TURBO[9] code. TURBO utilizes the PDQ-2 routine to calculate flux distributions. Fuel burnup in TURBO was achieved in short time increments with the new input parameters for the PDQ-2 routine computed at the end of each time increment.

The heterogeneous properties of the HWCTR lattice can be best represented in a three-dimensional model. The best candidate for this application is the TRIHET code,[10] but no work with this code has been completed.



Avg. Driver	1.000	
Max. Driver / Avg. Driver	1.046	
Avg. Outer Test	1.607	
Avg. Inner Test	1.740	
Avg. Test	1.681	
Temperature, °C	241°C	Ring Control Rods Banked-620 v.u.

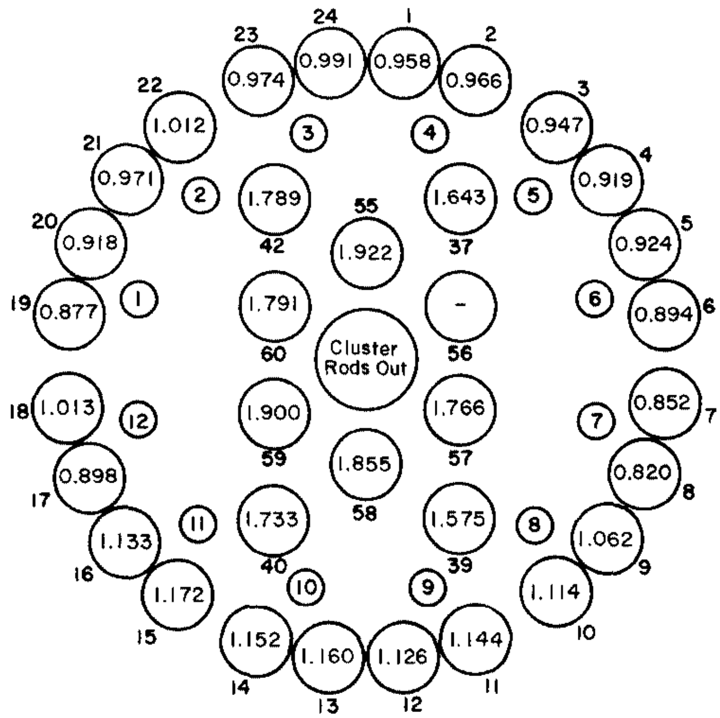
FIG. 22 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.095
Avg. Outer Test	1.645
Avg. Inner Test	1.756
Avg. Test	1.707
Temperature, °C	240°C

Ring Control Rods
Odd Numbers - 733 v.u.
Even Numbers Out

FIG. 23 MEASURED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.172
Avg. Outer Test	1.685
Avg. Inner Test	1.847
Avg. Test	1.775
Temperature, °C	239°C

Ring Control Rods
1 - 686 v.u.
7 - 786 v.u.
All other Rods - 586 v.u.

FIG. 24 MEASURED RADIAL FLUX DISTRIBUTION

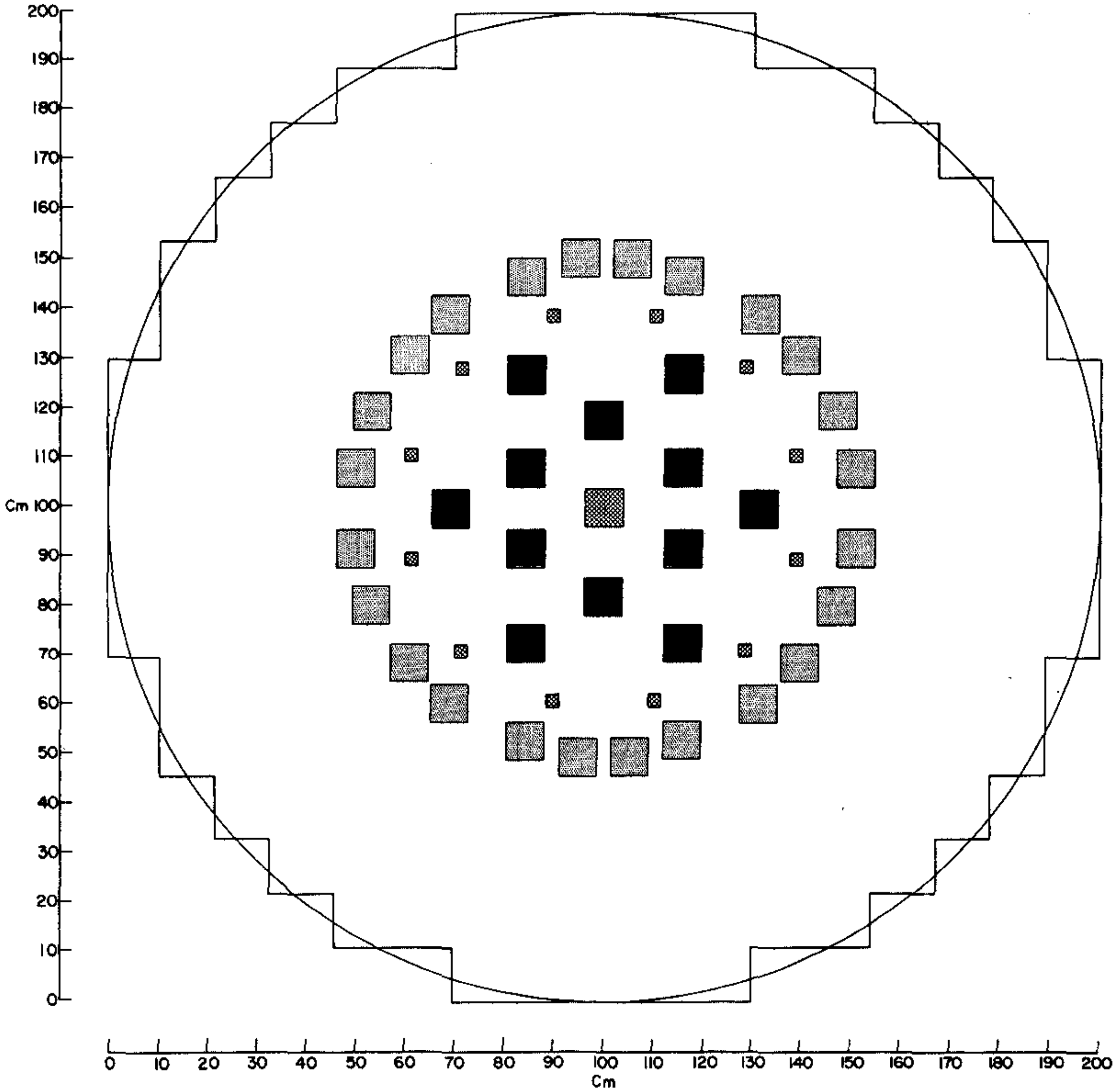


FIG. 25 RADIAL COMPUTATIONAL MODEL

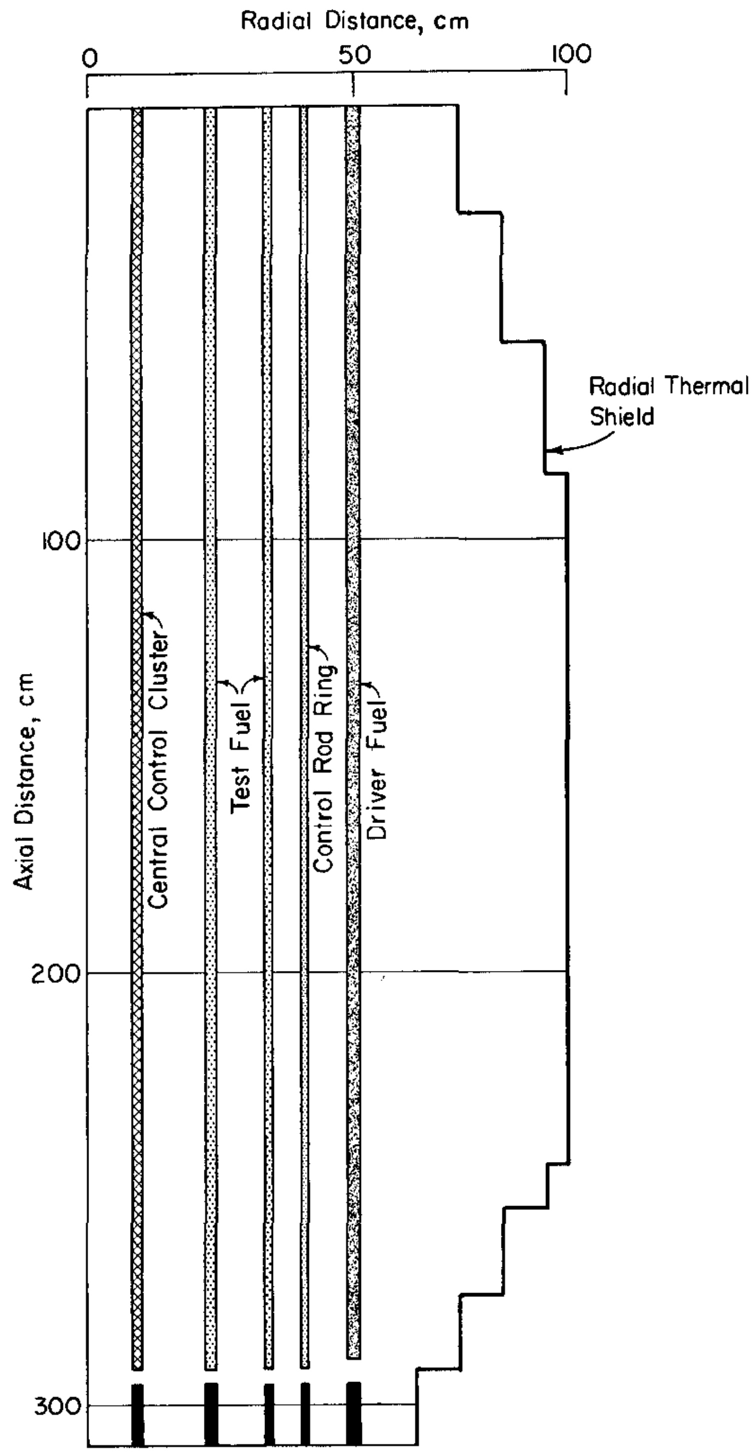
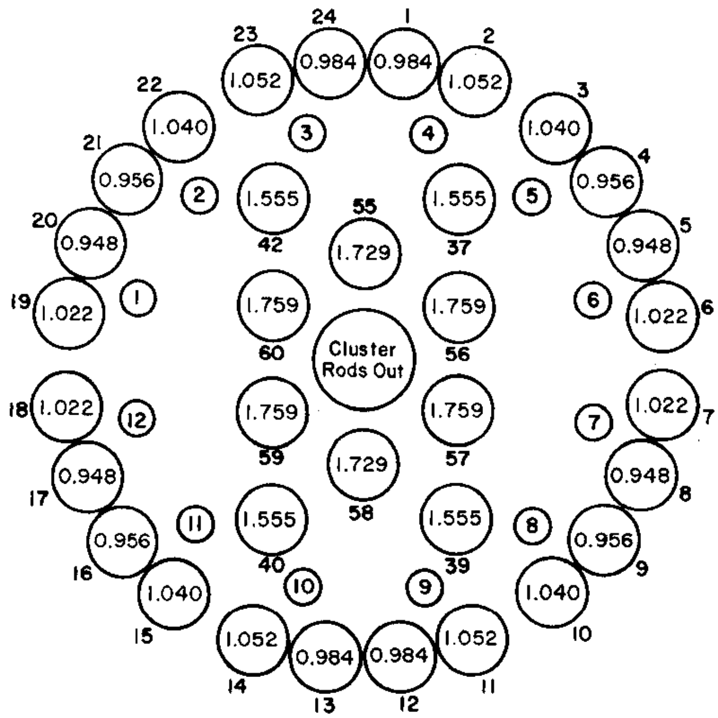


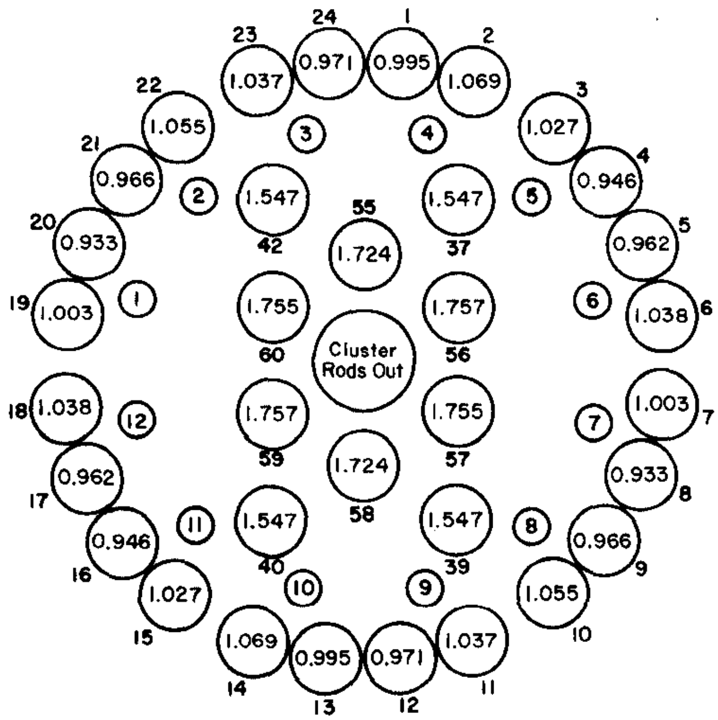
FIG. 26 AXIAL COMPUTATIONAL MODEL



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.052
Avg. Outer Test	1.555
Avg. Inner Test	1.749
Avg. Test	1.671
Temperature, °C	24°C

Ring Control Rods
Banked-793 v.u.

FIG. 27 CALCULATED RADIAL FLUX DISTRIBUTION



Avg. Driver	1.000
Max. Driver / Avg. Driver	1.069
Avg. Outer Test	1.547
Avg. Inner Test	1.745
Avg. Test	1.666
Temperature, °C	24°C

Ring Control Rods
Odd Numbers - 1000 v.u.
Even Numbers - 662 v.u.

FIG. 28 CALCULATED RADIAL FLUX DISTRIBUTION

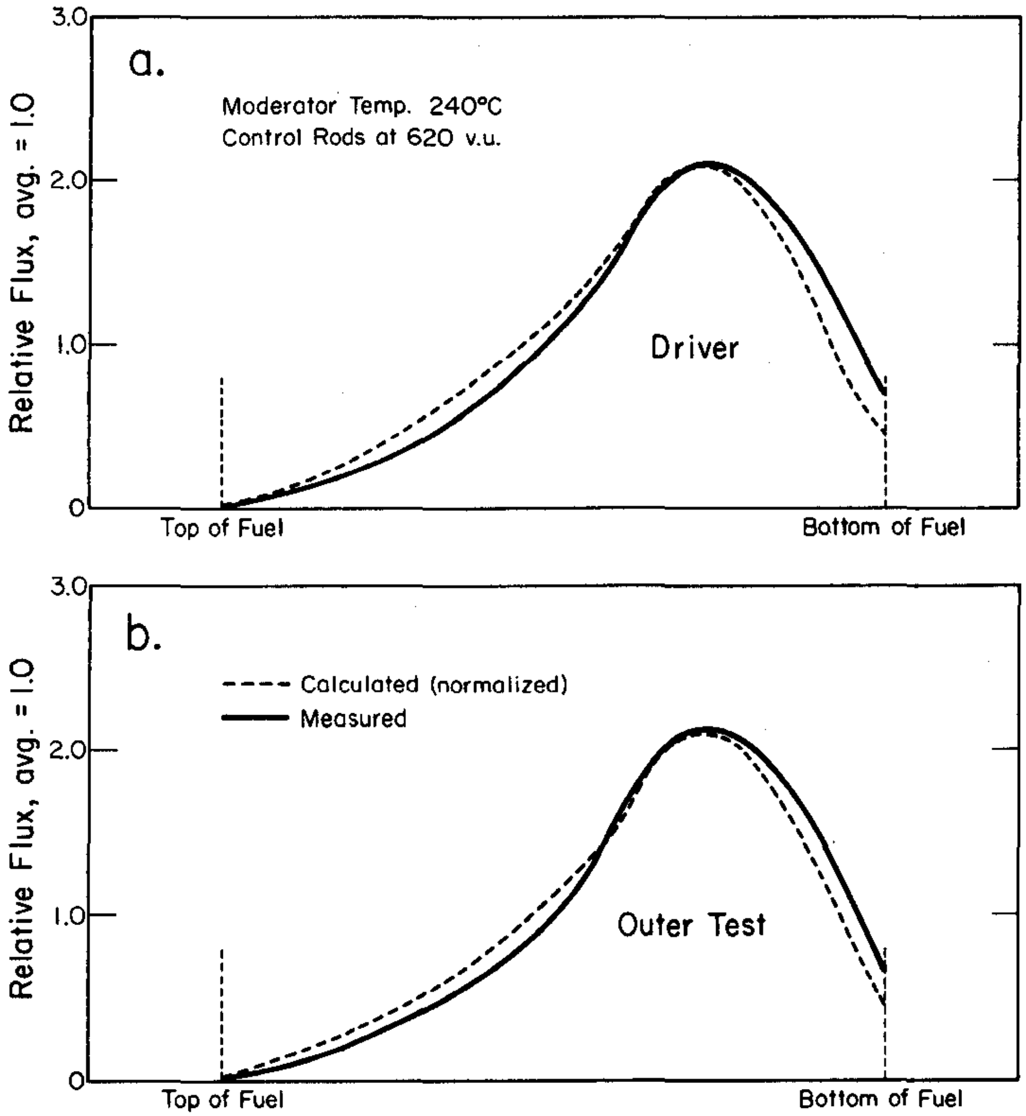


FIG. 29 MEASURED AND CALCULATED AXIAL FLUX PROFILES

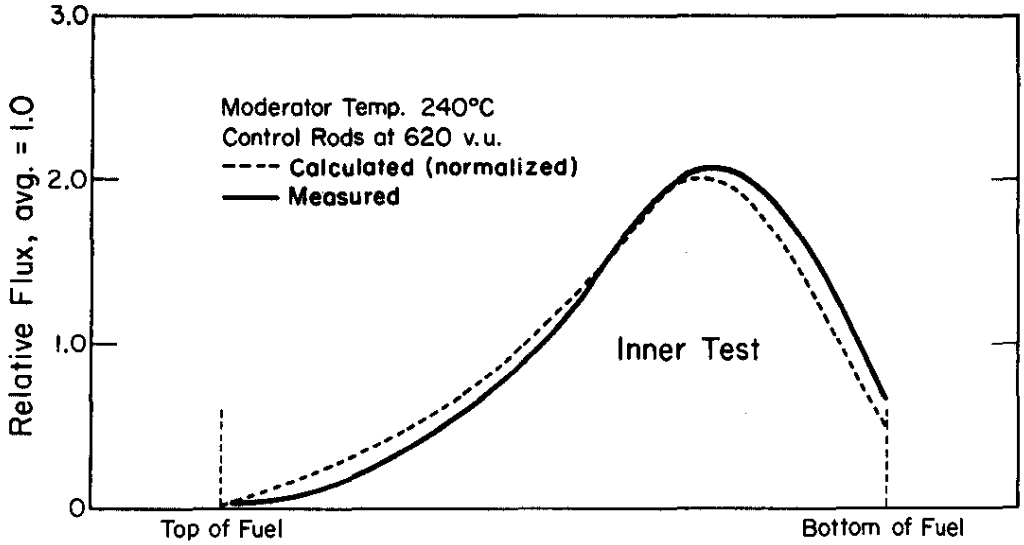


FIG. 30 MEASURED AND CALCULATED AXIAL FLUX PROFILES

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