DETERMINATION OF CONTROL ROD FLOAT IN THE ENRICO FERMI REACTOR

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FOREWORD

This report is one of a series of reports on the low-power (up to 1 Mwt) and high-power (up to 200 Mwt) nuclear testing of the Enrico Fermi reactor. The Nuclear Test Program is planned, directed and evaluated by Atomic Power Development Associates, Inc. (APDA). The tests are conducted by Power Reactor Development Company (PRDC). The reactor proper is owned and operated by PRDC. The steam generators and electrical generation facilities are owned by The Detroit Edison Company (DECo).

Many people have contributed to the success of the nuclear testing of the Fermi reactor. Listed below are the names of those people, exclusive of the authors, who made a significant contribution to some phase of the work reported in this document.

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SUMMARY

Tests were conducted during the period of September 10 through 18, 1963 to detect control rod float in the Enrico Fermi reactor. Each of the seven installed safety rods and the two operating control rods was individually tested, by means of subcritical nuclear measurements, to (1) confirm that safety rod floating does not occur at the primary sodium flow rate conditions that will exist in the reactor at Core A, 200-Mwt operation, and (2) to determine at what flow rate the control rods will float. The rods were also tested for floating at flow rates in excess of the Core A, 200-Mwt design value.

None of the safety or control rods were observed to float at the Core A, 200-Mwt design value of 8.85×10^6 lb/hr. In the case of the safety rods, floating did not occur at flows up to 120 per cent of the 200-Mwt design value. In the case of the two operating control rods, floating was observed when the flow was increased to approximately 107 per cent of the 200-Mwt design flow. These rods were expected to float.¹

During the course of this test, subcritical data were obtained which allowed preliminary evaluations to be made of the worth of the unshadowed safety rods and the shadowed operating control rods. An evaluation of the de-latching spring compression of the two operating control rods was also made. These measurements were in good agreement with the predicted values.

I. PURPOSE OF TEST

Rod float detection tests were performed in the Enrico Fermi reactor to confirm that the safety rods would not float at flow rate values of the primary sodium system up to and slightly in excess of the Core A, 200-Mwt design flow rate of 8.85×10^6 lb/hr. Essentially this test was a proof-test to verify that the hydraulic design of the safety rods was correct and that the rod channels were properly orificed. If floating of the safety rods occurred at full flow, it would prevent the rods from entering the core properly when the reactor was scrammed. Floating would also be of concern during refueling situations should the flow rate of the coolant be increased suddenly from refueling flow to full flow while the rods were disconnected from their drives.

Floating of the operating control rods in the Fermi reactor does not present a nuclear safety hazard during operation of the reactor because the rods are always connected to their drives. They are not released during a scram as are the safety rods. However, conservative design predictions indicated that these rods would float under shutdown conditions when disconnected from their drives if the flow rates were high enough.¹ Therefore, it was necessary to verify that this flow was in excess of the refueling flow, 6.0×10^6 lb/hr. Also, as confirmation of the flow and pressure drop calculations, it was of interest from an engineering viewpoint to determine the actual flow rate in excess of the refueling flow which would float the control rods.

In addition to the primary test purposes stated, it was possible to obtain preliminary reactivity worths of the unshadowed safety rods and of the shadowed shim and regulating rods. The amount of compression of the delatching springs of the two operating control rods could also be determined.

II. DESCRIPTION OF CONTROL RODS AND SAFETY RODS

A. GENERAL DESCRIPTION OF REACTOR

The Fermi reactor core and its associated structures are shown in perspective in Figure 1. The reactor is contained in a stainless steel reactor vessel sealed at the top by a rotating shield plug which supports the control mechanisms, the hold-down mechanism and the fuel handling mechanism. The reactor vessel is surrounded by borated graphite and plain graphite neutron shielding material which is contained inside the primary shield tank. The reactor is of the fast-breeder type, cooled by sodium, and operated at essentially atmospheric pressure. The maximum reactor power with the first core loading is 200 Mwt.

The core and blanket, located in the lower reactor vessel, consist of square subassemblies containing the fuel pins and blanket rods arranged to approximate a cylinder about 80 inches in diameter and 70 inches high. The core, contained in the central portion of the core subassemblies, approximates a right cylinder 31 inches in diameter and 31 inches high; it is axially and radially surrounded by breeder blankets. The fuel in Core A consists of zirconium-clad pins containing U-10 w/o molybdenum alloy with the uranium enriched to 25.6 per cent U-235. Each fuel subassembly in the core contains 140 fuel pins for a total mass of 4.75 kilograms of U-235 per subassembly. The blanket is depleted U-3 w/o molybdenum alloy.

The reactor cross section, shown in Figure 2, indicates the placement of individual components within the lower reactor vessel. There is a total of 149 central lattice positions that are occupied by core and inner radial blanket subassemblies, the neutron source, and the 10 operating control and safety rod channels. All these positions are supplied with sodium coolant flowing upward from a high-pressure plenum which is connected to the discharge lines of the three primary sodium pumps. The coolant flows upward through the individual core and inner radial blanket subassemblies into a large upper plenum and then by gravity to the three intermediate heat exchangers and then to the suction side of the primary pumps. Sodium also is used in the secondary cooling system.

The lattice positions surrounding the inner radial blanket comprise the outer blanket area and when filled with outer radial blanket subassemblies, form an annular region whose top and bottom are at the same elevation as the top and bottom of the inner radial blanket. Surrounding the outer radial blanket are lattice positions used for stainless steel subassemblies. These subassemblies provide thermal and neutron shielding. The outer radial blanket and shielding lattice positions are supplied with sodium coolant from a low-pressure plenum.

FIG. 1-PERSPECTIVE VIEW OF REACTOR

FIG. 2-REACTOR CROSS SECTION

A more detailed description of the Fermi reactor may be found in The Enrico Fermi Hazards Summary Report.¹

B. DESCRIPTION OF CONTROL RODS AND SAFETY RODS

Reactor control is normally accomplished by two operating control rods and eight safety rods. However, during this test only seven of the eight safety rods were installed. Safety rod No. 5 had been removed to allow for installation of an in-core, temporary instrument thimble. The location of the control and safety rods in the reactor core is shown in Figures 2 and 3. All of the rods are of the poison-type, containing boron carbide (B_4C) enriched in boron-10 ($B-10$). One operating control rod is for regulating purposes and the other is for shimming. The two rods together have a total negative reactivity worth of 92 cents.* The eight safety rods, which are symmetrically spaced around the center of the core, provide a total negative shutdown reactivity of approximately 9 dollars. During reactor operation, the safety rods are poised just above the axial blanket section of the core subassemblies. From this position they can be rapidly inserted into the core when the reactor is scrammed. They also provide the hold-down reactivity during refueling operations. The control and safety rods are actuated from the top and must be disconnected from their drive mechanisms while fuel is being loaded.

1. Control Rods

The two operating control rods are located on opposite sides of and 2-1/2 inches from the vertical centerline of the core (Figure 2). Each control rod is housed in a cylindrical guide tube as shown in Figure 4. The guide tubes are divided into upper and lower sections. The upper sections are mounted permanently in the core hold-down plate and column and move with them, whereas the lower guide tubes are seated in the upper and lower core support plates. In addition, the lower cylindrical guide tubes are mounted inside square cans or wrapper tubes having the same outside dimensions as a core subassembly. The upper guide tube sections have square adapters at their lower ends which mate with the square wrapper tubes of the lower guide tubes in the core of the reactor. Heat generated in a control rod is removed by sodium flowing from the core inlet plenum. The sodium passes through pressure breakdown orifices, inserted in the lower support plate, and into the bottom of the guide tube. Flow is then directed upward through the control rod assembly and through the annulus formed by the control rod assembly and the inner, round guide tube. The

* 1 cent = 3.19 inhours
1 inhour = $2.08 \times 10^{-5} \Delta k/k$
 $\beta_{eff} = 0.00662$

FIG. 3 - OPERATING CONTROL AND SAFETY ROD POSITIONS IN REACTOR VESSEL

FIG.4-OPERATING CONTROL ROD AND SAFETY ROD GUIDE TUBES

total coolant flow through a control rod guide tube at the 200 Mwt rated flow conditions is 39 gpm, of which 29 gpm is through the rod.

The two operating control rods are identical in design (Figure 5). Each rod contains 88 grams of B-10 in the form of 34 per cent enriched boron in B₄C giving a combined worth of approximately 92 cents. The poison is contained in 19 hermetically sealed, stainless steel tubes. The active poison section length is only 10 inches. A helium gas collection space is located in the tubes above the poison section. An extension rod connects the poison section to a pickup head which is located at the top of the rod. The pickup head connects to the control rod drive mechanism by means of rod gripper fingers which are in turn operated by a magnetic latching mechanism. An integral part of the extension rod is the delatching spring which acts to insure positive delatching of the control rod drive mechanism during normal reactor shutdown. The spring is compressed and held cocked by the downward motion of the drive shaft. When released, it acts to disengage the latch fingers of the drive mechanism from the rod pickup head. The total weight of a control rod in sodium is approximately 13 pounds.

One rod, the faster moving or regulating rod, is used for startup and control, while the slower rod is used primarily as a shim rod. The operating control rods are not released and dropped into the core during a scram but are instead driven slowly into the core. During reactor shutdown, they are delatched from their drives and rest on a pedestal or seat located in the lower guide tubes. The seat is positioned so that the bottom of the poison section is 2 inches below the core midplane (Figure 4). The seat also acts as the lower limit of travel for the operating control rod.

The full stroke of the operating control rods is normally 20 inches. Both rod drives are supplied with digital readout, fine-position indication systems capable of showing the elevation of the drive extension to within ± 0.03 inches. The rod position is read on Gilmore indicators located in the reactor control room.

2. Safety Rods

The eight safety rods are located approximately 7 inches from the vertical centerline of the core and are spaced almost uniformly around the centerline (Figure 2). Each one is designated by a number, 1 through 8, as shown in Figure 7. The design of the safety rod guide tubes (Figure 4) is essentially the same as that of the control rod guide tubes. There are three exceptions: (1) the upper guide tube sections of the safety rods are square tubes which mate directly with the square, outer cans of the lower guide tubes in the core, (2) the inner, round tubes in the lower safety rod guide tubes are perforated by scram relief holes over their length which divert the sodium flow, and reduce the pressure drop and drag forces on the safety rods when the reactor is scrammed, (3) dash pots are located in the

FIG. 5- OPERATING CONTROL ROD

lower part of the lower safety rod guide tubes which act as hydraulic shock absorbers to decelerate the safety rods after a scram. The safety rods are cooled in a manner similar to that of the control rods. Reduced coolant flow rate is used, however, because their normal operating position is above the core and less nuclear heat is generated in them. At Core A, 200-Mwt flow conditions, the total coolant flow through a safety rod guide tube is 27 gpm, of which 11 gpm is through the rod.

The safety rod design is shown in Figure 6. The four sections of the safety rod assembly are the dash ram, the poison section, the extension rod and the pickup head. The poison section of each rod contains approximately 535 grams of boron-10 in the form of 57 per cent enriched boron in B_4C , giving a negative reactivity worth of more than a dollar per rod. The poison section is approximately 36 inches long and the poison material is contained inside 6 hermetically sealed stainless steel tubes. The poison containment tubes are designed as pressure vessels to contain the helium gas released as a result of the (n, α) reaction in the boron-10. Located below the poison section is the dash ram. It is the piston section of the hydraulic shock absorbers used to decelerate the safety rods after a scram. The extension rod is located directly above the poison section and it connects the poison section to the pickup head. The extension rod contains a spring which is compressed and held cocked by the action of the safety rod drive mechanism. When released, the spring helps accelerate the safety rod into the core. The pickup head is located at the top of the safety rod and connects to the safety rod drive extension by means of gripper fingers and a magnetic latching mechanism. The total weight of a safety rod in sodium is approximately 35 pounds.

In the case of normal reactor startup, the ganged safety rods are driven out of the core slowly. They are dropped into the reactor under the force of gravity when a scram signal causes the magnetic latch mechanism to de-energize and the fingers to release the rods. The rods can also be driven into or out of the core individually if desired. The elevation of each of the safety rod drive extensions may be read on a Gilmore indicator located in the reactor control room. The full stroke of a safety rod is 54 inches.

FIG. 6- SAFETY ROD ASSEMBLY

III. EXPERIMENTAL PROCEDURE

A. DESCRIPTION OF THE TESTS

The control rod float detection tests for the Enrico Fermi reactor were carried out in accordance with a detailed preplanned procedure.² Prior to the conduct of the test, the procedure was reviewed for all aspects of completeness and safety. Revisions were made to incorporate improvements and additional steps which would facilitate the acquisition of complete and precise data during the test. The procedure was also the basis used by the reactor operating staff in the preparation of an operating guide for the conduct of the test.

The test data was obtained from subcritical count rate reactivity measurements over a range of primary sodium flow rates from refueling flow to a flow rate in excess of Core A, 200-Mwt design value. Each of the nine control and safety rods was tested separately. The tests were done with the reactor sufficiently subcritical to eliminate the possibility of the reactor achieving criticality in an uncontrolled manner in the event that a rod did float. During the experiment, the reactor temperature was monitored and count rate data were corrected for temperature drift.

1. Safety Rod Float Tests

The steps of the safety rod float detection procedure used were the same for each of the seven safety rods. The test sequence was as follows:

- (1) With the reactor shutdown and the seven safety rods and two operating control rods fully inserted, the primary sodium flow was adjusted to approximately 7.0×10^6 lb/hr,* the equilibrium value required to maintain an isothermal reactor temperature of 517 F with minimum temperature drift.
- (2) The seven ganged safety rods were fully withdrawn (54-inch elevation) and with the shim rod withdrawn 5 inches, the reactor was brought to criticality at a power level of approximately 1 kw with the regulating rod. The critical regulating rod position was measured and found to be 14.75-inches elevation.

* All sodium flows given refer to 3-loop operation unless otherwise stated.

- (3) The regulating rod was inserted until the reactor was approximately 9.4 cents (30 inhours) subcritical. The regulating rod position for this degree of subcriticality was approximately 10-inch elevation. Count rate, flow and temperature data were taken. The reactor was made subcritical at this point to insure that it would remain subcritical if the rod under test was ejected at the higher sodium flow rates. The degree of subcriticality used, 9.4 cents, was chosen as a compromise between two competing factors. It was desired that the degree of subcriticality be large enough so that the neutron count rate would have reasonable settling out time, and yet small enough so that sufficient counts would remain to enable a small amount of rod float to be detected when the safety rod under test was fully inserted. It was established prior to the experiment that with 9.4 cents subcriticality the maximum settling out time would be approximately 500 seconds⁴ and that a minimum rod float of 3 inches could be detected.²
- (4) With the reactor 9.4 cents subcritical, the primary sodium flow was increased from the equilibrium value, 7.0×10^6 lb/hr, to the Core A, 200-Mwt design flow rate, 8.85×10^6 lb/hr.
- (5) The safety rod to be tested was inserted to the 20-inch elevation position and count rate, flow and temperature data were taken.
- (6) The safety rod was inserted to the 11-inch elevation position and all data were again taken.
- (7) The safety rod was inserted to the 0-inch elevation position (fully inserted) and all data were taken.
- (8) The safety rod was delatched from its drive extension and the extension rod was slowly withdrawn to the 20-inch elevation position. All data were taken. During the extension withdrawal, the log count rate source range recorders were observed for any evidence of rod floating. No evidence of rod floating was observed. This was as anticipated. The position of the extension in this step was chosen so that had the rod floated, the count rate would have been approximately the same as that observed in Step 6. The accelerating spring relaxation was previously estimated to be 9 inches with the compressive force of the extension rod removed. (Section II, B.)

- (9) With the safety rod extension at the 20-inch elevation position, the primary sodium flow was reduced from the Core A value, 8.85×10^6 lb/hr, to the refueling value, 6.0×10^6 lb/hr, and all count rate, flow and temperature data were again recorded.
- (10) The primary sodium flow was rapidly increased from refueling flow to flow rates in excess of the Core A, 200-Mwt design value and all pertinent data were taken. This step was done to determine if the safety rod would float at flow values greater than the Core A, 200-Mwt design flow rate and to determine if a flow transient would unseat the rod. No floating was observed. This step was done with the safety rod drive extension withdrawn only 20 inches instead of fully withdrawn because it was feared that if the rod did float with the extension fully withdrawn, the reactor would scram because of the apparent period caused by rod motion. The maximum flow rate attained in this step was 10.5×10^6 lb/hr for safety rod No. 3 and the minimum flow rate was 9.0×10^6 lb/hr for rod No. 6.
- (11) Lastly, the flow was reduced from the elevated flow rate to the Core A, 200 Mwt value, 8.85×10^6 lb/hr, and the extension was reinserted and latched to the rod. The rod was then withdrawn to the fully retracted position (54-inch elevation) in preparation for the float test of the next safety rod (repeat Steps 5 through 11 above).
- (12) The reactor was shutdown after the last rod was tested.

2. Operating Control Rod Float Tests

The steps of the float detection procedure used for the regulating rod are given below. The procedure for the shim rod was the same except that its drive extension was never raised above the 5-inch elevation position when the shim rod was delatched (Steps 7 and 9 below). The test sequence follows:

- (1) With the reactor shutdown and all nine control and safety rods fully inserted, the primary sodium flow rate was adjusted to the equilibrium value (approximately 7.0×10^6 lb/hr) required to maintain an isothermal reactor temperature of 517 F with minimum temperature drift.
- (2) The seven ganged safety rods were fully withdrawn (54-inch elevation), and using the operating control rods, the reactor was brought to criticality at a power level of approxi-

mately 1 kw with the regulating rod fully withdrawn (20-inch elevation). The critical shim rod position was measured and found to be 3.50-inch elevation.

- (3) The shim rod was inserted until the reactor was approximately 9.4 cents (30 inhours) subcritical and count rate, flow and temperature data were taken. The shim rod position for 9.4 cents subcritical was 0-inch elevation, i.e., full insertion. In the case of the operating control rod float detection tests, previous studies had shown that with this degree of subcriticality in this step, the neutron count rate remaining when the control rod under test was fully inserted would be sufficient to detect 0.6 of an inch of rod float.^{2, 4}
- (4) With the shim rod in the above position, subcritical count rate data were taken with the regulating rod inserted to the 15-inch, 10-inch, 5-inch and 0-inch elevation positions.
- (5) With the regulating rod fully inserted, the primary sodium flow rate was increased from the equilibrium value, 7.0×10^6 lb/hr, to the Core A, 200-Mwt design value, 8.85×10^6 lb/hr.
- (6) The regulating rod drive extension was delatched and slowly withdrawn 5 inches and count rate, flow and temperature data were recorded. During the extension withdrawal, the log count rate source range recorders were observed for any evidence of rod floating. No evidence of rod floating was observed. It had been conservatively predicted that rod floating would occur at 72 per cent of the Core A, 200-Mwt design flow rate (6.37×10^6 lb/hr).¹
- (7) The extension rod was withdrawn to the 20-inch elevation position (fully withdrawn) and all data were again taken. Still no evidence of floating was observed.
- (8) The drive extension was reinserted to the 5-inch elevation position and the primary sodium flow was rapidly increased from Core A, 200-Mwt design value to 10.21×10^6 lb/hr and data were taken. The count rate had increased which indicated that the regulating rod had floated. This was also seen on the log count rate recorders. This step in the procedure was done with the extension withdrawn only 5 inches because it was feared that if the rod were allowed to float rapidly and completely out of the core, the reactor would scram because of the apparent period due to rod motion.

- (9) The extension rod was slowly withdrawn to the 10-inch and 20-inch elevation positions and count rate data were taken at each of these positions. The increase in count rate which occurred at each position indicated that the regulating rod had followed the extension up as it was withdrawn. This step was done to demonstrate that there were no changes in the pressure drop across the rod over the full stroke of the extension.
- (10) The regulating rod drive extension was reinserted to the 5-inch elevation position, the flow was decreased from the elevated flow, 10.2×10^6 lb/hr to 9.08×10^6 lb/hr, and all data were again taken. The count rate had decreased to the point which indicated that the regulating rod had settled back to its fully inserted position.
- (11) With the extension at the 5-inch elevation position, the primary sodium flow was slowly increased from 9.08×10^6 lb/hr until rod floating was again observed; this occurred when the flow reached 9.63×10^6 lb/hr. In case of the shim rod test, the minimum flow rate at which floating was observed in this step was 9.26×10^6 lb/hr.
- (12) The reactor was shutdown.

3. Rod Worths

To obtain the unshadowed worth of each of the safety rods over their full length of travel, the subcritical count rate data obtained in Step 3 (safety rods fully withdrawn) and Step 7 (safety rod fully inserted) of Section III, A.1 above were used. The analysis of the data is explained in Section IV, A. In a similar manner, the count rate data obtained in Steps 3 and 4 of Section III, A.2 were used to obtain the worth of the shadowed regulating and shim rods.

4. Delatching Spring Compression

The delatching spring compression for the regulating and shim rods was determined from the subcritical count rate data obtained in Steps 4, 8 and 9 of Section III, A.2 above. Three independent checks of the spring compression could be made. From the change in count rate which occurred when each rod floated with the rod extension withdrawn 5, 10 and 20 inches, respectively, the change in reactivity and consequently the amount of rod float could be determined for each extension position (see Section IV, C). In each case the distance the rod floated was less than the distance the extension had been withdrawn. This was true because with the rod delatched, the delatching spring decompression was included in the rod extension motion.

Therefore, the difference in each case between the distance the rod floated and the extension elevation was the spring compression.

B. REACTOR PLANT CONDITIONS

The reactor was loaded with fuel as shown in Figure 7. A total of 99 full-core subassemblies and one core-shim subassembly were loaded. This loading resulted in an excess reactivity of approximately 41 cents with the primary system at an isothermal temperature of 517 F and the safety and control rods fully withdrawn.

The three-loop primary sodium flow was maintained between the refueling level (6.0×10^6 lb/hr) and the maximum value permissible (11.0×10^6 lb/hr) as required for the conduct of the test.*

Whenever possible, the primary system temperature was maintained at 517 F during the test. The reactor temperature was controlled by balancing the heat input from the primary sodium pump operation and the heat removal by the below-floor ventilation. The auxiliary system, which consisted of the overflow pumps and the primary cold trap, was operated to minimize the upward drift in temperature which occurred when the primary flow was in excess of the equilibrium flow value.

The primary flow scrams were defeated during these tests and the intermediate and power range level scrams were set at flux levels corresponding to approximately 1 Mwt.

C. NEUTRON SOURCE AND INSTRUMENTATION

A neutron source was located in the reactor during the rod float detection tests to provide an observable neutron flux at the detectors with the reactor subcritical. In addition, to assure that large counting rates could be obtained, in-core and special high-sensitivity, out-of-core neutron detectors were installed.

1. Neutron Source

Throughout the rod float tests an antimony-beryllium (Sb-Be) neutron source was located at the core-blanket interface in core position

* The structural design of the core is such that a pressure drop greater than that occurring from a flow of 11.0×10^6 lb/hr is not permissible.

N06 N05 N04 N03 N02 N01 P00 P01 P02 P03 P04 P05 P06

DESCRIPTION

QUANTITY

	OPERATING CONTROL RODS	2
	SAFETY RODS	7
	CORE SUBASSEMBLIES (25 6 % ENRICHED U-10 W/O Mo ALLOY; ~ 4.74 kg U-235 / SUBASSEMBLY) . .	99
	CORE SHIM SUBASSEMBLY (APPROX. ONE-HALF DEPLETED, ONE-HALF ENRICHED URANIUM-2.37 kg U-235 / SUBASSEMBLY).	1
	DUMMY SUBASSEMBLY (NO FUEL- SODIUM FILLED) . .	1
	NEUTRON SOURCE SUBASSEMBLY (Sb - Be)	1
	TEMPORARY INSTRUMENT THIMBLE	1
	INNER RADIAL BLANKET SUBASSEMBLIES DEPLETED U-3 W/O Mo ALLOY	37
	TOTAL SUBASSEMBLIES .	149

FIG. 7 - REACTOR LOADING FOR TEST

N05-N04 (Figure 7). * The radioactive antimony-124 portion of the source is a rod approximately 0.7 inch in diameter by 25 inches long. It fits inside a beryllium assembly (3.4 kg of Be), which is in the form of a hollow cylinder. The beryllium assembly is in turn contained inside a steel can which has the external dimensions of a normal core subassembly can. The activity of the antimony-124 was approximately 200 curies at the start of the test (September 10, 1963). The antimony-124 half life is 60 days. The estimated photo-neutron source yield of 27-kev neutrons at this time was 1×10^9 neutrons per second. The source multiplication in the reactor for this location is about one-half the theoretical value of $(1-k_{eff})^{-1}$.

2. Instrumentation

The neutron flux monitoring instrumentation used during the test was the same as that described in detail in APDA-NTS-1.⁵ It was all temporary instrumentation installed especially for use during the low-power test program. Briefly, it consisted of four out-of-core, high-sensitivity source range BF₃ proportional detector channels and a fifth in-core count rate channel utilizing an absolute fission counter. The out-of-core detectors were located in neutron-counter tubes embedded in the graphite shield which surrounds the reactor vessel (Figure 1) and the in-core detector was located in the 2-inch diameter temporary instrument thimble which replaced safety rod No. 5 in core position P03-P00 (Figure 7). These five count rate detectors were connected to mechanical scalers and were referred to as Channels 1 through 4 and A, respectively. All of the channels were used to monitor the subcritical flux throughout the test. However, the count rate on the in-core channel proved to be too low for the data from this channel to be used reliably in the analysis of the test.

In addition to the nuclear instrumentation described above, two of the BF₃ detectors were used to supply both count rate and period signals to the source range safety system. The other nuclear instrumentation consisted of five boron-10 lined ion chambers, installed in the neutron-counter tubes, which provided both period and power level protection to the intermediate and power range safety system channels.

Primary system temperatures were monitored in the test by use of the normal plant temperature sensing elements. These consisted of iron-constantan thermocouples located on the reactor support plate and hold-down plate which measured the core inlet and outlet sodium temperatures, and

* The coordinate system used to locate subassemblies in the core lattice is shown in Figure 7. The first position number given is the X-coordinate and the second is the Y-coordinate. "P" stands for positive values and "N" for negative values. The core center is P00-P00.

platinum resistance temperature detectors located in the piping to and from the reactor which measured the reactor inlet and outlet temperatures. The data from these sensors were relayed via special circuits to a temporary, precision temperature readout station located in the reactor control room. The thermocouples were connected to a high-sensitivity potentiometer, and the resistance detectors were connected to a resistance bridge. This allowed temperatures to be read to an accuracy of approximately ± 1 F.

The normal plant instrumentation³ was used to obtain the remaining data such as primary sodium flows, pump discharge pressures, primary system cover gas pressure, reactor vessel sodium level, and operating control and safety rod positions.

IV. METHOD OF ANALYSIS

A. DETERMINATION OF ROD WORTH

The safety rod and operating control rod worths were obtained before the actual rod float measurements were made. They were both determined by means of subcritical count rate versus reactivity measurements. The count rate data measured during the rod insertions with the rods latched and fully withdrawn and latched and fully inserted were used.* Because of the test sequence, these data gave the unshadowed safety rod and shadowed control rod worths. The subcritical count rate data were obtained from the mechanical scalers connected to the four BF₃ high-sensitivity source range detectors located in the graphite shield (see Section III, C.2). As mentioned earlier, the data from the in-core channel were not used because the count rates obtained were too low to be reliable.

1. Relationship Between Count Rate and Rod Worth

The relationship between the subcritical count rate, subcritical reactivity, and rod worth is given by the following equation:**

$$W = R_w \left(\frac{C_w}{C_i} - 1 \right) \quad (1)$$

where: W = the rod worth, cents

R_w = the amount the reactor was subcritical with the rod under test fully withdrawn, 9.4 cents

C_w = the count rate with the rod fully withdrawn, cpm

C_i = the count rate with the rod fully inserted, cpm

The count rate data from the four out-of-core BF₃ channels were averaged and used in Equation (1) to obtain the worths of each of the safety and control rods.

* Steps 3 and 4 of the control rod float test sequence and Steps 3 and 7 of the safety rod float test sequence (Section III, A).

** Derived from simple subcritical multiplication theory, i.e.,
If, $M\alpha(1-k_{eff})^{-1}$, where M is the source multiplication
Then, $C = A(1-k_{eff})^{-1}$, where C is the count rate and A is a constant.

2. Temperature Corrections

To determine the rod worth, the count rates with the rod fully withdrawn and fully inserted were used. To make the data consistent, the count rate obtained with the rod fully withdrawn, C_w in Equation (1), was corrected for the drift in reactor temperature which occurred during the time interval between the two measurements. The equation used was:

$$C_w(t_2) = \frac{C_w(t_1)}{1 - \frac{\Delta R_f}{R_w(t_1)}} \quad (2)$$

where: t_1 = the isothermal temperature of the reactor at the time of the first measurement with the rod fully withdrawn, F

t_2 = the isothermal temperature of the reactor at the time of the second measurement with the rod fully inserted, F

$C_w(t_1)$ = the count rate obtained with the rod under test fully withdrawn at temperature t_1 , cpm

$C_w(t_2)$ = the corrected count rate with the rod under test fully withdrawn at temperature t_2 , cpm

ΔR_f = the reactivity feedback due to temperature drift, cents

= (temperature drift) (isothermal temperature coefficient)

= $(t_2 - t_1) (-0.26 \text{ cents/F})^6$

$R_w(t_1)$ = the amount the reactor was subcritical with the rod under test fully withdrawn at temperature t_1 , 9.4 cents.

In applying this correction to the data, the isothermal temperatures were obtained from the average of the thermocouple and resistance temperature detector readings. Using these values, Equation (2) was solved for the corrected count rate, $C_w(t_2)$, at the new temperature. This was the only correction made to the data. The data were not corrected for source decay because it was negligible during the time it took to make the worth measurements for one rod.

B. DETECTION OF ROD FLOAT

Floating of a safety rod or operating control rod was determined by observing whether any significant change occurred in the subcritical count rate, and thus in the reactivity state of the reactor, when the primary sodium flow rate was increased. Count rates were obtained with the rod under test fully inserted at refueling or equilibrium flow rates and with the rod delatched and its extension withdrawn at Core A design flow value and above.* In addition to the scaler count rate data available from the four out-of-core BF₃ detectors, evidence of rod floating could be obtained from observation of the two source range log count rate recorders, located in the reactor control room.

1. Relationship Between Count Rate and Rod Float

The relationship between the subcritical count rate, subcritical reactivity and rod float is given by the following equation:

$$\frac{C_i}{C_A} = 1 - \frac{\Delta R_A}{R_i} \quad (3)$$

where: C_i = the count rate with the rod under test fully inserted at refueling flow rate, cpm

C_A = the count rate after the increase in flow and after the rod has floated, cpm

ΔR_A = the reactivity addition due to the change in rod position after floating, cents

R_i = the amount the reactor is subcritical with the rod under test fully inserted, cents

If the rod does not float, ΔR_A in Equation (3) is zero, the count rate ratio, C_i/C_A , is unity and no change in count rate will occur. If the rod does float, the magnitude of the count rate change depends on the amount of float, or more specifically, on the change in the subcritical reactivity state of the reactor. In the test, therefore, floating of the rods was determined by observing whether any significant change in the count rate occurred when the flow was increased. The average count rate from the four out-of-core channels was used in making this comparison.

* Steps 9 and 10 of the safety rod float test sequence and Steps 1, 5 and 8 of the control rod float test sequence.

2. Anticipated Change in Count Rate

The anticipated changes in the subcritical count rates should the safety rod and control rod float, were predicted using Equation (3). The calculations were made as follows:

- a. The degree of subcriticality with the rod under test fully inserted, R_i , was estimated by assuming a safety rod worth of 100 cents and an operating control rod worth of 46 cents and adding to these values the 9.4-cent degree of subcriticality before rod insertion. Therefore, the resulting values of R_i used in the predictions of safety rod floating and control rod floating were 109.4 cents and 55.4 cents, respectively.
- b. The values of the reactivity additions due to the changes in rod position after floating, ΔR_A , used in the predictions were based on the assumption that the rod extensions were withdrawn 20 inches and that the rods floated up to the extensions. The amount of rod floating was estimated to be 19 inches for the operating control rods and 11 inches for the safety rods, based on assumed relaxations of the delatching springs of 1 and 9 inches, respectively. (See Sections II and III.) The resulting subcritical reactivity changes, ΔR_A , for control rod floating and safety rod floating were then estimated to be 45 cents and 10.9 cents, respectively.* These values are based on the assumed rod worths stated in Step (a) above and on the calibration curves obtained in the critical experiment.³
- c. Using the above values of R_i and R_A in Equation (3), the predicted count rate ratios, C_i/C_A , for control rod and safety rod floating were found to be 0.19 and 0.90, respectively.**

* The predicted reactivity change due to floating of the safety rods is small compared to that of the operating control rods because (1) the withdrawal of the safety rod extension is small compared to the full stroke of the safety rod (20 inches versus 54 inches), (2) the safety rod cocking spring compression is of a greater magnitude than that of the control rod (9 inches versus 1 inch) and (3) the unsymmetrical vertical position of the safety rods when fully inserted causes a slight decrease in reactivity, rather than an increase, for the first 6 inches of rod withdrawal.³

** In the shim rod float test, the extension was actually withdrawn only 5 inches instead of 20 inches as assumed here (Section III, A.2). The predicted count rate ratio for floating up to the extension for this case was determined in a similar manner and found to be equal to 0.83 instead of 0.19.

The analysis above assumed that in each case the rods floated up to the extensions. However, the possibility also existed that although a rod floated, it might not float up to the extension. For example, a rod might rise only a few inches and then remain suspended at equilibrium in the coolant stream. In this case, the reactivity addition due to rod floating can be estimated from Equation (3) by using the count rates obtained and solving for ΔR_A . The distance floated can then be estimated from the rod calibration curves.

3. Temperature Corrections

To determine whether the rod under test had floated, the average count rate obtained with the rod fully inserted at refueling or equilibrium flow, was compared to the average count rate obtained with the rod extension withdrawn at Core A, 200-Mwt flow value and above. To make a valid comparison of the two count rates, the count rate obtained with the rod fully inserted, C_i in Equation (3), was corrected for the reactor temperature drift which occurred during the time interval between the two measurements. The equation used for this was:

$$C_i(t_2) = \frac{C_i(t_1)}{1 - \frac{\Delta R_f}{R_i(t_1)}} \quad (4)$$

where: t_1 = the isothermal temperature of the reactor at the time of the first measurement with the rod fully inserted at refueling flow, F

t_2 = the isothermal temperature of the reactor at the time of the second measurement after the flow increase, F

$C_i(t_1)$ = the count rate obtained with the rod under test fully inserted at temperature t_1 , cpm

$C_i(t_2)$ = the corrected count rate with the rod under test fully inserted at temperature t_2 , cpm

ΔR_f = the reactivity feedback due to temperature drift, cents

= (temperature drift) (isothermal temperature coefficient)

= $(t_2 - t_1) (-0.26 \text{ cents/F})$

$R_i(t_1)$ = the amount the reactor was subcritical with the rod under test fully inserted at temperature t_1 , cents

In applying this correction to the data, the subcritical reactivity, $R_i(t_1)$, was determined using the individual rod worths measured in the test* and adding to these values the 9.4-cent degree of subcriticality before rod insertion. The isothermal temperatures were obtained from an average of the thermocouple and resistance temperature detector readings. Equation (4) was then solved for the corrected count rate, $C_i(t_2)$, at the new temperature.

The only correction made to the data was the temperature correction described above. The data were not corrected for source decay because it was insignificant during the time it took to make measurements for one rod (about 3 hours). Furthermore, no flow reactivity feedback corrections were required because measurements made previously had shown that flow reactivity effects were negligible.^{5, 7}

4. Experimental Error and Minimum Float Detectable

The accuracy of the rod float measurements depended upon the accuracy with which the count rate could be measured. An estimate of this was made in Reference 2. This study showed that the uncertainty in measuring the count rate was about ± 1 per cent and the uncertainty in correcting the count rate for temperature drift was approximately ± 1 F. On this basis, the resulting uncertainties in the reactivity changes due to safety rod and control rod floating that can be measured by Equation (3) were shown to be ± 1.6 cents and ± 0.9 cents, respectively. Therefore, these values are also the minimum detectable reactivity changes that could be measured in the test. In the safety rod test, 1.6 cents corresponds to a minimum detectable rod float of approximately 3 inches, and in the control rod test 0.9 cents corresponds to a rod float of approximately 0.6 of an inch.

C. DETERMINATION OF DELATCHING SPRING COMPRESSION

The compressions of the delatching springs on the shim and regulating rods were determined from the count rate data obtained with the rods fully inserted and with the rods floating and their extensions withdrawn 5 inches, 10 inches, and 20 inches.** Using these data, the reactivity addition due to rod floating at each extension elevation was determined by solving Equation (3) for R_A :

$$\Delta R_A = R_i \left(1 - \frac{C_i}{C_A} \right) \quad (5)$$

* See Section IV and Section V, Table III.

** Section III, A.2., Steps 4, 8 and 9.

The amount of rod float in each case was then found by determining the rod elevation that corresponded to this reactivity addition. The rod calibration curve shown in Figure 8 was used for this. In each case, the spring compression was the difference between the amount of rod float and the extension elevation.

FIG. 8 - CONTROL ROD CALIBRATION CURVE

V. EXPERIMENTAL RESULTS

A. ROD FLOAT TESTS

Analysis of the data from the rod float test showed that none of the seven safety or two operating control rods floated at the 200 Mwt, Core A design flow rate of 8.85×10^6 lb/hr. In the case of the safety rods, floating did not occur at flow rates up to 120 per cent of the Core A, 200-Mwt rated flow. In the case of the operating control rods, floating occurred when the flow rate was increased to 105 to 110 per cent of the Core A flow.

1. Results of the Safety Rod Float Test

Table I summarizes the results of the safety rod float tests. Not all of the data that were obtained in Steps 1 through 12 of the safety rod test sequence are given in the table. Only data pertinent to the determination of rod floating are given. Table I lists the count rates which were obtained on each channel for each safety rod under test when the rod was fully inserted in the reactor at refueling flow. It also gives the count rates obtained when the rod was delatched and its extension withdrawn 20 inches at 200 Mwt, Core A flow value and above. Included in the table are the count rates measured with the rods latched and withdrawn 11 inches. These latter data are given because they were the count rates anticipated in the event that the rods floated up to the extensions while the extensions were delatched and withdrawn 20 inches (see Section III, A. 1, Step 8). All count rates in Table I have been corrected for temperature drift between measurements.

To improve the statistical accuracy of the count rate data, the data from the four channels were added together to obtain an average count rate in each case. These values were then arbitrarily normalized to a count rate of 1 cpm with each rod fully inserted. This data is included in Table I. The last two columns in the table show the apparent reactivity change between the measurements made at refueling flow and elevated flow and give the estimated experimental error. The apparent reactivity change was calculated using the normalized average count rates and Equation (3). In Equation (3) the value of R_i (the degree of subcriticality with the rod fully inserted) was determined using the experimental rod worths from the test given in Table IV.

Table I shows that the apparent reactivity change was within the limits of experimental error for all safety rods tested. It was therefore concluded that none of the safety rods had floated at the Core A, 200-Mwt design flow rate of 8.85×10^6 lb/hr. In the case of safety rod No. 3, the

TABLE I - RESULTS OF SAFETY ROD FLOAT TESTS

Rod Under Test	Count Rates, cpm ^a						Apparent Reactivity Change, Refueling Flow to Full Flow, Cents	Experimental Error, ^b Cents	Conclusions
	Rod Inserted, Refueling Flow ($\sim 6.0 \times 10^6$ lb/hr.)		Rod Delatched, Extension Withdrawn 20 Inches, Core A, 200-Mwt Flow and Above ($\geq 8.85 \times 10^6$ lb/hr.)		Rod Latched and Withdrawn 11 Inches				
	Actual	Normal-ized Average	Actual	Normal-ized Average	Actual	Normal-ized Average			
Safety Rod No. 1	Ch. 1 - 5,234 Ch. 2 - 6,034 Ch. 3 - 178 Ch. 4 - 197	1.00	Ch. 1 - 5,206 Ch. 2 - 6,039 Ch. 3 - 174 Ch. 4 - 202	0.9981	Ch. 1 - 6,017 Ch. 2 - 6,927 Ch. 3 - 205 Ch. 4 - 216	1.1479 ^c	-0.26	± 1.6	Rod Did Not Float
Safety Rod No. 2	Ch. 1 - 4,535 Ch. 2 - 5,263 Ch. 3 - 154 Ch. 4 - 161	1.00	Ch. 1 - 4,533 Ch. 2 - 5,247 Ch. 3 - 171 Ch. 4 - 158	0.9996	Ch. 1 - 5,018 Ch. 2 - 5,844 Ch. 3 - 169 Ch. 4 - 179	1.1085	-0.04	± 1.6	Rod Did Not Float
Safety Rod No. 3	Ch. 1 - 5,199 Ch. 2 - 5,994 Ch. 3 - 168 Ch. 4 - 176	1.00	Ch. 1 - 5,180 Ch. 2 - 5,986 Ch. 3 - 170 Ch. 4 - 176	0.9978 ^d	Ch. 1 - 5,750 Ch. 2 - 6,609 Ch. 3 - 196 Ch. 4 - 202	1.1057	-0.29	± 1.6	Rod Did Not Float
Safety Rod No. 4	Ch. 1 - 5,090 Ch. 2 - 5,883 Ch. 3 - 156 Ch. 4 - 161	1.00	Ch. 1 - 5,095 Ch. 2 - 5,874 Ch. 3 - 165 Ch. 4 - 174	1.0015	Ch. 1 - 5,698 Ch. 2 - 6,539 Ch. 3 - 186 Ch. 4 - 193	1.1174	+0.21	± 1.6	Rod Did Not Float
Safety Rod No. 5	-	-	-	-	-	-	-	-	-
Safety Rod No. 6	Ch. 1 - 4,724 Ch. 2 - 5,494 Ch. 3 - 164 Ch. 4 - 172	1.00	Ch. 1 - 4,822 Ch. 2 - 5,486 Ch. 3 - 160 Ch. 4 - 166	1.0075	Ch. 1 - 5,327 Ch. 2 - 6,202 Ch. 3 - 165 Ch. 4 - 187	1.1257	+1.08	± 1.6	Rod Did Not Float
Safety Rod No. 7	Ch. 1 - 4,211 Ch. 2 - 4,903 Ch. 3 - 142 Ch. 4 - 146	1.00	Ch. 1 - 4,178 Ch. 2 - 4,866 Ch. 3 - 149 Ch. 4 - 142	0.9928	Ch. 1 - 4,722 Ch. 2 - 5,427 Ch. 3 - 166 Ch. 4 - 163	1.1144	-1.07	± 1.6	Rod Did Not Float
Safety Rod No. 8	Ch. 1 - 5,184 Ch. 2 - 5,941 Ch. 3 - 176 Ch. 4 - 176	1.00	Ch. 1 - 5,152 Ch. 2 - 5,964 Ch. 3 - 181 Ch. 4 - 180	0.9999	Ch. 1 - 5,755 Ch. 2 - 6,655 Ch. 3 - 186 Ch. 4 - 188	1.1139	-0.005	± 1.6	Rod Did Not Float

a. Corrected for temperature drift between measurements (Section IV, B. 3). Five-minute count rates were normally taken.

b. See Section IV, B. 4.

c. The values here were obtained with safety rod No. 1 withdrawn 12 inches instead of 11 inches.

d. The flow here was 120 per cent of the Core A flow (10.52×10^6 lb/hr.). This is the maximum flow at which a rod was tested.

flow was 120 per cent of Core A, 200-Mwt design flow rate and there was still no indication of floating.

2. Test Results of the Control Rod Float

Tables II and III summarize the results of the operating control rod float tests. They are similar to Table I and the data reductions were made in the same way. In Table II it is seen that no floating of either the shim or regulating rods occurred at the 200 Mwt, Core A design flow rate conditions. From Table III, however, it is evident that full floating of the shim and regulating rods occurred at flows slightly in excess of the Core A, 200-Mwt design flow value. In the case of the shim rod, floating occurred at approximately 105 per cent of Core A flow (9.26×10^6 lb/hr) and in the case of the regulating rod it was at approximately 109 per cent of Core A flow (9.63×10^6 lb/hr). The difference in flow required to float each rod was probably only an apparent difference due to inaccuracies in the flow meters and the difficulty of making the required small flow increments.

It had been predicted that the operating control rods would float at 72 per cent of full flow¹, but the calculations were intentionally made on a conservative basis. Consequently, it is felt that there is no sizable deviation from design in the as-built orificing of the control rod channels.

Evidence that the control rods had floated during the test was also seen on the two source range recorders of the safety system located in the control room. Figures 9 and 10 are photographs taken of one of the recorder charts showing the subcritical power traces which were obtained during the shim rod and regulating rod float tests, respectively. The times at which the various steps in the test sequence were initiated are also indicated in these figures. As can be seen, no increase in subcritical power (count rate) occurred when the primary sodium flow rate was raised to the Core A, 200-Mwt design value. However, a definite increase in subcritical power was seen when the flow rate was raised above the Core A value in the case of both rods. This indicates that floating occurred. Another interesting point seen in Figures 9 and 10 is the fact that the steady-state subcritical power which was attained after floating, with the rod extension delatched and withdrawn, was less than that which existed at the corresponding latched rod elevation. This indicates that relaxation of the delatching spring occurred in the former case.

B. ROD WORTHS

The rod worths of the 7 unshadowed safety rods and the 2 shadowed operating control rods were obtained from the subcritical count rates measured with the rods fully withdrawn and fully inserted. These data for each channel are given in Table IV. The data were analyzed by use of Equation

TABLE II - RESULTS OF OPERATING CONTROL ROD FLOAT TESTS AT CORE A FLOW RATES

Count Rates, cpm ^a								
Rod Under Test	Rod Down and Latched, Equilibrium Flow (~ 6.0 x 10 ⁶ lb/hr)		Rod Delatched, Regulating Rod Extension Withdrawn 20 Inches, Shim Rod Extension Withdrawn 5 Inches, Core A, 200-Mwt Flow (~ 8.85 x 10 ⁶ lb/hr)		Count Rate Expected if Full Floating Occurred ^b	Apparent Reactivity Change, Re-fueling Flow to Full Flow, Cents	Experimental Error, ^c Cents	Conclusions
	Actual	Normalized Average	Actual	Normalized Average	Normalized Average			
Regulating Rod	Ch. 1 - 13, 396		Ch. 1 - 13, 427					Rod Did Not Float at Core A, 200-Mwt Design Flow Conditions
	Ch. 2 - 15, 446		Ch. 2 - 15, 392					
	Ch. 3 - 433	1.00	Ch. 3 - 438	0.9994	5.3	-0.03	± 0.9	
	Ch. 4 - 468		Ch. 4 - 468					
Shim Rod	Ch. 1 - 13, 392		Ch. 1 - 13, 339					Rod Did Not Float at Core A, 200-Mwt Design Flow Conditions
	Ch. 2 - 15, 394		Ch. 2 - 15, 397					
	Ch. 3 - 438	1.00	Ch. 3 - 439	0.9985	1.2	-0.08	± 0.9	
	Ch. 4 - 463		Ch. 4 - 468					

a. Corrected for temperature drift between measurements (Section IV, B. 3). Five-minute count rates were normally taken.

b. See Section IV, B. 2.

c. See Section IV, B. 4.

TABLE III - RESULTS OF OPERATING CONTROL ROD FLOAT TESTS AT ELEVATED FLOW RATES

Rod Under Test	Rod Down and Latched, Equilibrium Flow (~ 7.0 x 10 ⁶ lb/hr.)		Count Rates, cpm ^a				Count Rate Expected if Full Floating Occurred ^c , Normalized Average	Experimental Error ^d , Inches of Float	Conclusions
	Rod Delatched		Percent Core A Flow	Extension Withdrawal, Inches	Count Rates				
	Actual	Normalized Average			Actual	Normalized Average			
Regulating Rod	Ch. 1 - 13,156			5	Ch. 1 - 16,688 Ch. 2 - 19,147 Ch. 3 - 539 Ch. 4 - 554	1.261	1.2		Full Floating of Rod Occurred at Indicated Flow in Excess of Core A Flow
	Ch. 2 - 15,120								
	Ch. 3 - 418	1.00	109 ^b	10	Ch. 1 - 26,547 Ch. 2 - 30,570 Ch. 3 - 878 Ch. 4 - 895	2.021	2.0	+ 0.6	
	Ch. 4 - 450			20	Ch. 1 - 67,692 Ch. 2 - 77,754 Ch. 3 - 2,164 Ch. 4 - 2,366	5.146	5.3		
Shim Rod	Ch. 1 - 13,348 Ch. 2 - 15,344 Ch. 3 - 437 Ch. 4 - 461	1.00	105	5	Ch. 1 - 16,391 Ch. 2 - 18,863 Ch. 3 - 534 Ch. 4 - 477	1.229	1.2	+ 0.6	Same as Above

a. Corrected for temperature drift between measurements (Section IV, B. 3). Five-minute count rates were normally taken.

b. The actual flow at the time of these measurements was 115 percent of the Core A flow (10.21×10^6 lb/hr). However, it was later determined that the minimum flow which caused floating was 109 per cent of Core A flow (9.63×10^6 lb/hr). See Section III, A. 2, Step 11.

c. These are approximate values based on predicted rod calibration curves³ and determined as described in Section IV, B. 2.

d. See Section IV, B. 4.

TABLE IV - MEASUREMENT OF ROD WORTH

Count Rates, cpm ^a							
Rod Under Test	Rod Fully Inserted		Rod Fully Withdrawn Safety Rods, 54 Inches Control Rods, 20 Inches		Degree of Subcriticality with Rod Fully Withdrawn, R _w , Cents	Measured Rod Worth, Cents Safety Rods, Unshadowed Control Rods, Shadowed	Predicted Rod Worth, Cents ³
	Actual	Normalized Average	Actual	Normalized Average			
Safety Rod No. 1	Ch. 1 - 5,223 Ch. 2 - 6,039 Ch. 3 - 184 Ch. 4 - 192	1.00	Ch. 1 - 74,427 Ch. 2 - 85,679 Ch. 3 - 2,553 Ch. 4 - 2,635	14.20	9.5	126	145
Safety Rod No. 2	Ch. 1 - 4,529 Ch. 2 - 5,255 Ch. 3 - 151 Ch. 4 - 158	1.00	Ch. 1 - 72,822 Ch. 2 - 84,306 Ch. 3 - 2,490 Ch. 4 - 2,546	16.07	9.1	136	165
Safety Rod No. 3	Ch. 1 - 5,156 Ch. 2 - 5,967 Ch. 3 - 173 Ch. 4 - 184	1.00	Ch. 1 - 74,437 Ch. 2 - 85,588 Ch. 3 - 2,465 Ch. 4 - 2,588	14.38	9.2	123	145
Safety Rod No. 4	Ch. 1 - 5,063 Ch. 2 - 5,862 Ch. 3 - 177 Ch. 4 - 177	1.00	Ch. 1 - 74,913 Ch. 2 - 86,144 Ch. 3 - 2,401 Ch. 4 - 2,607	14.72	9.2	126	134
Safety Rod No. 5	-	-	-	-	-	-	-
Safety Rod No. 6	Ch. 1 - 4,754 Ch. 2 - 5,482 Ch. 3 - 160 Ch. 4 - 170	1.00	Ch. 1 - 73,060 Ch. 2 - 84,029 Ch. 3 - 2,358 Ch. 4 - 2,528	15.33	9.4	135	145
Safety Rod No. 7	Ch. 1 - 4,247 Ch. 2 - 4,907 Ch. 3 - 141 Ch. 4 - 151	1.00	Ch. 1 - 68,247 Ch. 2 - 78,402 Ch. 3 - 2,212 Ch. 4 - 2,394	16.02	9.3	140	165
Safety Rod No. 8	Ch. 1 - 5,166 Ch. 2 - 6,051 Ch. 3 - 175 Ch. 4 - 178	1.00	Ch. 1 - 67,927 Ch. 2 - 78,212 Ch. 3 - 2,189 Ch. 4 - 2,347	13.02	9.4	114	145
Regulating Rod	Ch. 1 - 13,447 Ch. 2 - 15,506 Ch. 3 - 435 Ch. 4 - 470	1.00	Ch. 1 - 87,619 Ch. 2 - 100,365 Ch. 3 - 2,865 Ch. 4 - 3,022	6.49	8.5	46.5	47.5
Shim Rod	Ch. 1 - 13,380 Ch. 2 - 15,381 Ch. 3 - 438 Ch. 4 - 462	1.00	Ch. 1 - 76,528 Ch. 2 - 88,188 Ch. 3 - 2,514 Ch. 4 - 2,688	5.73	9.4	44.3	47.5

a. Corrected for temperature drift between measurements (Section IV, A. 2). Five-minute count rates were normally taken.

FIG. 9- SUBCRITICAL POWER DURING SHIM ROD FLOAT TEST

FIG. 10- SUBCRITICAL POWER DURING REGULATING ROD FLOAT TEST

(1) and the resulting rod worths are given in Table IV. For comparison purposes, the predicted rod worth values are also given in the table. The measured shim and regulating rod worths are in good agreement with the predicted values. In the case of the safety rods, the measured worths average about 14 per cent less than predicted. However, in view of the preliminary nature of the measurements, the agreement is satisfactory. Part of the discrepancy in the individual safety rod worths is known to be caused by variation in the boron concentration in the as-built rods.⁸

C. DELATCHING SPRING COMPRESSION

The delatching spring compressions on the shim and regulating control rods were obtained from the change in subcritical count rate which was measured when the rods floated. The pertinent data are given in Table V. The normalized average count rate data that were measured before and after rod floating are given in Table III and are repeated in Table V. Table V also gives the calculated reactivity change due to rod motion and the amount of rod float as determined from Equation (5) and Figure 8, respectively. Lastly, the table gives the resulting spring compression obtained by subtracting the amount of float from the extension elevation which existed at the time of the float measurements. The measured delatching spring compressions are the same, 1.10 inches average, for each rod and are within the limits of the experimental error (Section IV, B.4). They are in good agreement with the predicted value of 1 inch.

TABLE V - DELATCHING SPRING COMPRESSION MEASUREMENTS

Rod Under Test	Count Rate Before Rod Floated, cpm ^a Normalized Average	Count Rate After Rod Floated, cpm ^a		Calculated Reactivity Change Due to Rod Motion, Cents	Amount of Rod Float, in.	Spring Compression, in.	Experimental Error ^b , in.
		Extension Withdrawal, in.	Normalized Average				
Regulating Rod	1.00	5	1.261	+ 11.20	4.10	0.90	± 0.6
		10	2.021	+ 27.74	8.90	1.10	
		20	5.146	+ 44.95	18.70	1.30	
Shim Rod	1.00	5	1.229	+ 9.95	3.90	1.10	± 0.6

a. See Table III.

b. See Section IV, B. 4.

V. CONCLUSIONS

The determination of rod float in the Enrico Fermi reactor was conducted to confirm the hydraulic design of the control rods. The purpose was to verify that the safety rods will not float under Core A, 200-Mwt design flow rates (8.85×10^6 lb/hr) and that the operating control rods will not float under refueling flow rates (6.0×10^6 lb/hr). The test results showed that the rod channels are properly orificed to prevent floating. None of the seven safety or two operating control rods tested were found to float as a result of the pressure drop which exists at the 200-Mwt design flow rate. This assures that the safety rods will enter the core properly following a scram and that rod floating will not occur accidentally during refueling operations.

In addition to confirming the primary test objectives above, the test also showed that the preliminary reactivity worths of the safety and operating control rods are close to the predicted values and that the delatching spring compressions on the shim and regulating rods are in good agreement with the design values.

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