ENRICO FERMI ATOMIC POWER PLANT

NUCLEAR TEST SERIES

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WORTH MEASUREMENTS OF CORE AND BLANKET SUBASSEMBLY MATERIALS IN THE ENRICO FERMI REACTOR

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DISCLAIMER

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 fast breeder 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 generator 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 described in this report.

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SUMMARY

During the period February 18 through April 1, 1964, measurements were made of the reactivity worths of U-235 and U-238 in the core, and of fuel and blanket subassemblies in the radial blanket of the Enrico Fermi reactor. The columnar reactivity worths of U-235 and U-238 were determined at various core positions by means of reactivity measurements made using specially constructed subassemblies. The reactivity worth difference between a core subassembly and a blanket subassembly was determined as a function of position within the inner radial blanket array by substitution measurements. The reactivity worth difference between a blanket subassembly and a sodium-filled dummy subassembly was determined at both inner and outer radial blanket positions, also by substitution measurements.

The reactivity determinations were made by means of both critical rod position and positive period measurements. All measured worth values were predicted prior to the test using data from the Core A critical assembly mockup on ZPR-III and/or two-dimensional, first-order perturbation theory analysis. With the exception of the outer radial blanket, where agreement is uniformly poor, both sets of predicted values typically agree with the measured values within about 10 per cent; there are a few discrepancies in the order of 20 per cent.

I. PURPOSE OF TEST

Fuel material worths were measured in the reactor core to obtain data from which the reactivity coefficients of U-235 and U-238 could be determined as a function of radial position in the core. Fuel subassembly worths were measured in the inner radial blanket to determine the net reactivity effect of expanding the core loading into the blanket. Blanket subassembly substitution worths were measured to obtain the reactivity worths of the depleted uranium pins within each subassembly in the inner radial blanket and in the first several rows of the outer radial blanket.

These data will provide a basis for making reactivity adjustments for normal reactor operation, and will provide checks on the techniques for calculating reactivity worth coefficients.

II. DESCRIPTION OF THE ENRICO FERMI 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 subassembly hold-down mechanism, and the subassembly handling mechanism. The reactor is of the fast breeder type, cooled by sodium, and is operated at essentially atmospheric pressure. The maximum reactor power with the first core loading (Core A) is 200 Mwt.

The core and blanket, located in the lower reactor vessel, consist of 2.646-inch-square subassemblies containing the fuel pins and blanket rods. The core and blanket subassemblies are arranged to approximate a right cylinder about 80 inches in diameter and 70 inches high. The core, which is 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 is in the form of zirconium-clad pins, 0.158 inch in diameter, containing U-10 w/o molybdenum alloy in which the uranium is enriched to 25.6 per cent U-235. Each fuel subassembly contains 140 fuel pins for a total mass of approximately 4.75 kg of U-235 per subassembly. The inner and outer radial blanket subassemblies each contain 25 blanket rods, 0.443 inch in diameter, that are composed of 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. A total of 149 central lattice positions is occupied by core and inner radial blanket subassemblies, the antimony-beryllium (Sb-Be) 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. From there it flows 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 contain the outer radial blanket subassemblies. Surrounding the outer radial blanket are lattice positions used for stainless-steel-filled, thermal shield subassemblies. These subassemblies provide thermal and neutron shielding for the reactor vessel. The outer radial blanket and shielding lattice positions are both supplied with sodium coolant from a low pressure plenum.

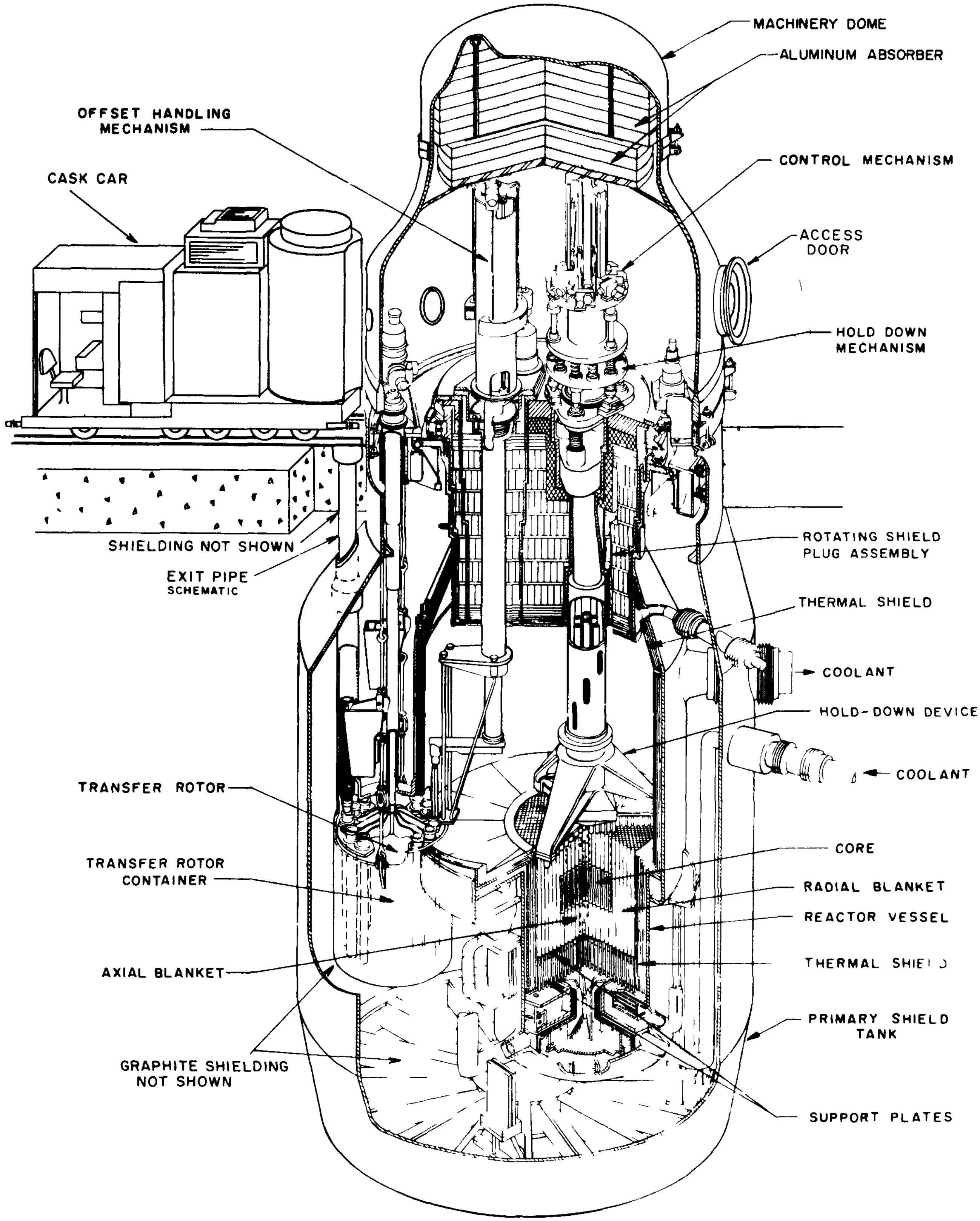


FIG. I - PERSPECTIVE VIEW OF REACTOR

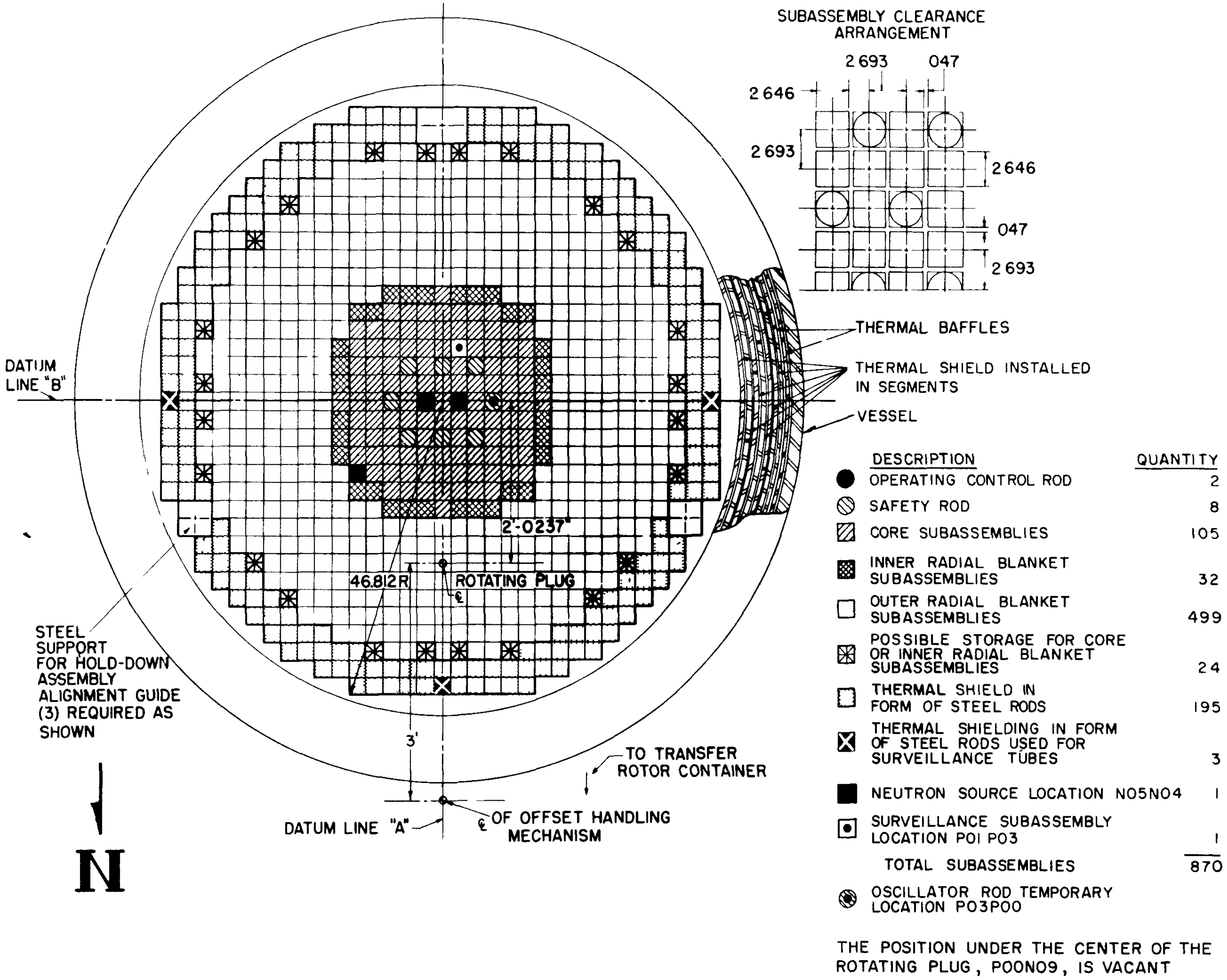


FIG. 2-REACTOR CROSS SECTION

The reactor is controlled by two operating control rods and seven installed safety rods. Provisions also are made for installation of an eighth safety rod. The rods are of the poison type, containing boron carbide (B_4C) in which the boron is enriched in boron-10 (B-10). One operating control rod is for regulating purposes and the other for shimming; the average reactivity insertion rates of these rods are approximately one cent per second and one cent per minute, respectively. The safety rods provide shutdown reactivity. During operation of the reactor, the safety rods are held just above the axial blanket section of the core so that they can be rapidly inserted into the core if necessary. During a normal shutdown, the rods--driven and actuated from the top--are slowly lowered by motor into the core, where they remain during refueling to provide the necessary shutdown reactivity.

The neutron detectors (fission chambers and ion chambers), for reactor operation at power, are located in six neutron-counter tubes embedded in the graphite neutron shield surrounding the reactor vessel. The 11 channels of nuclear instrumentation are distributed throughout the six neutron-counter tubes in a manner that will cover the full flux level or power range during reactor operation.

An antimony-beryllium (Sb-Be) neutron source is normally located in the reactor at the core-blanket interface (Figure 2) to provide a neutron flux at the neutron detectors during reactor start-up, and to maintain a measurable flux when the reactor is shut down. The radioactive antimony portion of the source is made as a separate piece for easy replacement and is in the form of a rod approximately 0.5 inch in diameter. The radioantimony rod fits inside a beryllium assembly which is in the form of a hollow cylinder inside a can having the external dimensions of a normal core subassembly can. In many preliminary low-power tests, where it was necessary to retract the source frequently during operation, the neutron source assembly was installed in one of the safety rod channels where the safety rod extension drive could be used to retract the radioactive antimony rod from the stationary beryllium cylinder.

A more detailed description of the reactor may be found in the Hazards Summary Report.[1]

III. EXPERIMENTAL PROCEDURE

A. EXPERIMENTAL APPARATUS AND EQUIPMENT

During the test, specially constructed test subassemblies were substituted sequentially for normal core and blanket subassemblies and the resultant reactivity changes were determined by measuring the critical rod position and by positive period measurements. The desired reactivity worths were then calculated from the measured reactivity changes and the physical composition of the subassemblies. A description of the subassemblies and the instrumentation used for the reactivity measurements follows:

1. Description of Test Subassemblies

The dimensions and compositions of the subassemblies, normal and special purpose, used in the tests are summarized in Table I and are described briefly below.

A normal fuel subassembly refers to any one of the fuel subassemblies comprising the normal fuel loading of the Fermi Core A (Figure 2). A normal fuel subassembly contains a square array of 140 enriched fuel pins and 4 stainless steel pins, each 32.78 inches in length, as well as 32 depleted uranium rods, 16 each in the upper and lower axial blanket sections of the subassembly (Figure 3).

A shim subassembly differs from a normal fuel subassembly; 72 of the 140 enriched uranium pins are replaced by depleted uranium pins, leaving approximately half the U-235 content of a normal fuel subassembly.

A proof-test subassembly contains 140 depleted uranium pins instead of the normal enriched uranium pins. The axial blanket sections, however, are identical to those of a normal fuel subassembly.

A core dummy subassembly consists of the stainless steel wrapper can of a normal fuel subassembly which becomes completely filled with sodium when in place in the reactor.

A normal blanket subassembly refers to any of the subassemblies included in the radial blanket loading of the reactor (Figure 2). Each blanket subassembly contains 25 rods of depleted uranium-3 w/o molybdenum alloy, 61.75 inches in length (Figure 4).

TABLE I - SUBASSEMBLY DIMENSIONS AND COMPOSITIONS

	Subassembly Type					
Dimension or Quantity	Normal Fuel	Shim	Proof Test	Core Dummy	Normal Blanket	Blanket Dummy
Enriched Fuel Pins, no. 25.6 w/o U-235	140	68	0	0	0	0
Depleted Fuel Pins, no. 25.6 w/o U-235	0	72	140	0	25	0
Stainless Steel Pins, no.	4	4	4	0	0	0
Axial Blanket Pins	Yes	Yes	Yes	No	--	--
Active Pin Length, in.	30.5	30.5	30.5	--	61.75	--
Pin Diameter, in.	0.158	0.158	0.158	--	0.443	--
Cladding Thickness, mils	5	5	5	--	10	--
Sodium Bond Thickness, mils	--	--	--	--	14	--
U-235, kg, nominal	4.75	2.317	0.065	0	0.194	0
U-235, kg, nominal	13.77	16.22	18.51	0	55.08	0
Molybdenum, kg, nominal	2.06	2.06	2.06	0	1.71	0
Zirconium, kg. nominal	1.08	1.08	1.08	0	0	0
Stainless Steel, kg, nominal (excluding can)	0.99	0.99	0.99	0	3.07	0
Sodium, kg, nominal (within pin length)	1.42	1.42	1.42	2.673	2.468	5.745

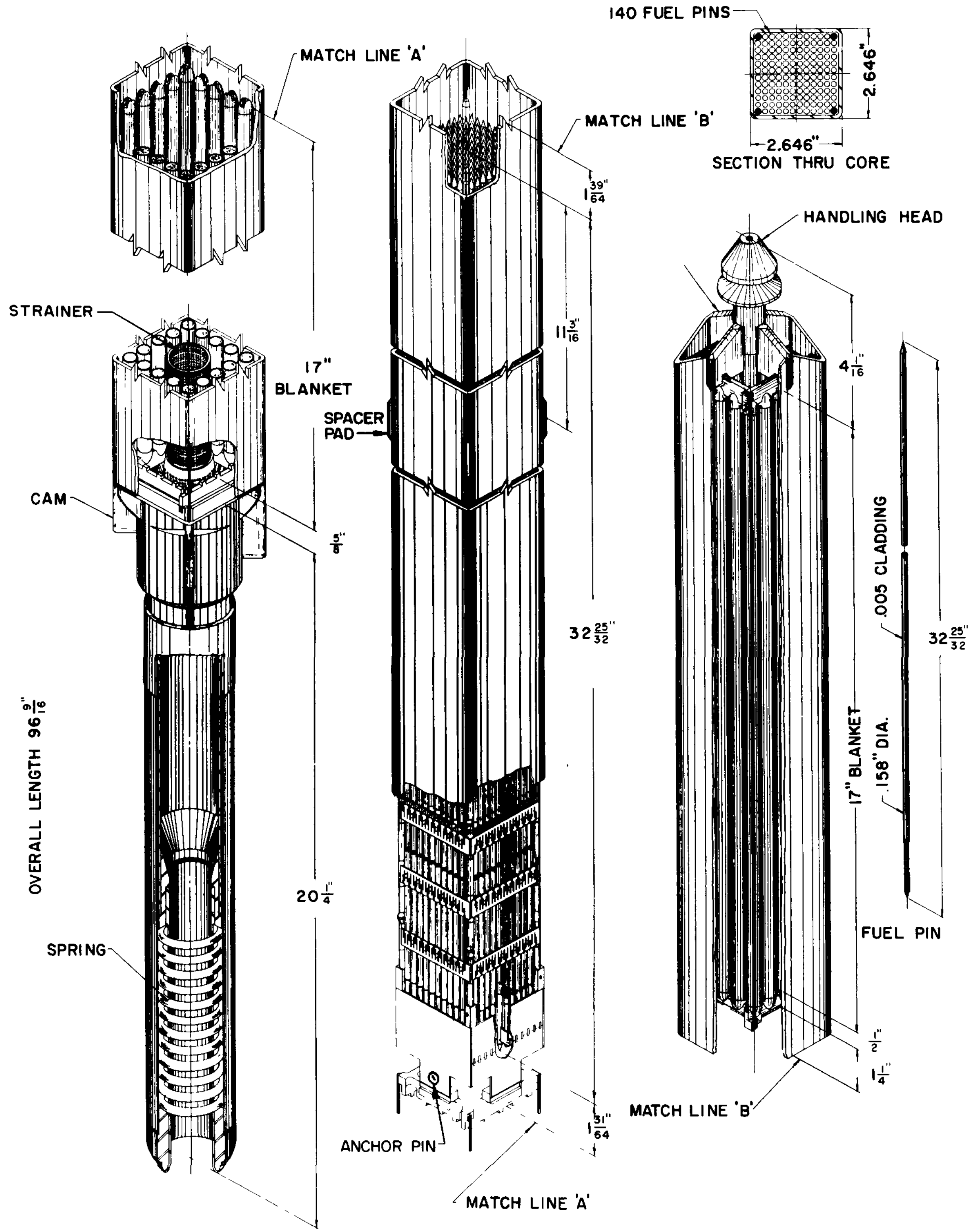


FIG. 3 CORE SUBASSEMBLY DESIGN

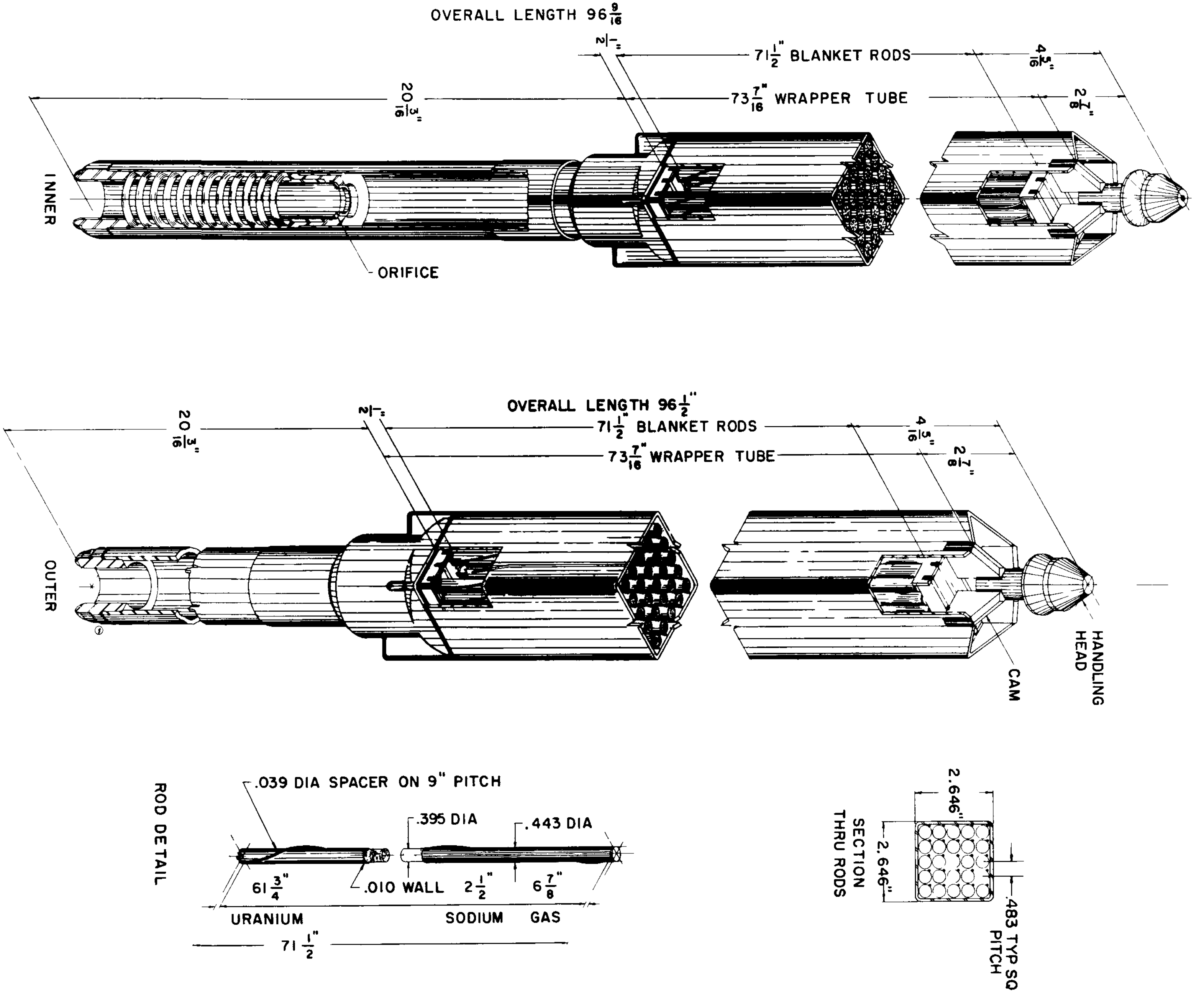


FIG.4 RADIAL BLANKET SUBASSEMBLY DESIGN

An inner radial blanket (IRB) subassembly is a normal blanket subassembly with special handling attachments and coolant orifices which allow it to be placed in the outer row of the 149 central lattice positions designed to accommodate core subassemblies (Figure 2).

A blanket dummy subassembly consists only of the wrapper can of a normal blanket subassembly that completely fills with sodium when in place in the reactor.

2. Instrumentation

The reactor power level during the test was nominally 1500 watts. The power was measured by an uncompensated ion chamber connected to the recorder of a Keithley micromicroammeter. In addition, power data were obtained from three compensated ion chambers connected to the three intermediate range channels of the safety system.

The critical control rod positions were read from Gilmore position indicators located in the reactor control room and from direct-reading scales attached to each control rod drive. As small errors were found to exist in the Gilmore readings during the test, only the scale readings--estimated to be accurate to $\pm$ 0.01 inch--were used for most of the analyses. The reactor periods were obtained using a scaler readout from the two source range channels of the safety system and a direct readout from the Keithley micromicroammeter. The two scalers were stopped and started by a Flex-o-pulse timer set to count 12 seconds. The count versus time data were plotted as semi-logrithmic graphs to obtain the period information. An integral clock-timer was used in conjunction with the Keithley micromicroammeter recorder to permit direct readout of the period in seconds. However, this was abandoned in later measurements when it became obvious that it was inconsistent with both the Keithley recorder chart and the period data obtained using the scalers.

The drift in power level during critical rod position measurements was determined using the Keithley micromicroammeter. With the reactor approximately critical at the desired power level, a bucking current was supplied to suppress most of the ion chamber current. The net current read on the meter and chart was then very sensitive to power drift; i.e., a drift of 0.25 per cent in five minutes was easily and accurately measured. The drift data were used to correct the critical rod data.

The reactor temperature during the measurements was maintained as nearly as possible at 517 F, the normal start-up temperature. All reactivity measurements were corrected to 517 F based on the data obtained from six temperature sensors of the platinum resistance type; located in the primary piping to measure both the core and reactor inlet and outlet temperatures. The temperature sensors were connected to a resistance bridge which allowed temperature readout to within an estimated accuracy of $\pm$ 0.5 F.

B. REACTOR PLANT CONDITIONS

The nominal reactor fuel loading during the test consisted of 99 core fuel subassemblies in the core and inner radial blanket lattice positions. The excess reactivity of any fuel loading was limited to less than 92 cents at any test temperature with the safety and control rods fully withdrawn and the antimony section of the retractable neutron source withdrawn to 30 inches.

The retractable antimony-beryllium neutron source was located in the reactor during the test in the normal position of safety rod No. 5 in core position PO3-POO.* The antimony section of the source was inserted and retracted with the safety rod drive extension.

The retractable source was used during the test because it permitted accurate reactivity measurements to be made at low power, thus minimizing the activation of core components. The reactor could be started safely with the antimony source rod fully inserted and, after attaining low-power criticality, the source could be withdrawn to eliminate source reactivity during reactivity measurements. (Calibration measurements made when the retractable source was installed had demonstrated that source reactivity effects were negligible with the antimony rod retracted 30 inches.)

Whenever possible, the primary system was maintained at an isothermal temperature of 517 F and the temperature drift between reactivity measurements was kept to a minimum. The reactor temperature was controlled by maintaining a balance between the heat input, resultingfrom primary sodium pump operation, and the heat removal, resulting from the operation of the below-floor ventilation system. The auxiliary cooling system, consisting of the overflow pumps and the primary system cold trap, was operated to reduce the upward drift in temperature when required.

The primary sodium flow rate was held at refueling flow, which is about 6×10^6 lb/hr for three-loop operation, or 68 per cent of the nominal 200-Mwt operation flow rate. To allow the tests to be made under these conditions, the low sodium flow trip setting of the reactor safety system was reduced from its normal setting of 75 per cent to 40 per cent of the nominal 200-Mwt flow value. The intermediate and power range level scrams were set at flux levels corresponding to powers less than 1 Mwt.

C. DESCRIPTION OF TEST

Each type of test consisted of a series of individual worth determinations, each series being structured according to a written, preplanned

* 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" represents positive values and "N" negative values. The core center is POO-POO.

program.[2,3,4,5] Each individual worth determination was made by ascertaining the difference between the reactivity state of a nominal reference loading core and that of a revised core or blanket loading. To maintain experimental uncertainties at a practical minimum, each reactivity state determination consisted of two or more independent measurements each of the critical regulating rod position and of the positive reactor period resulting from a known, slightly super critical rod position. The nominal reference loading throughout all series of measurements was composed of 99 core subassemblies and the normal surrounding array of blanket subassemblies.

The critical regulating rod positions were determined using the direct-reading scale on each control rod drive. Rod positions were converted to reactivity equivalents using the rod calibration curves. (The regulating rod calibration curve is shown in Figure 5.) The power level drift rate at the time of each critical rod measurement was found over a 5-minute period using the Keithley micromicroammeter recorder. Reactivity corrections for power drift were then applied to the rod position to obtain all data at the true critical conditions of zero drift. The temperature, maintained as closely as possible during the measurements at 517 F, was determined from the mean value of the readings from six temperature sensors in the primary sodium loops. It was required that all temperature sensor readings be within a range of 2 F to insure an isothermal condition. Temperature-reactivity-feedback corrections were applied to compensate for any mean temperature deviations from 517 F.

Each positive period determination was based on three separate measurements. One was obtained from the clock-timer or power trace of the Keithley recording micromicroammeter. Two additional readings of period were derived graphically from the counts recorded by two RIDL 49-51 scalers connected to the two reactor safety system source range channels. Each period value obtained was converted to a reactivity value using the inhour relationship of the reactor. Reactivity corrections were applied to compensate for any mean temperature deviations from 517 F.

1. U-235 Worth in the Core

To obtain measurements of the columnar reactivity worth of U-235 versus U-238 as a function of radial position in the core, a shim subassembly was taken from a storage position in the outer blanket region and substituted sequentially for a normal core subassembly in the nine separate core positions illustrated in Figure 6. Critical rod and positive period measurements were made to determine the reactivity state of the reactor after each substitution, and also for the reference core loading. The difference between the reactivity state of the reference loading and of each loading perturbed by a shim subassembly substitution in a given core position constituted a direct determination of the columnar reactivity worth of approximately 2.43 kg of U-235 versus an equal mass of U-238 in that core position.

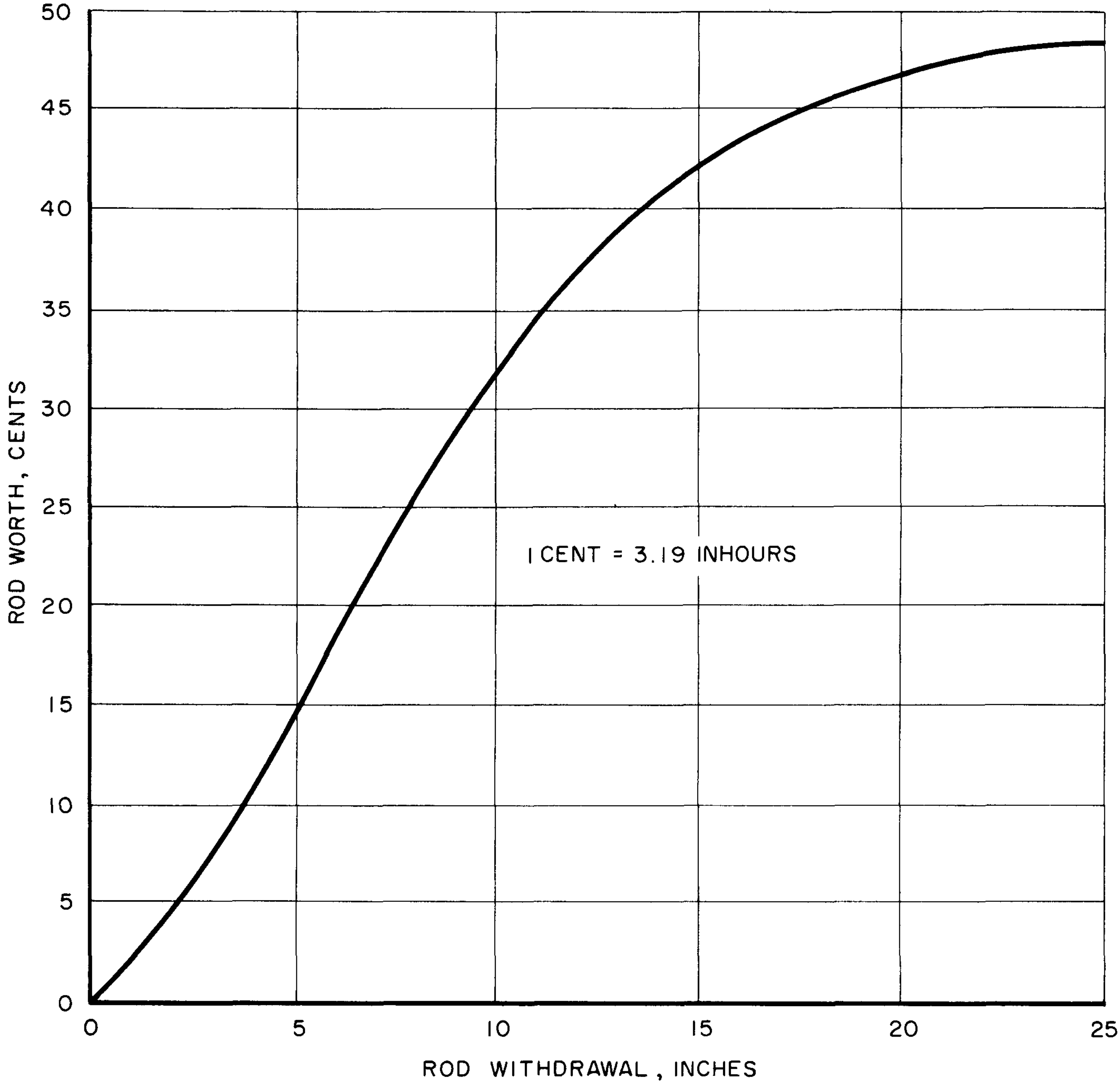
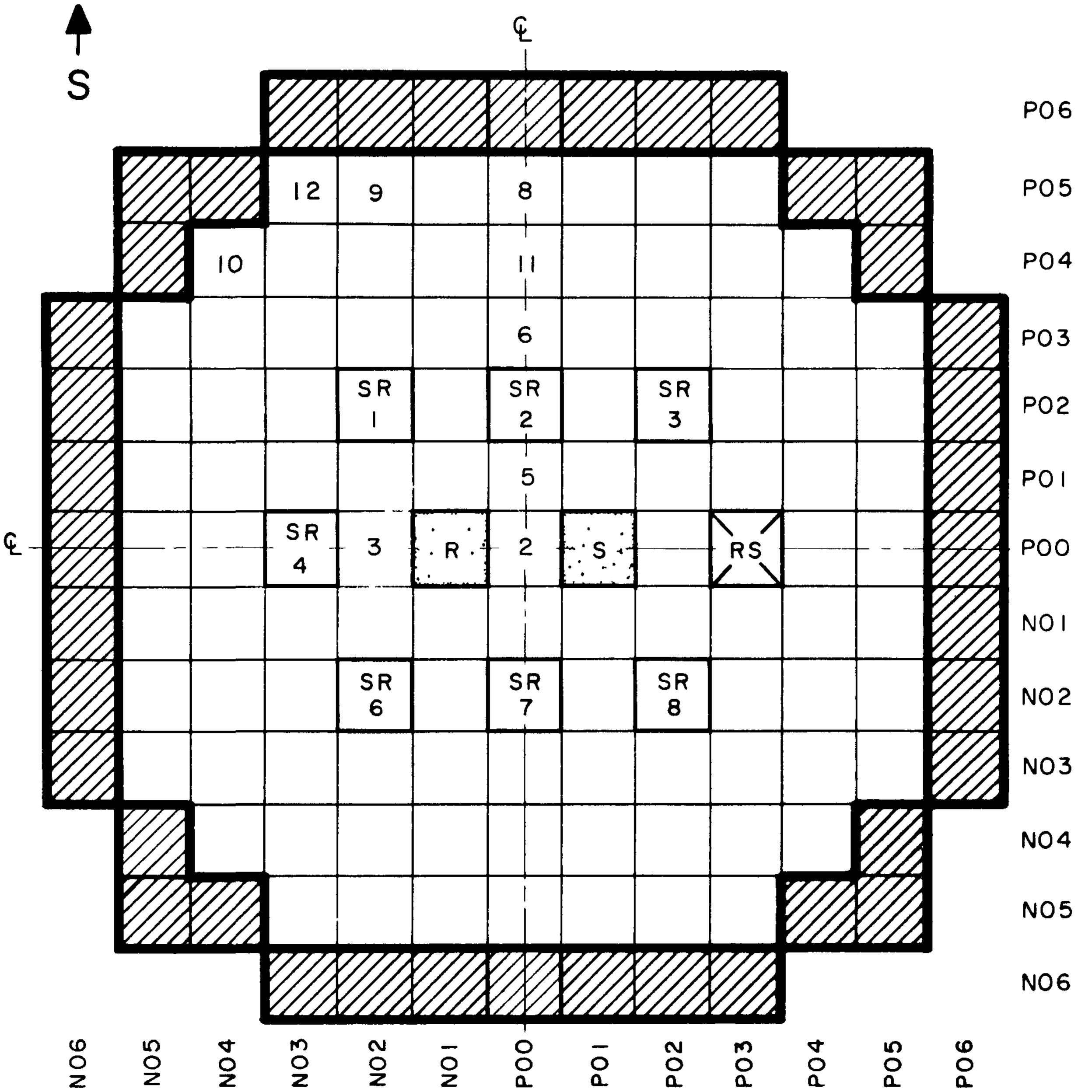


FIG. 5 REGULATING ROD CALIBRATION CURVE



LEGEND

- R REGULATING ROD
- S SHIM ROD
- SR SAFETY RODS
- CORE SUBASSEMBLIES
- RS NEUTRON SOURCE SUBASSEMBLY
- INNER RADIAL BLANKET SUBASSEMBLIES

THE NUMBERED BLOCKS REPRESENT SEQUENTIAL LOCATIONS OF THE SHIM SUBASSEMBLY. SEQUENCE NUMBERS 1, 4, 7 AND 13 ARE MEASUREMENTS OF THE REFERENCE REACTIVITY.

FIG. 6 LOCATION OF U-235 WORTH MEASUREMENTS IN THE CORE

The reference reactivity conditions of the reactor was found to increase slowly with time during the period of the test.* To avoid obtaining a separate reference reactivity measurement for comparison with each shim substitution measurement, the time variation of the reference reactivity state was inferred from four sets of measurements--one at both the beginning and end of the substitution sequence--and two spaced intermediately between these. To obtain the reference reactivity condition at any given time during the substitution sequence, the measured reference reactivity values were interconnected linearly, with the exception of the fourth one. After the third reference measurement, the reference reactivity state was perturbed by the insertion of a new tantalum-clad, retractable antimony source rod, which had appreciably more negative reactivity worth in its fully retracted position than the stainless-steel-clad source rod used previously. Since the specific change in the source reactivity worth was not known, and since only one reference measurement had been made after the source rod change; the reference reactivity state of the reactor for all subsequent measurements was assumed to be unvarying and equal to the single,measured value obtained at the end of the substitution sequence.

2. Fuel Subassembly Replacement Worth in the Inner Radial Blanket

The normal reference loading was considered as the primary reference for this set of measurements. A revised secondary reference loading was necessitated for one measurement, as will be explained in this section. To find the reactivity worth of a normal core subassembly relative to that of a blanket subassembly in all positions in the inner radial blanket, a normal fuel subassembly (taken from storage in the outer radial blanket) was substituted for an IRB subassembly in each of the seven positions in Figure 7. The octagonal symmetry of the IRB subassembly lattice permitted the worths of the entire array to be determined from measurements at only seven positions.

The reactivity state of the reactor after each substitution was measured by critical rod and positive period methods and compared to the reactivity state of the primary reference loading. The latter had been determined by three linearly connected sets of reference reactivity measurements that were made during the measurement sequence and spaced to describe any drifts with time. (However, since the reference loading itself included a normal fuel subassembly in the test octant of the IRB, the reference reactivity had to be corrected for the worth of that subassembly to permit a direct determination of each replacement worth by comparison with the reference.

To provide additional data, two other substitutions were made. A second normal fuel subassembly was inserted in one of the IRB positions

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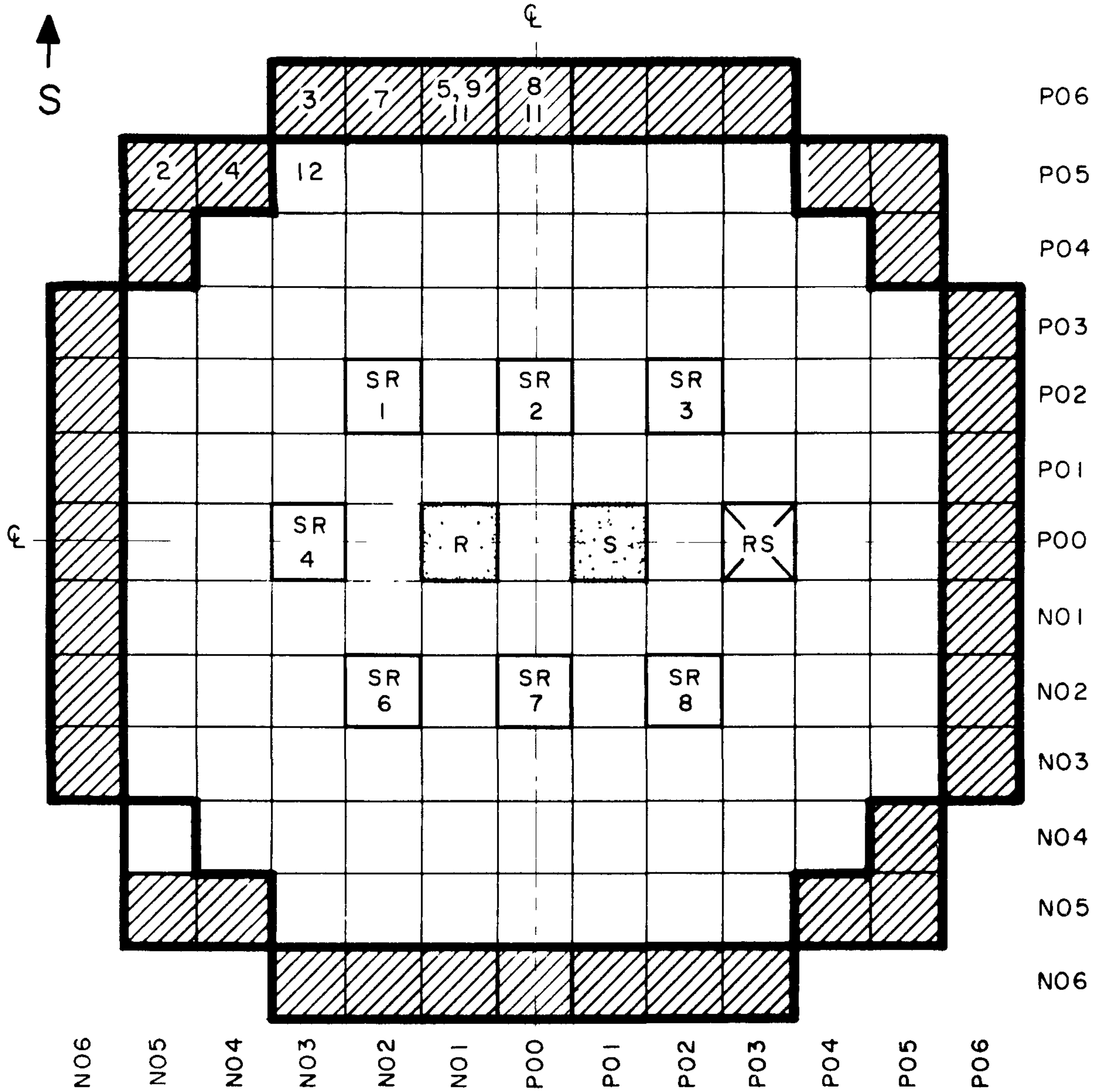
*The reference reactivity state of the reactor increased at the rate of approximately 2 inhours per month. This increase has been attributed to phase transformation shrinkage of the U-Mo alloy and/or hydrogen pickup by the zirconium cladding.



LEGEND

- R REGULATING ROD
- S SHIM ROD
- SR SAFETY RODS
- CORE SUBASSEMBLIES
- RS NEUTRON SOURCE SUBASSEMBLY
- INNER RADIAL BLANKET SUBASSEMBLIES

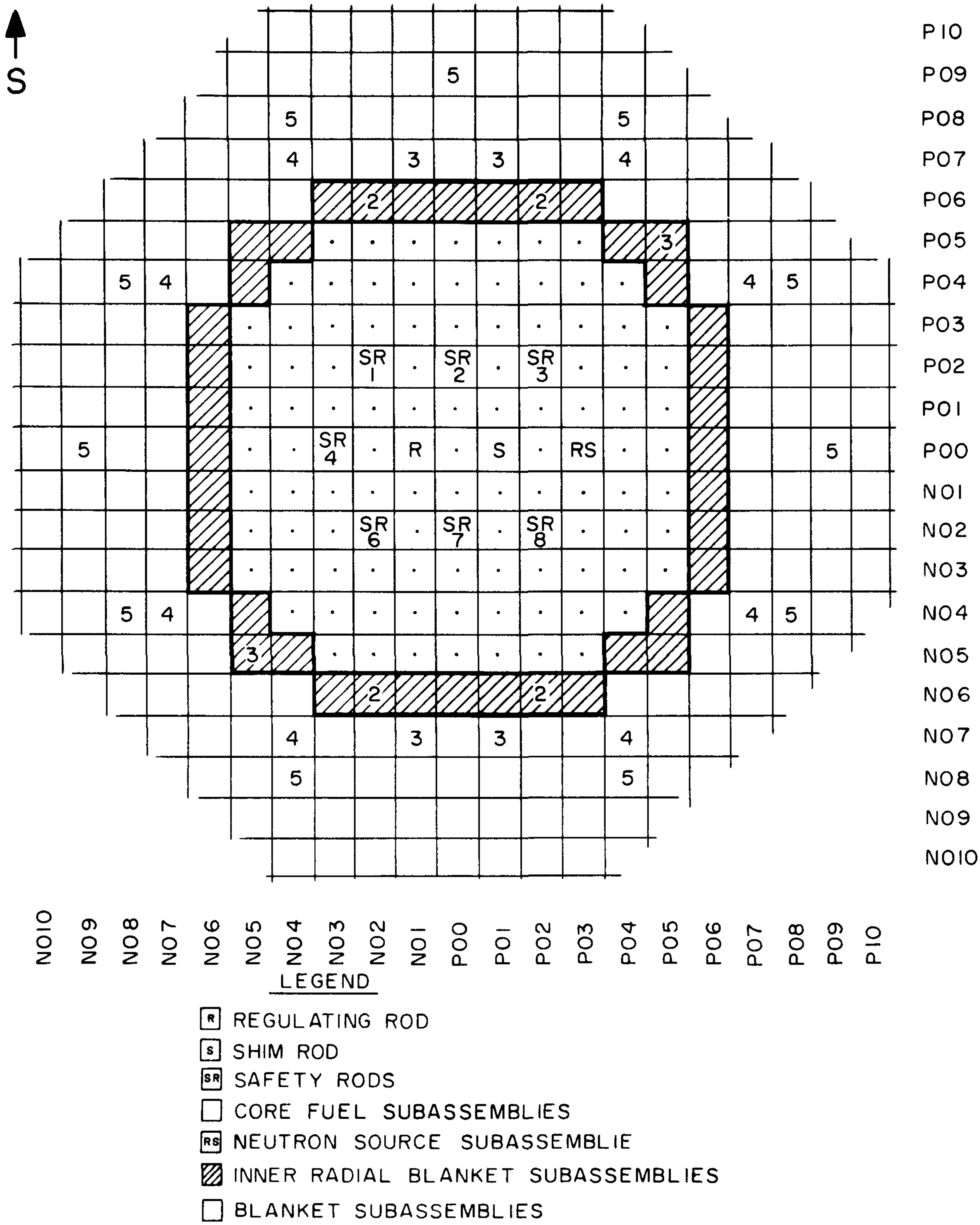
THE NUMBERED BLOCKS REPRESENT SEQUENTIAL LOCATIONS OF NORMAL CORE SUBASSEMBLIES IN THE INNER RADIAL BLANKET POSITIONS. SEQUENCE NUMBER 11 INVOLVES A DOUBLE SUBASSEMBLY SUBSTITUTION. SEQUENCE NUMBERS 1, 6, 10, AND 13 ARE MEASUREMENTS OF THE REFERENCE REACTIVITY.

FIG. 7 LOCATIONS OF FUEL SUBASSEMBLY FOR IRB SUBASSEMBLY REPLACEMENT WORTH MEASUREMENTS previously occupied by the first fuel subassembly to determine whether any reactivity worth difference existed between the two. Then, to determine the coupling effect between them, they were substituted in adjacent IRB positions. The resultant reactivity increase was measured and compared to the sum of the increases resulting from individual substitutions in these two identical positions. These two additional measurements are indicated in Figure 7 as steps 9 and 11, respectively.

Due to the relatively large net reactivity increase resulting from the double IRB substitution, it was necessary to make a secondary reference loading of lower reactivity than the primary reference loading prior to the double substitution. Core dummy subassemblies were substituted for normal fuel subassemblies at the core edge for this purpose. To minimize any resulting worth perturbations, the substitutions were made at the edge of the core opposite to that of the IRB substitutions. The reactivity state of this secondary reference loading was related to that of the primary reference loading by means of an additional measurement. Finally, the primary reference reactivity which had been used as an arbitrary comparative reactivity base for all worth measurements, was translated into an absolute reactivity worth permitting each subsequently measured reactivity, relative to the reference, to be converted into an absolute reactivity worth. This was accomplished by measuring the worth of the fuel subassembly in IRB position NO3-PO5, relative to a blanket subassembly. Thus, any change in the reactivity state of the reactor, relative to the primary reference reactivity state, represented the difference in fuel subassembly worth at any given position and the known worth value at position NO3-PO5.

3. Blanket Subassembly Replacement Worth

To determine the reactivity worths of blanket subassemblies relative to sodium-filled dummy subassemblies in the inner radial blanket and in the first three rows of the outer radial blanket, groups of blanket dummy subassemblies were substituted for normal blanket subassemblies at four successive radii. The dummy subassembly locations for each of the four blanket measurements are shown in Figure 8. The number of subassemblies substituted for each measurement was determined by the magnitude of the reactivity change needed to minimize the experimental error and yet keep the fuel handling within practical limits. The reactivity state of the reference loading was measured twice during the blanket worth tests, and was found to be approximately the same each time. The reactivity state of the reactor resulting from each group of substitutions was determined by critical rod and positive period measurements. These values were then compared to the reference reactivity state to find the net reactivity change attributable to each substitution and each subassembly.



NUMBERED BLOCKS REPRESENT RADIAL BLANKET LOCATIONS OF SUBASSEMBLY GROUP SUBSTITUTIONS BY SEQUENTIAL STEPS. STEPS I AND 6 WERE REFERENCE REACTIVITY MEASUREMENTS

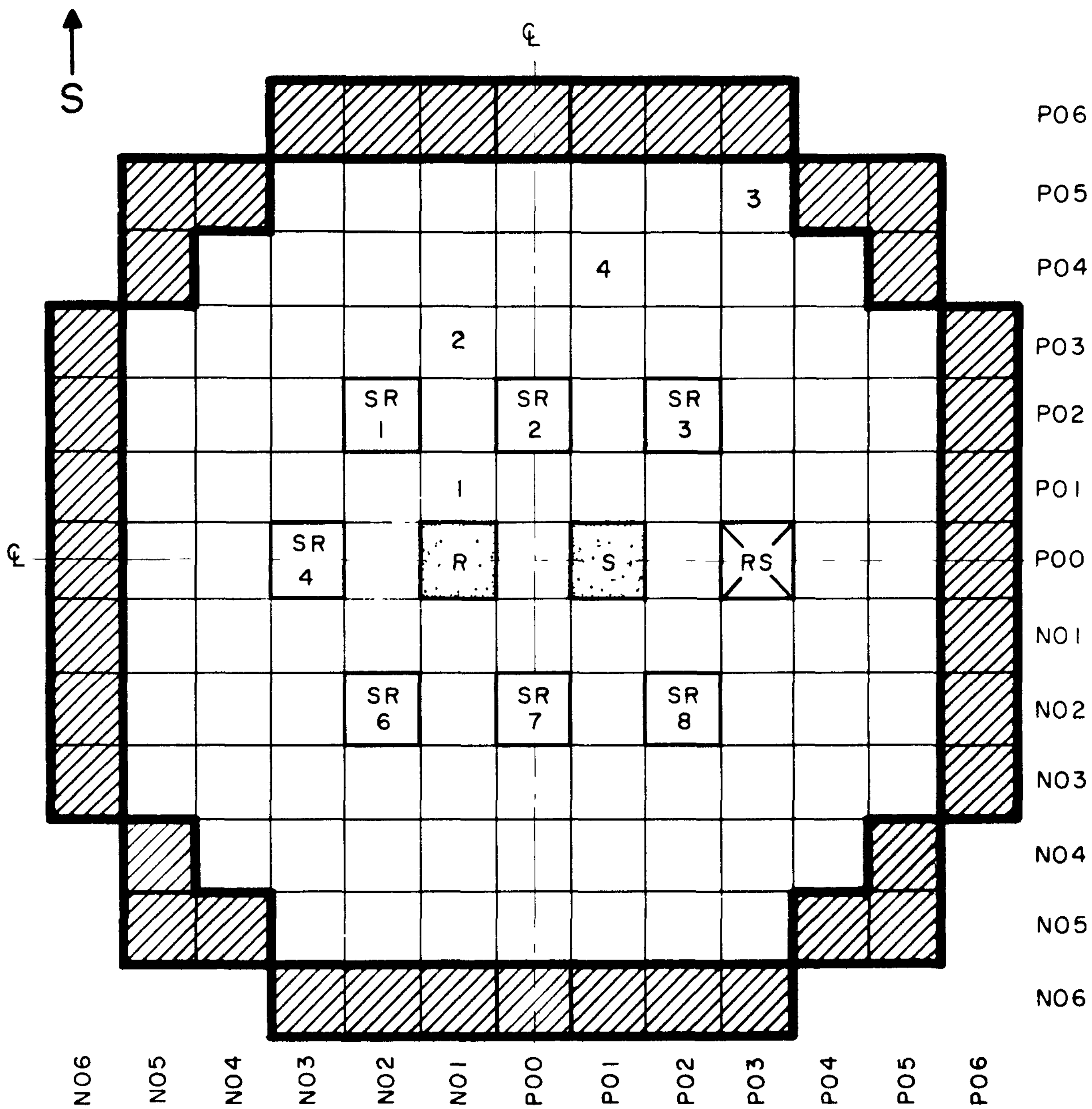
FIG. 8 LOCATIONS OF DUMMY SUBASSEMBLY FOR BLANKET SUBASSEMBLY REPLACEMENT WORTH MEASUREMENTS

4. U-238 Worth in the Core

The test procedure for determining the columnar worth of U-238 versus sodium in the core consisted of measuring the reactivity state of the reactor with a proof-test subassembly and then a core dummy subassembly located in each of the four core positions shown in Figure 9. The difference between the reactivities at each position was a measure of the worth, relative to an equal volume of sodium, of 140 depleted uranium pins contained in the proof-test subassembly. Also contributing to the pin worths obtained, were the zirconium cladding, the molybdenum alloy constituent, the four stainless steel corner pins and the pin support grids.

The reactivity determinations were made both by critical rod position and positive period measurements, except in the case when the dummy subassembly was located in position NO1-PO3. This reactivity measurement was made only by subcritical count rate analysis because the count rates, as the safety rods were being withdrawn on the approach to criticality after the substitution, indicated that the excess reactivity of the reactor closely approached the 92-cent limitation stated in the plant technical specifications. It was decided not to reload the reactor to gain a more accurate measurement in this position.

To insure that no reactivity drift corrections were required for the data, the reactivity state of the reference loading was checked repeatedly during the test to detect any variation with time in the reference state; no variation was found.



LEGEND

- R REGULATING ROD
- S SHIM ROD
- SR SAFETY RODS
- CORE SUBASSEMBLIES
- RS NEUTRON SOURCE SUBASSEMBLY
- INNER RADIAL BLANKET SUBASSEMBLIES

NUMBERED BLOCKS REPRESENT SEQUENTIAL LOCATIONS OF PROOF-TEST SUBASSEMBLY FOR CORE DUMMY SUBASSEMBLY SUBSTITUTIONS.

FIG.9 SUBASSEMBLY LOCATIONS FOR U-238 WORTH MEASUREMENTS

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. WORTH MEASUREMENTS IN THE CORE

The columnar reactivity worth of U-235 versus U-238 was determined, as a function of radial core position, from the reactivity changes measured following sequential substitutions of a shim subassembly for a normal fuel subassembly. The columnar reactivity worth of U-238 versus sodium was determined, as a function of radial core position, by measuring the reactivity difference between a proof-test subassembly and a core dummy subassembly in identical core positions, and using calculated corrections for the worth contributions of the nonuranium metallic constituents of the depleted uranium pins and the pin support grids contained in the proof-test subassembly. By combining these results with the previously measured results for the reactivity worth of sodium versus void,[7] it was possible to derive reactivity worths for U-235 versus void and U-238 versus void.

1. U-235 Worth Measurements

The critical rod and positive period measurements of the reactor reactivity state following each shim subassembly substitution indicated in Figure 6 are listed in Table II, together with the measured reference reactivity values and the mean reactivity difference attributable to each subassembly substitution. Also included are the net reactivity worths of U-235 versus U-238 obtained from these data, and the probable errors associated with each determination. The precise mass of U-235 substituted for U-238 was determined earlier from direct measurements on individual subassemblies during fabrication; the nominal value is 2.43 kg (see Table I). The probable errors listed in Table II were obtained, essentially, from a statistical analysis of the data scatter.

Prior to measuring the U-235 versus U-238 worth in the core, worth predictions were made to assist in the measurements using Core A clean, critical assembly mockup data obtained on ZPR-III.[8] However, the core size and critical mass of the Fermi reactor are larger than those of the critical assembly mockup because design changes were made in the fuel subassemblies subsequent to the ZPR-III measurements. As a result of the size difference alone, the ZPR-III worth predictions were estimated to be 10 per cent too high. Also, the average slope of the predicted worth curve from the core edge to the core center was estimated to be too steep because the clean critical mockup did not take into account the control or safety rod channels. Figure 10 compares the ZPR-III predictions and the measured worths.

TABLE II - COLUMNAR MEASUREMENTS OF U-235 FOR U-238 REPLACEMENT WORTHS IN THE CORE

			Measured Reactivity State, Inhours[a]				Reactivity Worth of Shim Versus Core Subassembly, Inhours						
			Positive Period Measurements			Critical Rod Position Measurements	Positive Period Measurements				Critical Rod Position Measurements	Mean of Period and Critical Rod Measurements	
Measurement No. and Core Position	Average Radius cm	Date-Time	Keithley	Scaler 1	Scaler 2		Keithley	Scaler 1	Scaler 2	Mean			Net Worth of U-235 versus U-238, ih/kg
1 Reference		Feb 19 1530	- 40.33 ± 0.16	- 40.74 ± 0.31	- 40.50 ± 0.18	- 40.37 ± 0.03							
2 PO0-PO0	0	Feb 20 0900	-233.04 ± 0.07 (-40.19 ± 0.16)[b]	-233.40 ± 0.06 (-40.59 ± 0.17)	-233.46 ± 0.11 (-40.38 ± 0.12)	-232.81 ± 0.03 (-40.23 ± 0.07)	-192.85 ± 0.17	-192.81 ± 0.20	-193.08 ± 0.16	-192.91 ± 0.19	-192.58 ± 0.08	-192.74 ± 0.25	+78.0 ± 0.2
3 NO2-PO0	13.69	Feb 21 0050	-203.80 ± 0.19 (-40.09 ± 0.16)	-204.58 ± 0.25 (-40.45 ± 0.19)	-204.52 ± 0.23 (-40.28 ± 0.12)	-202.94 ± 0.01 (-40.09 ± 0.07)	-163.71 ± 0.25	-164.13 ± 0.31	-164.24 ± 0.26	-164.03 ± 0.32	-162.85 ± 0.07	-163.44 ± 0.51	+66.4 ± 0.2
4 Reference		Feb 24 1230	-39.62 ± 0.16	-39.73 ± 0.13	-39.72 ± 0.13	-39.40 ± 0.03							
5 PO0-PO1	6.84	Feb 24 2345	-226.92 ± 0.13 (-39.67 ± 0.32)	-227.45 ± 0.20 (-39.58 ± 0.13)	-227.39 ± 0.15 (-39.49 ± 0.22)	-226.68 ± 0.01 (-39.28 ± 0.03)	-187.25 ± 0.35	-187.87 ± 0.24	-187.90 ± 0.27	-187.67 ± 0.35	-187.40 ± 0.03	-187.54 ± 0.37	+75.8 ± 0.2
6 PO0-PO3	20.52	Feb 25 1000	-189.41 ± 0.07 (-39.72 ± 0.32)	-189.37 ± 0.09 (-39.45 ± 0.13)	-189.44 ± 0.05 (-39.29 ± 0.22)	-188.20 ± 0.05 (-39.18 ± 0.03)	-149.69 ± 0.33	-149.92 ± 0.16	-150.12 ± 0.23	-149.92 ± 0.28	-149.02 ± 0.06	-149.47 ± 0.51	+60.5 ± 0.2
7 Reference		Feb 25 1900	-39.76 ± 0.20	-39.33 ± 0.18	-39.11 ± 0.03	-39.07 ± 0.03							
8 PO0-PO5	34.19	Feb 26 0910	-119.96 ± 0.57 (-42.96 ± 0.34)	-119.71 ± 0.76 (-42.59 ± 0.28)	-119.73 ± 0.77 (-42.80 ± 0.28)	-119.24 ± 0.91 (-42.64 ± 0.28)	-77.00 ± 0.66	-77.12 ± 0.81	- 76.93 ± 0.82	- 77.02 ± 0.77	- 76.60 ± 0.95	- 76.81 ± 1.24	+30.9 ± 0.5
9 NO2-PO5	36.83	Feb 26 1830	-108.78 ± 0.03 (-42.96 ± 0.34)	-108.42 ± 0.01 (-42.59 ± 0.28)	-108.29 ± 0.09 (-42.80 ± 0.28)	-107.71 ± 0.01 (-42.64 ± 0.28)	-65.82 ± 0.34	-65.82 ± 0.28	- 65.35 ± 0.29	- 65.66 ± 0.34	- 65.07 ± 0.28	- 65.36 ± 0.52	+26.7 ± 0.3
10 NO4-PO4	38.66	Feb 27 0905	-100.71 ± 0.08 (-42.96 ± 0.34)	-100.63 ± 0.11 (-42.59 ± 0.28)	-100.73 ± 0.11 (-42.80 ± 0.28)	- 99.86 ± 0.03 (-42.64 ± 0.28)	-57.75 ± 0.35	-58.04 ± 0.30	- 57.93 ± 0.30	- 57.91 ± 0.34	- 57.22 ± 0.28	- 57.56 ± 0.55	+23.6 ± 0.3
11 PO0-PO4	27.36	Mar 2 1915	-157.53 ± 0.20 (-42.96 ± 0.34)	-157.78 ± 0.06 (-42.59 ± 0.28)	-158.04 ± 0.00 (-42.80 ± 0.28)	-157.19 ± 0.08 (42.64 ± 0.28)	-114.57 ± 0.39	-115.19 ± 0.29	-115.24 ± 0.28	-115.00 ± 0.38	-114.55 ± 0.29	-114.78 ± 0.52	+46.7 ± 0.3
12 NO3-PO5	39.88	Mar 3 0825	- 95.32 ± 0.06 (-42.96 ± 0.34)	- 95.12 ± 0.07 (-42.59 ± 0.28)	- 95.11 ± 0.01 (-42.80 ± 0.28)	- 94.72 ± 0.01 (-42.64 ± 0.28)	- 52.36 ± 0.35	- 52.53 ± 0.29	- 52.31 ± 0.28	- 52.40 ± 0.31	- 52.08 ± 0.28	- 52.24 ± 0.44	+21.2 ± 0.3
13 Reference		Mar 3 1715	- 42.96 ± 0.20	- 42.59 ± 0.08	- 42.80 ± 0.08	- 42.64 ± 0.01							

a. The values shown are the measured excess reactivity state of the reactor, adjusted to the condition of full insertion of the regulating and shim control rods. The uncertainty indicated for each reactivity state or worth prior to averaging worths from different period data instruments and reactivity determination methods does not represent probable error, but it does represent the non systematic or random component of the probable error. The averaging process incorporates the random and systematic instrument response errors into the net probable error.

b. Quantities in parentheses represent values of the interpolated reference reactivity state of the reactor.

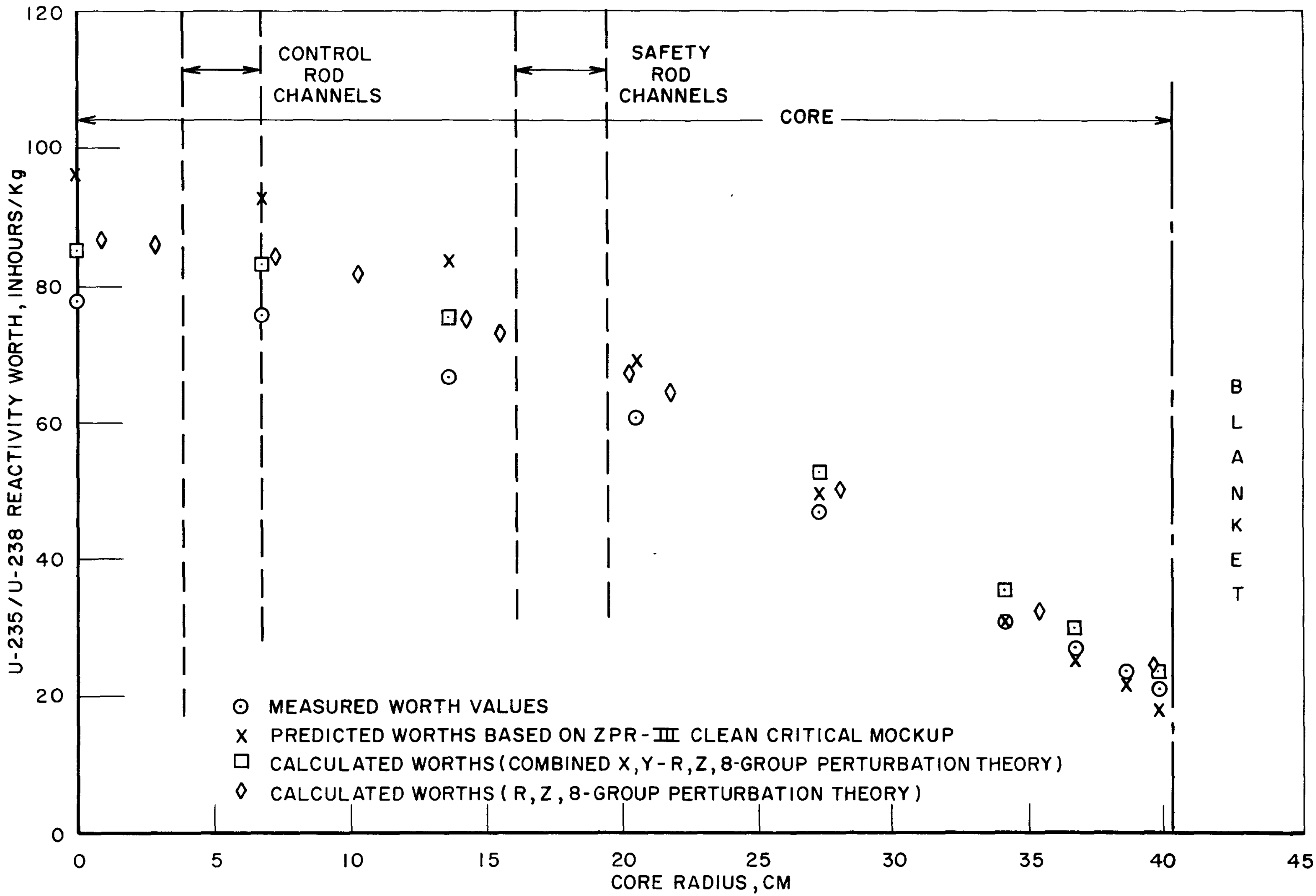


FIG. 10 COLUMNAR REACTIVITY WORTHS OF U-235 VERSUS U-238 IN THE CORE

Since completion of the worth measurements in Fermi, an attempt has been made to calculate the columnar U-235 versus U-238 worths as a function of core position. "Pseudo-three-dimensional," first-order, multigroup perturbation theory calculations were made using the CRAM diffusion theory code. This was done primarily to indicate the accuracy of this technique in calculating reactivity worths. The cross sections used in these calculations were based upon a 24-group set,[10] collapsed to 8-energy groups weighted by region-averaged flux spectra. The "pseudo-three-dimensional" calculations were derived by synthesizing the results of a 2-dimensional core midplane (X, Y) worth analysis, with the axial worth profiles obtained in a separate 2-dimensional, cylindrical (R, Z) analysis. Figure 10 shows these calculated worths.

Table III summarizes the experimentally determined U-235 versus U-238 columnar worths and the measured U-238 versus void worth values (Section IV, A.2) that were used to correct the U-235 versus U-238 values to U-235 versus void values. The data in this table are illustrated graphically in Figures 10 and 11. Note that the largest discrepancies between measured and calculated worths occur in the vicinity of the regulating and shim control rod channels, where the effect of rod insertion was not accounted for in the calculation. However, the calculated U-235 worths are consistently high, suggesting the need for revision of the group cross sections.

2. U-238 Worth Measurements

Table IV contains a summary of the results of the reactivity measurements that were made to determine the worth of a proof-test subassembly versus a core dummy subassembly in each of the four core positions shown in Figure 9. Two measurements of the reactivity state of the nominal reference loading made during the test period indicated no time variation in the reference reactivity state; consequently, no corrections for reference loading reactivity drift were required for the basic reactivity measurements. The errors shown in Table IV are the probable errors obtained from statistical analysis of the data scatter.

To derive a columnar U-238 versus void worth value for each core position from the measured reactivity decrease resulting from the exchange of a proof-test subassembly for a core dummy subassembly, it was necessary to correct the data for the columnar worths of all other materials involved. Measured values existed for the worths of U-235 and sodium,[7] but it was necessary to use calculated worths of stainless steel (SS), molybdenum (Mo), and zirconium (Zr). The masses involved in the exchange are listed in Table I. The worth calculations for SS, Mo, and Zr were made with the CRAM diffusion theory code, employing "pseudo-three-dimensional," first-order, multigroup perturbation theory. The cross sections used were taken from a 24-group set,[9] collapsed to 8-energy groups weighted by region-averaged flux

TABLE III - REACTIVITY WORTH OF U-235 RELATIVE TO VOID

Measurement Position		Measured and Adjusted Reactivity Worths, Inhours/kg		
Subassembly Coordinate	Core Radius, cm	Measured U-235 for U-238 Replacement Worth	Measured* U-238 vs Void Worth	Adjusted U-235 vs Void Worth
POO-POO	0	78.0 ± 0.2	-2.6 ± 0.1	75.4 ± 0.4
NO2-POO	13.69	66.4 ± 0.2	-2.1 ± 0.1	64.3 ± 0.4
POO-PO1	6.84	75.8 ± 0.2	-2.5 ± 0.1	73.3 ± 0.5
POO-PO3	20.52	60.5 ± 0.2	-1.5 ± 0.2	59.0 ± 0.5
POO-PO4	27.36	46.7 ± 0.3	-0.7 ± 0.1	46.0 ± 0.5
POO-PO5	34.19	30.9 ± 0.5	+0.1 ± 0.1	31.0 ± 0.6
NO2-PO5	36.83	26.7 ± 0.3	+0.4 ± 0.1	27.1 ± 0.4
NO3-PO5	39.88	21.2 ± 0.3	+0.5 ± 0.1	21.7 ± 0.4
NO4-PO4	38.66	23.6 ± 0.3	+0.5 ± 0.1	24.1 ± 0.4

* Measured U-238 worth value depended upon minor components calculated by means of perturbation theory (Section IV, A.2).

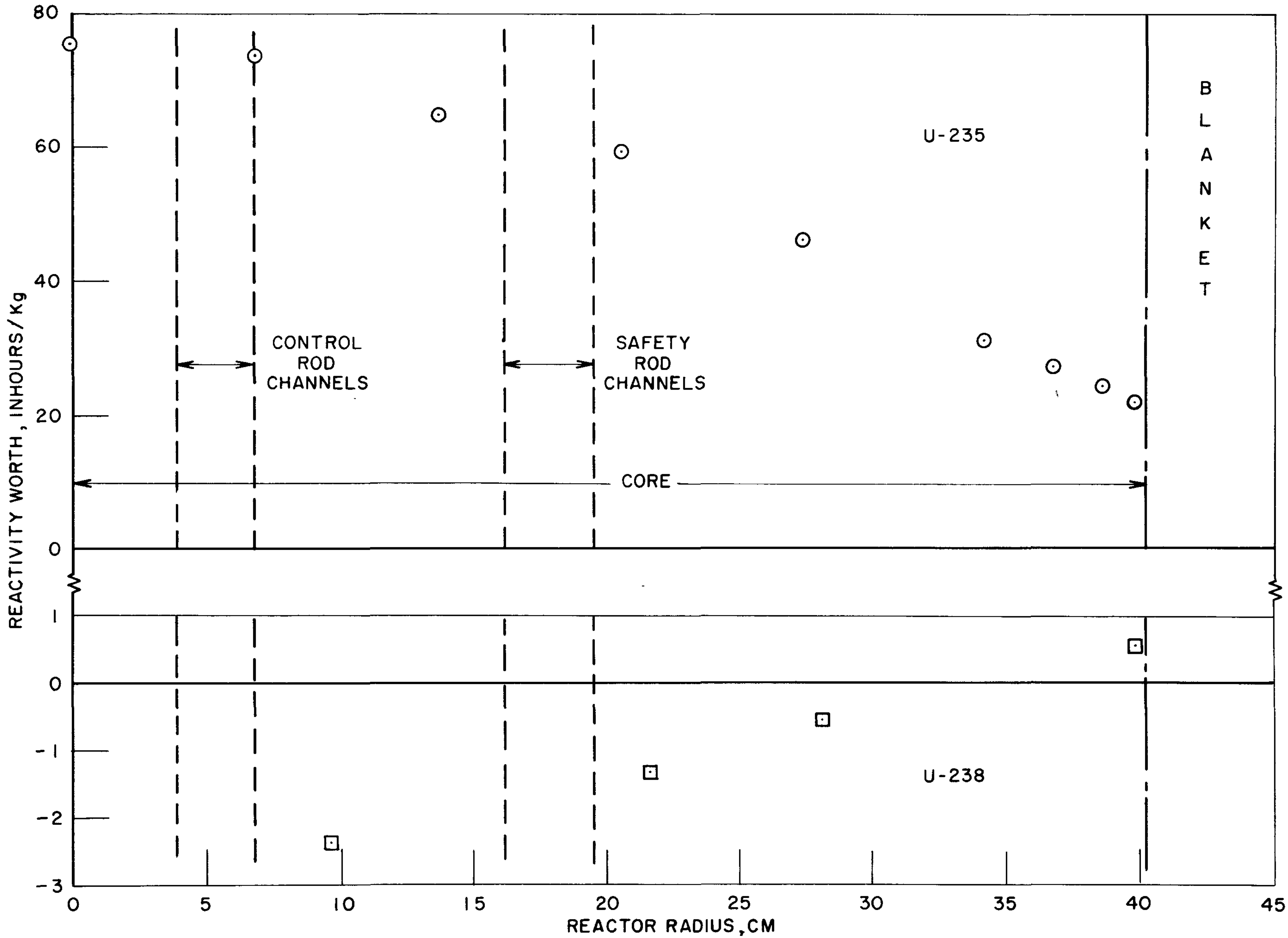


FIG. 11 CORRECTED COLUMNAR REACTIVITY WORTHS OF U-235 VERSUS VOID AND U-238 VERSUS VOID

TABLE IV - REACTIVITY MEASUREMENTS WITH PROOF-TEST AND DUMMY SUBASSEMBLIES IN THE CORE

Measurement No.	Subassembly Type Inserted	Core Position	Average Core Radius, cm	Measured Reactivity State,[a] Inhours						Mean Reactivity Difference Between Measurements A and B, Inhours
				Positive Period Measurements				Critical Rod Position Measurements	Mean of Period and Critical Rod Measurements	
				Keithley	Scaler 1	Scaler 2	Mean			
1A	Proof-Test			-113.78 ± 0.02	-113.81 ± 0.05	-113.82 ± 0.05	-113.80 ± 0.04	-113.46 ± 0.08	-113.63 ± 0.13	
		NO1-PO1	9.68							-56.59 ± 0.15
1B	Dummy			- 58.00 ± 0.06[b]	- 57.93 ± 0.10[b]	- 58.11 ± 0.06[b]	- 58.11 ± 0.07	- 56.06 ± 0.02	- 57.04 ± 0.07	
2A	Proof-Test			- 44.35 ± 0.05	- 44.25 ± 0.03	- 44.34 ± 0.03	- 44.31 ± 0.05	- 44.15 ± 0.02	- 44.23 ± 0.07	
		NO1-PO3	21.63							-35.1 ± 2.7
2B	Dummy			-	-	-	-	- 9.1 ± 2.7[c]	- 9.1 ± 2.7	
3A	Proof-Test			- 46.18 ± 0.03	- 46.16 ± 0.13	- 46.24 ± 0.01	- 46.19 ± 0.08	- 46.34 ± 0.06	- 46.27 ± 0.09	
		PO3-PO5	39.88							+ 9.84 ± 0.19
3B	Dummy			- 56.11 ± 0.08	- 56.52 ± 0.03	- 56.28 ± 0.06	- 56.30 ± 0.13	- 55.90 ± 0.05	- 56.10 ± 0.17	
4A	Proof-Test			- 86.08 ± 0.04	- 85.76 ± 0.02	- 86.01 ± 0.02	- 85.95 ± 0.10	- 85.42 ± 0.01	- 85.68 ± 0.19	
		PO1-PO4	28.20							-14.53 ± 0.32
4B	Dummy			- 71.55 ± 0.03	- 71.56 ± 0.13	- 71.44 ± 0.06	- 71.52 ± 0.09	- 70.78 ± 0.01	-71.15 ± 0.26	

a. The values shown are the measured excess reactivity states of the reactor, adjusted to the condition of full insertion of the regulating and shim control rods. The uncertainty indicated for each reactivity state prior to obtaining a mean valve represents only the nonsystematic or random component of the probable error. The averaging process incorporates the random errors and the systematic instrumental errors into the net probable error.

b. Values based on only one measurement; uncertainty based on mean uncertainty of all similar measurements.

c. Reactivity state determined by subcritical count rate analysis only. The uncertainty assigned was based on a statistical comparison of subcritical count rate predictions and final measured reactivity values for all other measurements in this test.

spectra. Similar calculations of U-238 worth were performed for comparison with the experimental values. Table V summarizes the step-by-step derivation of the U-238 versus void worths from the experimental and calculated worth values and includes a comparison of these values.

B. WORTH MEASUREMENTS IN THE BLANKET

The worth of a normal fuel subassembly versus a normal blanket subassembly was measured as a function of position in the inner radial blanket. In addition, the reactivity effect due to bunching of two adjacent fuel subassemblies in the IRB was measured. The difference in reactivity worths between two arbitrarily selected fuel subassemblies alternated in the same IRB lattice position was also measured.

The reactivity worths of normal blanket subassemblies versus dummy blanket subassemblies were determined in the IRB and in each of the first several rows of the outer radial blanket. This procedure effectively yielded the reactivity worth of the depleted uranium pins in a blanket subassembly as a function of the position.

1. Fuel Subassembly Worth Measurements in the Inner Radial Blanket

Table VI is a summary of the measured reactivity states from which fuel subassembly worths were derived in the IRB. This table includes the measured values of the reactivity state of the reactor for each isolated fuel subassembly substitution, or pair of substitutions, for blanket subassemblies in the IRB positions shown in Figure 7. Also included are the measured and linearly interpolated values (with time) of the reactivity state of the reference loading.

In this case, the fuel for blanket subassembly substitutions were not simple loading perturbations on the nominal reference loading and, therefore, the fuel worths could not be found directly by comparing the measurements with the reference reactivity. This was true because these reactivity measurements were made to provide loading guidelines and, in general, it was desired that they be isolated from fuel bunching effects within the IRB. However, the reference loading contained one core subassembly in the test octant of the IRB (position NO3-PO5). It was, therefore, necessary to replace this fuel subassembly with a blanket subassembly during all nonreference loading measurements. For this reason the substitutions merely served to establish the relative worths of fuel subassemblies in various IRB positions and the reference reactivity measurements only provided an arbitrary reactivity comparison at any given time for the reactivity state resulting from each substitution.

TABLE V - DERIVATION OF WORTHS OF U-238 VERSUS VOID

Quantity	Core Position			
	NO1-PO1	NO1-PO3	PO3-PO5	PO1-PO4
Average Core Radius, cm	9.68	21.63	39.88	28.20
Measured Reactivity Worth of Proof-Test vs Dummy Subassembly, inhours	-56.6 ± 0.2	-35.1 ± 2.7	+9.8 ± 0.2	-14.5 ± 0.3
Reactivity Worths of Contents of Proof-Test Subassembly Other Than U-238, inhours				
Measured Worths				
U-235 vs Void	+4.6 ± 0.0	+3.8 ± 0.0	+1.4 ± 0.0	+2.9 ± 0.0
Sodium vs Void	-7.2 ± 0.2	-7.8 ± 0.2	-8.8 ± 0.2	-7.8 ± 0.2
Sum	-2.6 ± 0.2	-4.0 ± 0.2	-7.4 ± 0.2	-4.9 ± 0.2
Calculated Worths				
SS vs Void	-0.1	+0.2	+2.1	+1.6
Mo vs Void	-10.0	-6.8	+2.4	-2.9
Zr vs Void	+0.2	+0.5	+3.0	+2.2
Sum	-9.9 ± 2.0	-6.1 ± 1.5	+7.5 ± 0.5	+0.9 ± 1.5
Total	-12.5 ± 2.0	-10.1 ± 1.5	+0.1 ± 1.5	-4.0 ± 1.5
Derived Worth				
U-238 vs Void, inhours per SA	-44.1 ± 2.0	-25.0 ± 3.1	+9.7 ± 1.5	-10.5 ± 1.5
Inhours, kg	-2.38 ± 0.11	-1.35 ± 0.17	+0.52 ± 0.08	-0.57 ± 0.08
Calculated Worth				
U-238 vs Void, inhours/kg	-2.58	-1.68	+0.46	-0.68

TABLE VI - FUEL SUBASSEMBLY REPLACEMENT WORTH MEASUREMENTS IN THE INNER RADIAL BLANKET

Measurement No. and IRB Position	Average Radius, cm	Date-Time	Measured Reactivity State, Inhours[a]: Positive Period Measurements: Keithley	Positive Period Measurements: Scaler 1	Positive Period Measurements: Scaler 2	Critical Rod Position Measurements	Reactivity State Relative to Reference, Inhours[a]: Positive Period Measurements: Keithley	Positive Period Measurements: Scaler 1	Positive Period Measurements: Scaler 2	Positive Period Measurements: Mean	Critical Rod Position Measurements	Mean of Period and Critical Rod Measurements
1 (Reference) NO3-PO5		Mar 11 2130	- 41.81 ± 0.33	- 41.32 ± 0.42	- 41.19 ± 0.27	- 41.47 ± 0.15						
2 NO5-PO5	48.37	Mar 12 0840	- 97.17 ± 0.01 (-41.74 ± 0.30)[b]	- 97.35 ± 0.10 (-41.27 ± 0.37)	- 97.25 ± 0.02 (-41.19 ± 0.27	- 96.87 ± 0.05 (-41.41 ± 0.13)	- 55.43 ± 0.30	- 56.08 ± 0.38	- 56.06 ± 0.27	- 55.86 ± 0.44	- 55.46 ± 0.14	- 55.66 ± 0.38
3 NO3-PO6	45.88	Mar 12 1810	- 85.86 ± 0.16 (-41.69 ± 0.28)	- 85.64 ± 0.10 (-41.24 ± 0.35)	- 85.64 ± 0.29 (-44.20 ± 0.21)	- 86.65 ± 0.05 (-41.37 ± 0.12)	- 44.17 ± 0.32	- 44.40 ± 0.38	- 44.44 ± 0.36	- 44.34 ± 0.37	- 45.28 ± 0.13	- 44.81 ± 0.55
4 NO4-PO5	43.80	Mar 13 0900	- 70.79 ± 0.07 (-41.60 ± 0.26)	- 70.75 ± 0.15 (-41.17 ± 0.29)	- 70.86 ± 0.16 (-41.20 ± 0.21)	- 70.13 ± 0.02 (-41.30 ± 0.10)	- 29.19 ± 0.27	- 29.58 ± 0.33	- 29.66 ± 0.26	- 29.48 ± 0.35	- 28.83 ± 0.10	- 29.16 ± 0.41
5 NO1-PO6	41.61	Mar 13 1740	- 56.61 ± 0.05 (-41.54 + 0.26)	- 56.53 ± 0.02 (-41.12 ± 0.25)	- 56.37 ± 0.02 (-41.20 ± 0.21)	- 55.86 ± 0.08 (-41.26 ± 0.09)	- 15.07 ± 0.27	- 15.41 ± 0.21	- 15.17 ± 0.21	- 15.22 ± 0.28	- 14.60 ± 0.12	- 14.91 ± 0.38
6 (Reference) NO3-PO5		Mar 16 0900	- 41.16 ± 0.41	- 40.87 ± 0.23	- 41.22 ± 0.29	- 40.98 ± 0.02						
7 NO2-PO6	43.26	Mar 16 1645	- 68.14 ± 0.02 (-41.11 ± 0.38)	- 67.87 ± 0.02 (-40.83 ± 0.22)	- 68.00 ± 0.07 (-41.13 ± 0.26)	- 67.36 ± 0.03 (-40.91 ± 0.02)	- 27.03 ± 0.38	- 27.04 ± 0.22	- 26.87 ± 0.27	- 26.98 ± 0.31	- 26.45 ± 0.04	- 26.72 ± 0.35
8 PO0-PO6	41.04	Mar 17 0830	- 50.54 ± 0.14 (-41.00 ± 0.31)	- 50.54 ± 0.02 (-40.76 ± 0.21)	- 50.43 ± 0.05 (-40.95 ± 0.22)	- 49.80 ± 0.03 (-40.77 ± 0.02)	- 9.54 ± 0.34	- 9.78 ± 0.21	- 9.48 ± 0.23	- 9.60 ± 0.30	- 9.03 ± 0.04	- 9.32 ± 0.36
9 NO1-PO6	41.61	Mar 17 1530	- 57.37 ± 0.07 (-40.95 ± 0.28)	- 57.30 ± 0.11 (-40.73 ± 0.22)	- 57.24 ± 0.04 (-40.87 ± 0.21)	- 56.70 ± 0.05 (-40.71 ± 0.03)	- 16.42 ± 0.29	- 16.57 ± 0.25	- 16.37 ± 0.21	- 16.45 ± 0.27	- 15.99 ± 0.06	- 16.22 ± 0.30
10[c] Secondary Reference	-	Mar 18 0845	-263.43 ± 0.10 (-40.82 ± 0.24)	-263.23 ± 0.22 (-40.65 ± 0.27)	-263.30 ± 0.08 (-40.67 ± 0.20)	-263.50 ± 0.05 (-40.56 ± 0.04)	-222.61 ± 0.26	-222.58 ± 0.35	-222.63 ± 0.22	-222.61 ± 0.28	-222.94 ± 0.06	-222.77 ± 0.26
11[c] No. 1, PO0-PO6 No. 2, NO1-PO6	41.04 41.61	Mar 18 1830	- 77.63 ± 0.06 (-40.75 ± 0.23)	- 77.40 ± 0.05 (-40.60 ± 0.32)	- 77.36 ± 0.07 (-40.56 ± 0.21)	- 77.00 ± 0.02 (-40.48 ± 0.05)	- 36.88 ± 0.24	- 36.80 ± 0.32	- 36.80 ± 0.22	- 36.83 ± 0.39	- 36.52 ± 0.05	- 36.68 ± 0.32
12[c] NO3-PO5	39.88	Mar 19 0915	-161.73 ± 0.20 (-40.65 ± 0.25)	-161.74 ± 0.01 (-40.53 ± 0.39)	-161.74 ± 0.01 (-40.40 ± 0.23)	-160.42 ± 0.03 (-40.34 ± 0.06)	-121.08 ± 0.32	-121.21 ± 0.40	-121.34 ± 0.23	-121.21 ± 0.34	-120.08 ± 0.07	-120.65 ± 0.62
13 (Reference) NO3-PO5		Mar 19 2030	- 40.57 ± 0.28	- 40.48 ± 0.45	- 40.27 ± 0.27	- 40.25 ± 0.07						

a. The values shown are the measured excess reactivity states of the reactor adjusted to the fully inserted condition of the regulating and shim control rods.
The uncertainty indicated for each reactivity state prior to obtaining a mean value represents only the random component of the probable error. The averaging process incorporates the probable random error and systematic instrumental errors into the net probable error.

b. Quantities in parentheses represent values of the interpolated reference reactivity state of the reactor.

c. These measurements were made at a less reactive core loading than the others.

To obtain the desired fuel versus IRB subassembly worths, it was necessary to establish the worth of the IRB fuel subassembly relating to the reference loading. This was done in measurement steps 10 and 12 which, as a matter of convenience, were made at a less reactive core loading than the other measurements. The less reactive core loading was necessary to allow a large, safe, single step reactivity insertion in measurement No. 11, where two subassemblies were substituted simultaneously for adjacent subassemblies in the IRB. The reactivity state, measured in step 10 was defined as the secondary reference, and through it the less reactive core loading was related to the primary nominal reference reactivity.

Table VI summarizes the reactivity values of all loadings, relative to the primary reference reactivity, along with the probable error associated with each value based upon a statistical analysis of data scatter. These relative worths, therefore, give the difference in worth between a fuel subassembly located in the various test IRB positions compared with the worth of a fuel subassembly in the reference reactivity IRB position, NO3-PO5. To obtain the absolute worths of the fuel-for-blanket subassembly substitutions in the IRB, the worth of the fuel subassembly in position NO3-PO5 (obtained by taking the difference between the reactivities of steps 10 and 12) was added to these values. These absolute worths are summarized in Table VII; a comparison between the worths resulting from the substitution of two different arbitrarily selected fuel subassemblies (Numbers 1 and 2) in IRB position NO1-PO6 is also given. The worth difference of 1.3 inhours, or 1.5 per cent, is mostly attributable to a U-235 mass deficit of 1.14 per cent in subassembly No. 2 (relative to subassembly No. 1). The reactivity increment beyond that attributable to U-235 content cannot be considered to be significant when compared to the experimental errors. In measurement No. 11, the bunched reactivity worth of two fuel subassemblies inserted in adjacent IRB positions is shown to exceed the sum of the two isolated worths in these positions by 6.1 inhours, or 3.4 per cent.

As an aid to test planning, predictions had first been made of the worth of fuel and IRB subassemblies by the fairly approximate means of radially extrapolating U-235 versus U-238 reactivity worth data obtained from the ZPR-III critical assembly mockup of the Fermi Core A.[8] The worths of other subassembly materials such as stainless steel, zirconium, and molybdenum had been calculated, and when found to be relatively small were ignored. The resulting predictions appear in Table VII for comparison with the measured values. A graphical comparison is made in Figure 12, where it will be noted that the slope of the predicted worth curve closely agrees with that of the measured curve although the magnitudes differ by about 10 per cent. This difference is primarily due to the greater core radius of Core A relative to its mockup on ZPR-III (see Section IV, A.1) and the accompanying radial displacement of the worth curve in the inner radial blanket.

TABLE VII - MEASURED AND CALCULATED REACTIVITY CHANGES DUE TO FUEL-FOR-INNER RADIAL BLANKET SUBASSEMBLY SUBSTITUTIONS

Measurement No.	IRB Position	Average Radius, cm	Fuel Subassembly No.	Measured Reactivity Change, ih	Remarks	Predicted Reactivity Change, inhours: ZPR-III Crit Experiment Data[a]	Predicted Reactivity Change, inhours: Perturbation Theory Calculation[b]
2	NO5-PO5	48.37	1	46.46 $\pm$ 0.77		37	52.1
3	NO3-PO6	45.88	1	57.31 $\pm$ 0.87		52	65.3
4	NO4-PO5	43.80	1	72.96 $\pm$ 0.79		66	81.0
5	NO1-PO6	41.61	1	87.21 $\pm$ 0.77	Compare with Measurement No. 9	81	95.5
7	NO2-PO6	43.26	1	75.40 $\pm$ 0.76		69	82.8
8	POO-PO6	41.04	1	92.80 $\pm$ 0.76		86	99.9
9	NO1-PO6	41.61	2	85.90 $\pm$ 0.74	Compare with Measurement No. 5	80	94.4
10 & 12	NO3-PO5	39.88	1	102.12 $\pm$ 0.67		93	110.6
11	POO-PO6 NO1-PO6	41.04 41.61	1 2	186.09 $\pm$ 0.41	Compare with the sum of Measurements No. 5 and 8 (180.01 $\pm$ 1.08 ih)	-	-

a. Predictions based upon radially extrapolated U-235 versus U-238 worth data from ZPR-III critical assembly mockup.

b. Cylindrical (R, Z) model results synthesized with (X, Y) model results; differences in axial blanket zone compositions were ignored.

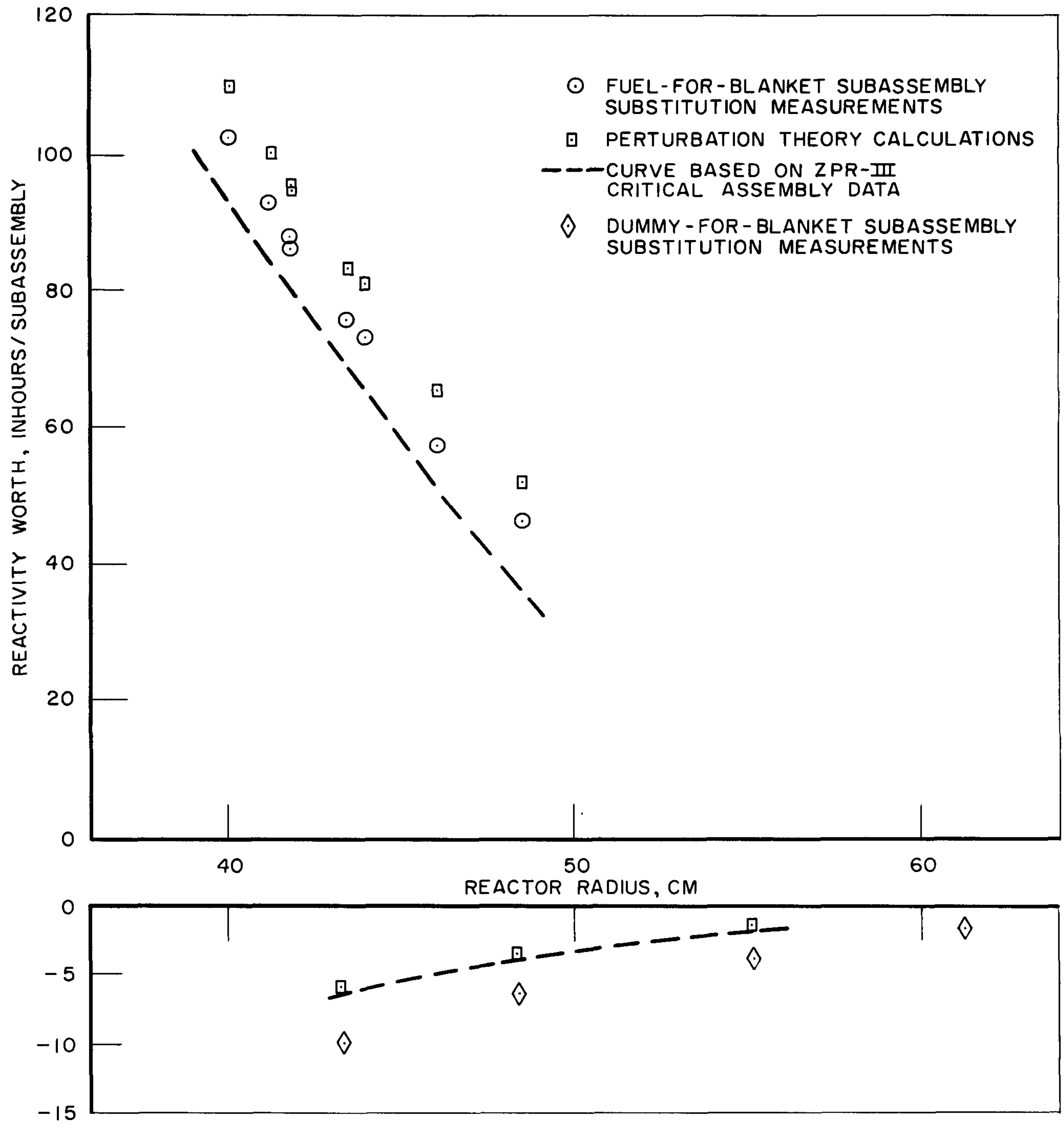


FIG. 12 MEASURED VERSUS PREDICTED WORTHS IN THE RADIAL BLANKET

Also shown in Table VII and Figure 12 are the results of "pseudo-three-dimensional" (combined 2-dimensional analyses), first-order perturbation theory calculations using the CRAM diffusion theory code. The 24-group cross sections[9] were collapsed to 8-energy groups weighted by region-averaged flux spectra. All materials in the two subassembly types were included in the calculations. However, the compositional differences in the axial blanket zones of the two subassembly types were ignored since their reactivity effects are both small and difficult to calculate. Predictions were not made of the two-subassembly bunching effect in the IRB.

2. Blanket Subassembly Worth Measurements

The reactivity measurements made with blanket dummy subassemblies replacing normal blanket subassemblies are summarized in Table VIII (see Figure 8 for the subassembly portions). Also given is a comparison between the measured reactivity state resulting from each set of substitutions and the measured reactivity state of the reference loading. The reference reactivity, which changed slightly with time, was inferred at any given time by linear interpolation between the measured values obtained before and after the series of substitution measurements. Finally, the total reactivity change relative to the reference reactivity was converted to the reactivity change per subassembly used in the substitutions. The probable errors given in Table VIII were based on a statistical analysis of the data scatter. The probable errors for the interpolated values of the reference reactivity state do not include any component to account for deviations from linearity with time.

Prior to the measurements, relatively crude predictions were made of the expected worths for each substitution. They were based on the Core A critical studies made on ZPR-III.[8] Refined predictions based on the critical experiment data were not possible due to the absence of sodium worth data in the blanket; aluminum worth data were used to simulate the worth of sodium. Aluminum density extrapolations were required, as were columnar height extrapolations for the worths of both depleted uranium and aluminum. Consequently, as can be seen in Table IX and Figure 12, the predictions do not agree well with the measured values.

For purposes of comparison, Table IX and Figure 12 include a second set of calculated worths, which were obtained with the CRAM diffusion code, employing two-dimensional (R, Z), first-order perturbation theory. These calculated worths include sodium and all subassembly materials; i.e., U-235, U-238, stainless steel, molybdenum, and zirconium. The calculations--utilizing 8-group cross sections collapsed from 24 groups weighted by means of region-averaged flux spectra--were performed after the measurements were made to test the ability of such codes to predict columnar worths in blanket regions. The lack of agreement with the measured worths is rather disappointing. It is attributed primarily to poor cross-section data, especially for sodium, rather than to inadequacy of the calculational method.

TABLE VIII - MEASUREMENT OF DUMMY-FOR-BLANKET SUBASSEMBLY REPLACEMENT WORTHS

			Measured Reactivity State, Inhours[a]				Reactivity State Relative to Reference, Inhours[a]						
			Positive Period Measurements				Positive Period Measurements						
Measurement No. (Blanket Positions)	Average Radius, cm	Date-Time	Keithley	Scaler 1	Scaler 2	Critical Rod Position	Keithley	Scaler 1	Scaler 2	Mean	Critical Rod Position Measurement	Mean of Period and Control Rod Measurements	Reactivity Change per Dummy Subassembly, Inhours
1 (Reference)		Mar 19 2030	-40.57 ± 0.28	-40.48 ± 0.45	-40.27 ± 0.27	-40.25 ± 0.07							
2	43.26	Mar 20 0840	-79.17 ± 0.00	-79.12 ± 0.13	-79.14 ± 0.06	-78.54 ± 0.04	-38.61 ± 0.25	-38.67 ± 0.42	-38.87 ± 0.24	-38.72 ± 0.33	-38.26 ± 0.07	-38.49 ± 0.33	-9.62 ± 0.08
(PO2-PO6, NO2-PO6 NO2-NO6, PO2-NO6)			(-40.56 ± 0.25)[b]	(-40.45 ± 0.40)[b]	(-40.27 ± 0.23)	(-40.28 ± 0.06)							
3	48.37	Mar 21 1150	-77.94 ± 0.02	-77.70 ± 0.07	-77.70 ± 0.03	-77.14 ± 0.03	-37.39 ± 0.21	-37.30 ± 0.33	-37.44 ± 0.18	-37.38 ± 0.26	-36.79 ± 0.06	-37.09 ± 0.35	-6.18 ± 0.06
(NO1-NO7, PO1-NO7 NO1-PO7, PO1-PO7 PO5-PO5, NO5-NO5)			(-40.55 ± 0.21)	(-40.40 ± 0.32)	(-40.27 ± 0.18)	(-40.35 ± 0.05)							
4	55.15	Mar 23 0835	-70.15 ± 0.03	-70.08 ± 0.13	-70.02 ± 0.01	-69.25 ± 0.04	-29.63 ± 0.11	-29.79 ± 0.10	-29.76 ± 0.10	-29.72 ± 0.16	-28.78 ± 0.06	-29.25 ± 0.49	-3.66 ± 0.06
(PO7-PO4 and 7 symmetrical positions)			(-40.52 ± 0.11)	(-40.30 ± 0.17)	(-40.26 ± 0.10)	(-40.47 ± 0.05)							
5	61.28	Mar 24 0830	-56.46 ± 0.11	-56.46 ± 0.05	-56.66 ± 0.14	-55.23 ± 0.02	-15.96 ± 0.13	-16.21 ± 0.10	-16.34 ± 0.15	-16.17 ± 0.20	-14.70 ± 0.05	-15.44 ± 0.75	-1.40 ± 0.07
(PO9-PO0, PO0-PO9, NO9-PO0, PO8-PO4 and 7 symmetrical positions)			(-40.50 ± 0.06)	(-40.25 ± 0.09)	(-40.26 ± 0.06)	(-40.53 ± 0.05)							
6 (Reference)		Mar 25 1035	-40.49 ± 0.04	-40.20 ± 0.06	-40.26 ± 0.05	-40.60 ± 0.05							

a. The values shown are the measured excess reactivity states of the reactor adjusted to the condition of full insertion of the regulating and shim control rods.
The uncertainty indicated for each reactivity state prior to averaging represents only the random component of the probable error. The random errors and systematic instrumental errors are combined in the averaging process to obtain the net probable error.

b. Quantities in parentheses represent interpolated values of the reference reactivity state of the reactor.

TABLE IX - MEASURED AND PREDICTED REACTIVITY CHANGES DUE TO DUMMY-FOR-BLANKET SUBASSEMBLY SUBSTITUTIONS

Measurement No.	Average Radius of Substituted Subassemblies, cm	Reactivity Worth of a Dummy vs a Blanket Subassembly, inhours		
		Measured	Predicted	
			ZPR-III Crit Assembly	Perturbation Theory
2	43.26	9.62 ± 0.08	-6.4	-6.04
3	48.37	6.18 ± 0.06	-3.9	-3.62
4	55.15	3.66 ± 0.06	-1.9	-1.46
5	61.28	1.40 ± 0.07	-	-1.22

V. CONCLUSIONS

The objectives of this test were achieved in a highly satisfactory manner. All desired reactivity worth data for core and blanket subassemblies and their constituent materials were obtained with a high degree of accuracy. The data obtained in this test will permit the precise planning of future operational reactivity adjustments and will serve as a guide for any major revisions in loading and/or composition of either the core or blanket regions. The precision of these data also enhances their value in providing checks for refined calculational technqiues.

The reactivity predictions for the test, although based on the data from a clean critical assembly mockup only marginally adequate to describe the larger Fermi core, permitted sufficient accuracy to permit efficient planning of reactor operations to be made for each series of measurements. Single and combined sets of two-dimensional perturbation theory analyses made after the test provided close agreement with the measurements in all cases except for the outer radial blanket subassembly worths. Calculated columnar U-235 and U-238 worths in the core were uniformly over-predicted by about 10 per cent, which is regarded as representing adequate agreement. However, this over-prediction indicates that the basic group cross sections are in need of refinement. Apparently, the worth of sodium in the blanket was over-predicted also, leading to under-prediction of blanket versus dummy subassembly worths. The close agreement between the calculated and measured reactivity worth gradients in the vicinity of compositional discontinuities has offered strong support of the validity and capability of the multi-dimensional application of perturbation theory.

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