ENRICO FERMI ATOMIC POWER PLANT

NUCLEAR TEST SERIES

APDA - NTS - 4

INVESTIGATION OF CORE REPRODUCIBILITY OF THE ENRICO FERMI REACTOR

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APRIL 1965

ATOMIC POWER

DEVELOPMENT ASSOCIATES, INC.

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 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

The reproducibility of the Enrico Fermi reactor core was studied by means of nuclear measurements made during the period October 19 to 23, 1963. In the test, the fuel subassembly hold-down mechanism was raised, rotated, and returned to its original operating position a number of times. Critical rod and positive period reactivity measurements were made after each movement to determine whether any significant core perturbation resulted from operation of the hold-down mechanism. The primary purpose of the test was to determine whether an experimental error due to the movement of the hold-down mechanism will occur in those nuclear tests where fuel handling is required.

The test results show that no significant change in the reactivity state of the reactor was caused by movement of the hold-down mechanism. The test, therefore, verified that the core configuration was highly reproducible, and that no error due to hold-down movement will occur in subsequent nuclear tests. These results are consistent with those obtained earlier in the preoperational tight-core test. The tight-core test consisted of mechanical measurements made under preoperational reactor conditions. In the tight-core test, it was found that the core was tight to within $\pm$ 1 mil on the average core diameter. The results of the nuclear measurements made in this test, under actual reactor operating conditions, indicated that the reactivity is reproducible to within $\pm$ 0.35 cents. This also corresponds to a change in the average core diameter of about $\pm$1 mil.

I. PURPOSE OF TEST

The reproducibility of the Enrico Fermi reactor core was studied to determine whether any significant change in the reactivity state of the reactor occurred when the fuel subassembly hold-down mechanism (HDM) was raised, rotated, and then returned to its original operating position. These data are necessary for evaluation of those subsequent nuclear tests in which fuel loading changes will be made and the reactivity effect of the changes will be measured. Because the HDM will be operated during these tests, it is important to be certain that the reactivity effect measured will be due only to the perturbation made in the core loading. In the core reproducibility test, therefore, the reproducibility of the relative position of the fuel subassemblies in the core was checked after hold-down movement. If a significant nonreproducibility was found, as indicated by a change in the reactivity state of the reactor, this would have to be incorporated as an additional source of experimental error in those nuclear tests which require hold-down mechanism operation.

Core tightness had been checked earlier in tests made during the reactor preoperational test program.[1] In the tight-core test, mechanical measurements of core tightness were made in an air atmosphere at an ambient temperature, with dummy subassemblies in the reactor. Therefore, the core reproducibility results obtained in this test by means of nuclear measurements made in sodium at a temperature of 517 F with fuel subassemblies in the reactor, could also be compared to the tight-core test results to determine whether general agreement with those results existed. Core tightness is important because it assures that the reactivity effects due to subassembly bowing and radial core expansion will be negative.

The data obtained in the test also allowed an indirect estimate to be made of the experimental error associated with critical rod and positive period reactivity measurements.

II. DESCRIPTION OF THE ENRICO FERMI REACTOR AND ITS FUEL SUPPORT SYSTEM

A. GENERAL DESCRIPTION

A detailed description of the Enrico Fermi fast breeder reactor is given in the Enrico Fermi Atomic Power Plant Hazards Summary Report.[2] The reactor and its associated structures are shown in perspective in Figure 1. Figure 2 is a cross-sectional view of the reactor core and blanket.

The reactor is contained in a cylindrical stainless steel reactor vessel sealed at the top by a rotating shield plug made of borated graphite and steel. The shield plug supports the control rod mechanisms, the fuel subassembly hold-down mechanism (HDM), and an offset fuel-handling mechanism (OHM). The rotating shield plug is used in conjunction with the OHM to load and unload the reactor fuel. The primary function of the HDM is to prevent the subassemblies located in the central lattice positions, that are fed from a high-pressure plenum, from being lifted by the pressure drop from the sodium coolant flowing through the core. The HDM also serves as a guide for the control rod drives. When the HDM is lowered into operating position it gathers the subassemblies together to form a tight core.

The reactor is controlled by two operating control rods and seven installed safety rods located near the center of the reactor. Provision for an eighth rod has been included in the design and construction of the reactor. The rods are driven and actuated from the top. They are all of the poison type, containing boron carbide (B_4C) in which the boron is enriched in boron-10 (B-10). The two control rods have reactivity worths of approximately 46 cents each. The seven safety rods are worth more than $1.00 each.

B. FUEL ARRANGEMENT IN THE LOWER REACTOR VESSEL

The core and blanket subassemblies are located in the lower reactor vessel in a square lattice, and are arranged to approximate a cylinder about 80 inches in diameter by 70 inches high. There is a total of 149 central core lattice positions (Figure 2) that are occupied by core and inner radial blanket subassemblies, the neutron source, and the 10 control rod and safety rod channels. All of these positions are supplied with sodium coolant flowing upwards from a high-pressure plenum. The lattice positions surrounding the inner radial blanket contain the outer radial blanket subassemblies. Beyond the outer radial blanket are lattice positions used for stainless steel filled thermal shield bar subassemblies which 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.

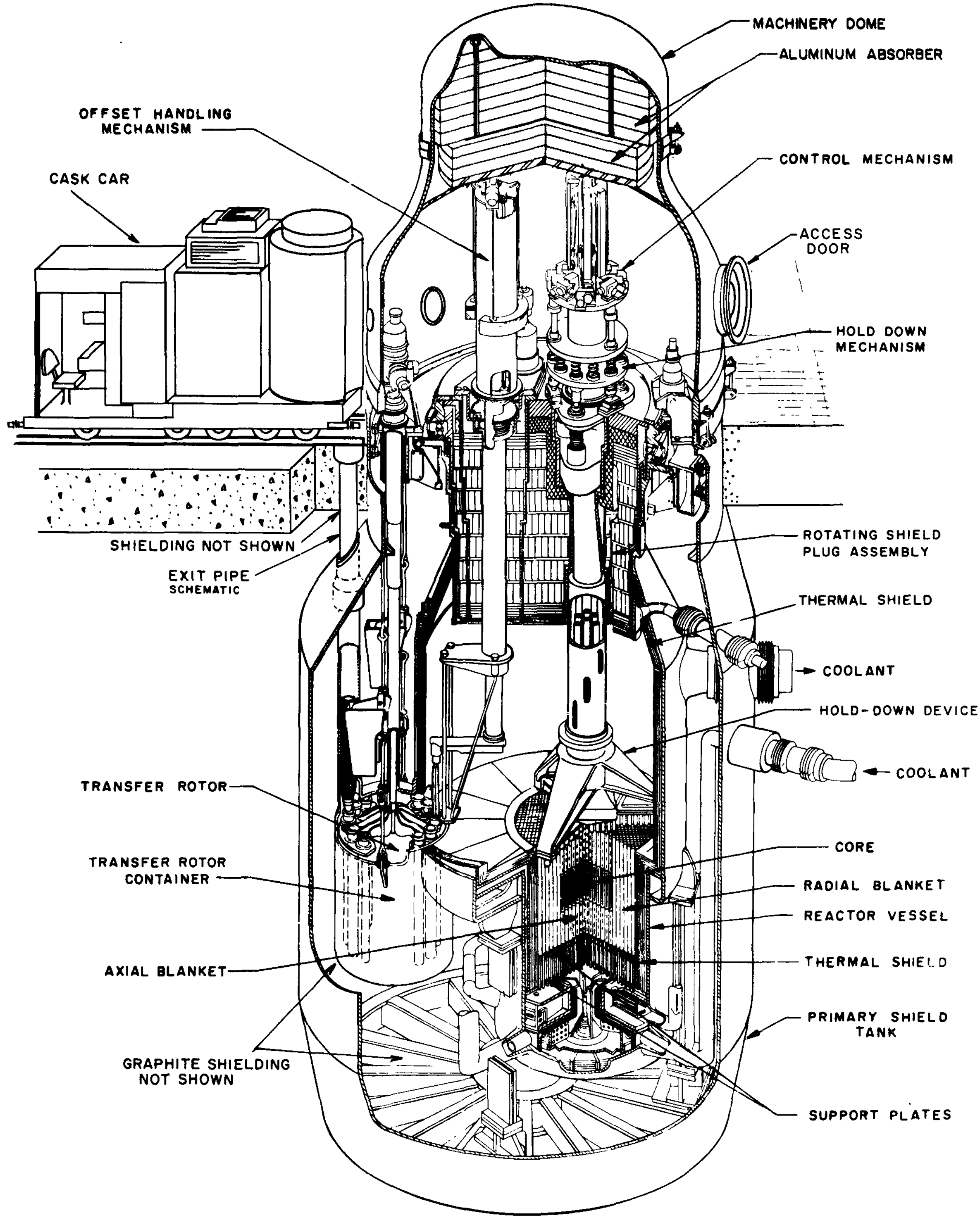


FIG. I - PERSPECTIVE VIEW OF REACTOR

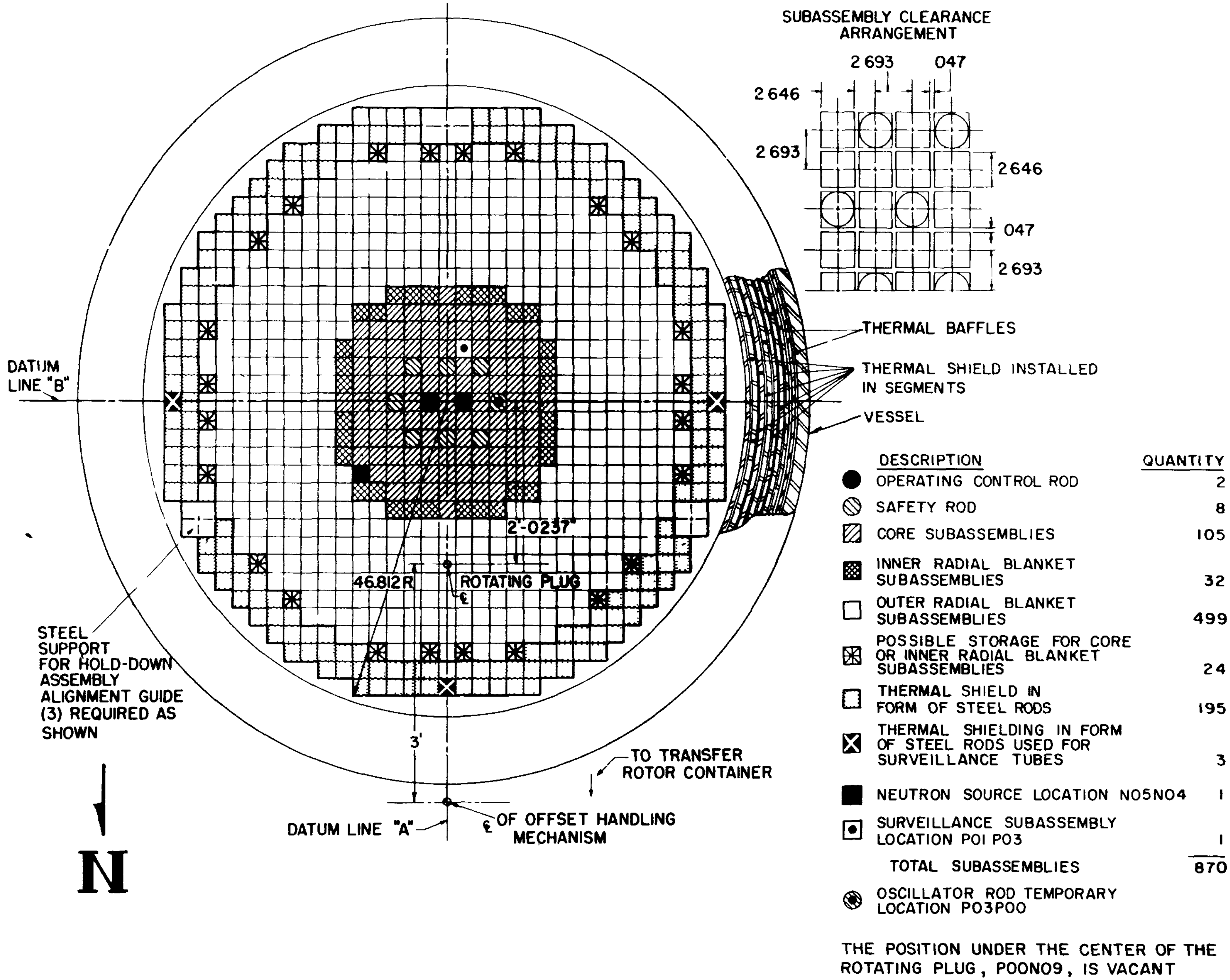


FIG. 2-REACTOR CROSS SECTION

The core subassembly design is shown in Figure 3. Both the core and inner radial blanket subassemblies have exterior spacer pads located on their subassembly wrapper cans a few inches above the core midplane. These spacers prevent the subassemblies from bowing toward the center of the reactor when subjected to a radial thermal gradient. Inward bowing of the subassemblies would create a positive power coefficient of reactivity.

The two support plates in the lower reactor vessel provide the basic definition of the reactor lattice. The support plates are 2 inches thick and are spaced 14 inches apart. The subassemblies are supported in the lattice at their lower ends by the support plates (Figure 4). Each core and blanket subassembly has an 18-inch-long nozzle attached to its base for insertion in the holes provided in the two support plates. The holes in both support plates are spaced in a square array on 2.693-inch centers and their diameters correspond to the subassembly nozzle diameters. Since the support plates provide positive support only along the lower portions of the subassemblies, the upper ends of the subassemblies have a slight tendency to lean outwards when the hold-down mechanism is not down in place.

C. HOLD-DOWN MECHANISM

The central lattice positions used for core subassemblies, inner radial blanket subassemblies, and control elements are supplied with sodium coolant flowing upward from the high-pressure plenum. Because of the high pressure drop, subassemblies located in this region require downward mechanical restraint, in addition to their own weight, to prevent their ejection from the lower support plates; this restraint is provided by the hold-down mechanism. The lattice positions occupied by the outer radial blanket and shielding subassemblies are supplied with sodium coolant from the low-pressure plenum and the pressure drop force acting on these subassemblies is less than their weight; therefore, no mechanical restraint is required.

The hold-down mechanism (Figure 5) is mounted on the rotating shield plug located in the neck of the reactor vessel and is comprised of the hold-down plate spider assembly and the hold-down actuator assembly. The actuator assembly provides the reaction force to the hold-down spider assembly necessary to resist the upward hydraulic forces. The restraining force on the subassemblies is administered by means of hold-down fingers, attached to a hold-down plate, which engage the subassembly handling heads and restrain the subassemblies both vertically and horizontally. The force is supplied by a drive motor and ball-screw drives acting through a set of springs which transmit the force to the hold-down plate. The actuator assembly is also used to raise the hold-down plate during refueling operations. During these operations, the hold-down plate is raised approximately

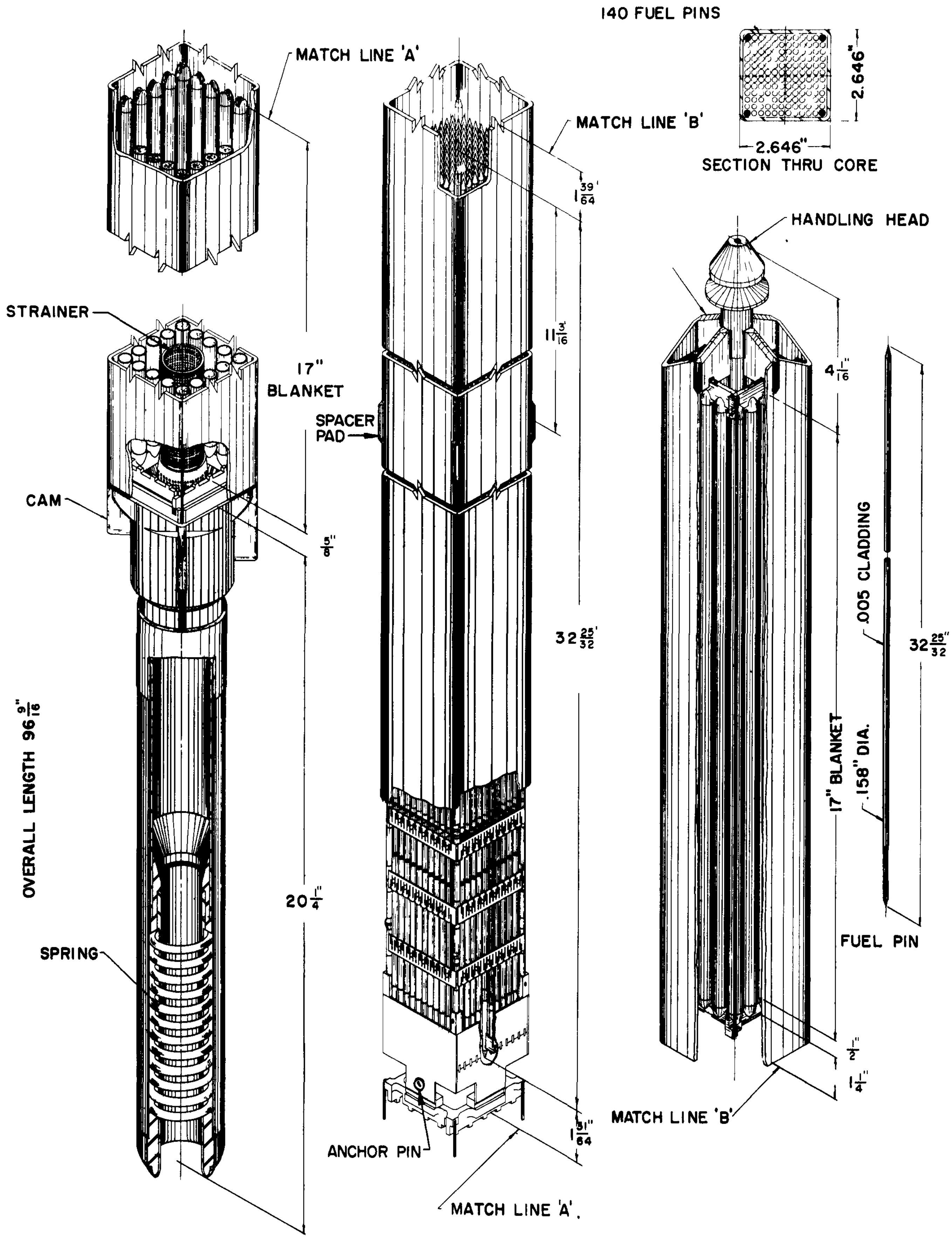


FIG. 3 - CORE SUBASSEMBLY DESIGN

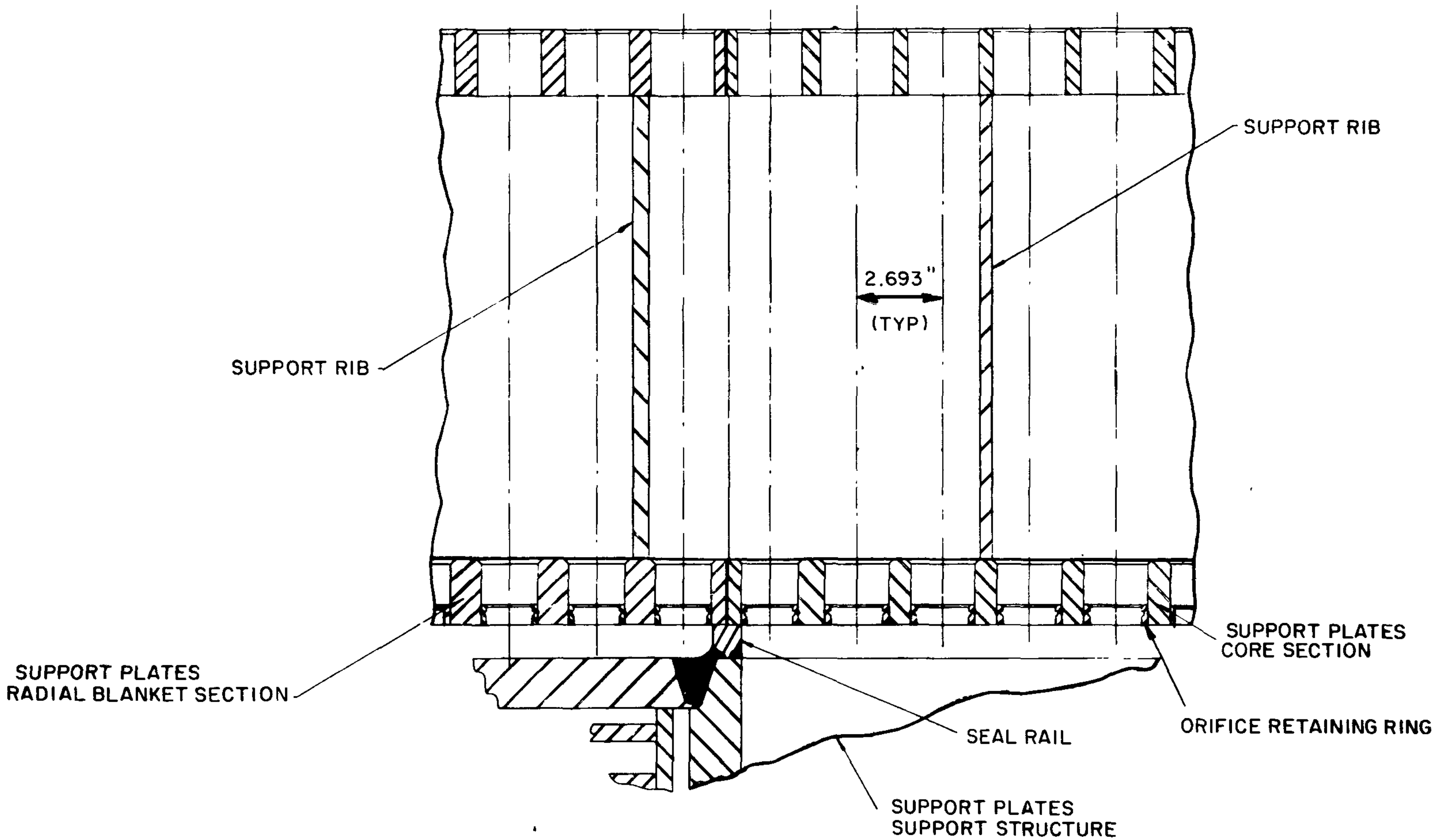


FIG. 4 - PARTIAL SECTION THROUGH SUPPORT PLATES

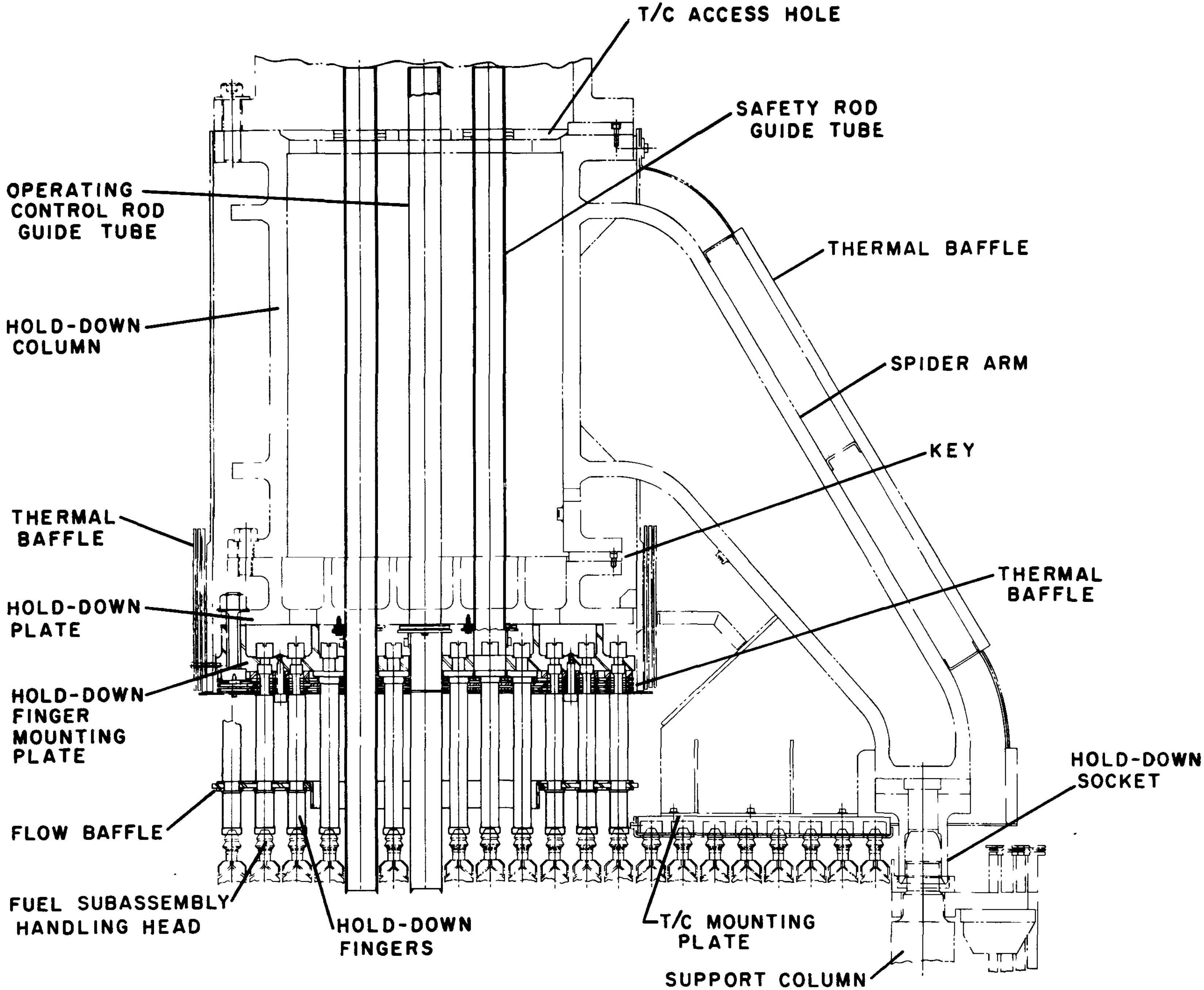


FIG.5 - HOLD-DOWN MECHANISM

9 inches to clear the tops of the subassemblies, thus permitting the shield plug to be rotated.

The hold-down mechanism also provides support for the upper ends of the subassemblies. The method of support used assures that a tight core will exist during reactor operation. This was accomplished by designing the HDM with a slight inward offset of the hold-down fingers and with the pitch for the spacing between the cups in the fingers being less than that for the lower support plate and the subassembly spacer pads. Thus, when the HDM is lowered into position and the fingers engage the subassembly handling heads, the tendency of the subassemblies to lean outwards at their upper ends is overcome. As the HDM is lowered further, the subassemblies are gathered together to form a tight core, assuring that full contact will exist between adjacent subassembly spacer pads during reactor operation at all power levels. The total amount of gathering is approximately 42 mils on the core radius at the elevation of the handling heads, and 20 mils on the core radius at the core midplane.

III. EXPERIMENTAL PROCEDURE

A. DESCRIPTION OF THE TEST

The core reproducibility test for the Enrico Fermi reactor was carried out in accordance with a detailed test procedure.[3] This procedure was the basis used by the reactor operating staff for the preparation of an operating guide for the conduct of the test.

The reactivity changes due to movement of the HDM were investigated by making a series of HDM movements and taking critical rod and positive period reactivity measurements after each movement. Thus, any changes in the reactivity state of the reactor because of core nonreproducibility would be evidenced by a change in the critical rod and positive period reactivity data after hold-down movement. Two critical rod and two positive period measurements were made after each movement to improve the statistical accuracy of the data.

The test consisted of a series of seven separate sets of reactivity measurements. First, to obtain an arbitrary reactivity base, the reactivity state of the reactor was determined with the HDM down. Next the HDM was raised and the shield plug was rotated 20 to 30 degrees away from its operating position, the shield plug was returned and the hold-down mechanism was lowered to its original operating position; reactivity measurements were taken. This specific HDM operation was repeated five times and reactivity measurements were obtained after each operation. One last reactivity measurement was made after the HDM was raised and lowered with the plug rotation eliminated.

The reactor temperature was measured whenever a critical rod or positive period reactivity measurement was taken so that the data could be corrected for temperature-reactivity feedback due to temperature drift. Also, the power drift rate was measured at the time of the critical rod measurements and the critical data was corrected accordingly. Because a retractable neutron source was installed in the reactor during the test (Section III, C. 1), source reactivity effects were negligible and had no effect on the data.

1. Base Reactivity Measurement

The steps followed in making the initial arbitrary base reactivity measurement for the test were as follows:

(a) With the reactor shut down (all safety and control rods fully inserted) and the hold-down mechanism in its operating down position, the primary sodium flow rate was adjusted to the equilibrium value (~6.0 x 10^6 lb/hr*) required to maintain an isothermal reactor temperature of ~517 F with minimum drift.

(b) The safety rods were fully withdrawn, the shim rod was withdrawn 5 inches, and the reactor was brought to criticality on the regulating rod at a power level of approximately 500 watts. The neutron source was then retracted and slight adjustments were made in the critical regulating rod position to account for its withdrawal. The critical regulating rod position was measured (~7-1/4-inch elevation), as were the primary sodium flow rate, the reactor temperature, the power drift rate, the shield plug and HDM positions, and the spring loading on the hold-down column.

(c) The regulating rod was withdrawn from its critical position to a position (~10-inch elevation) which put the reactor on an approximate 100-second positive period. The reactor period was measured, as well as the primary sodium flow rate, the reactor temperature, the regulating and shim rod positions, the shield plug and HDM positions, and the spring loading on the hold-down column.

(d) The regulating rod was reinserted, the reactor power was reduced, and the critical rod and period measurements of Steps (b) and (c) were repeated to improve the statistical accuracy of the data.

(e) The reactor was shut down.

2. Reactivity Measurements after Hold-Down Mechanism Movement

The following steps outline the experimental procedure used for each of the six HDM movements. The steps were the same in each case, except that the shield plug was rotated in opposite directions on alternate movements (Step (b) below) and the plug was not rotated on the last movement. The steps were as follows:

(a) With the reactor shut down (all safety and control rods fully inserted) and the hold-down mechanism in its operating down position, the primary sodium flow rate was adjusted to the equilibrium value (~6.0 x 10^6 lb/hr) required to maintain an

* All primary sodium flow rates given refer to 3-loop operation unless otherwise stated.

isothermal reactor temperature of ~517 F with minimum drift. It was known that with this flow rate the subassemblies would not float when the hold-down mechanism was raised.[2]

(b) The hold-down mechanism was raised to its refueling elevation (~9 inches) and the shield plug was rotated 20 to 30 degrees away from its normal operating position. The shield plug was then returned to its operating position and the HDM was lowered and locked into place.

(c) The safety rods were fully withdrawn, the shim rod was withdrawn 5 inches, and the reactor was brought to criticality on the regulating rod at a power level of ~500 watts. The neutron source was then retracted and the critical regulating rod position was adjusted slightly to account for its withdrawal. Because of the retractable source, it was not necessary in this step to repeat exactly the critical power level attained in Step (b) of the base reactivity measurement. The critical regulating and shim rod positions were measured, along with the primary sodium flow rate, the reactor temperature, the power drift rate, the shield plug and hold-down mechanism positions, and the spring loading on the hold-down column.

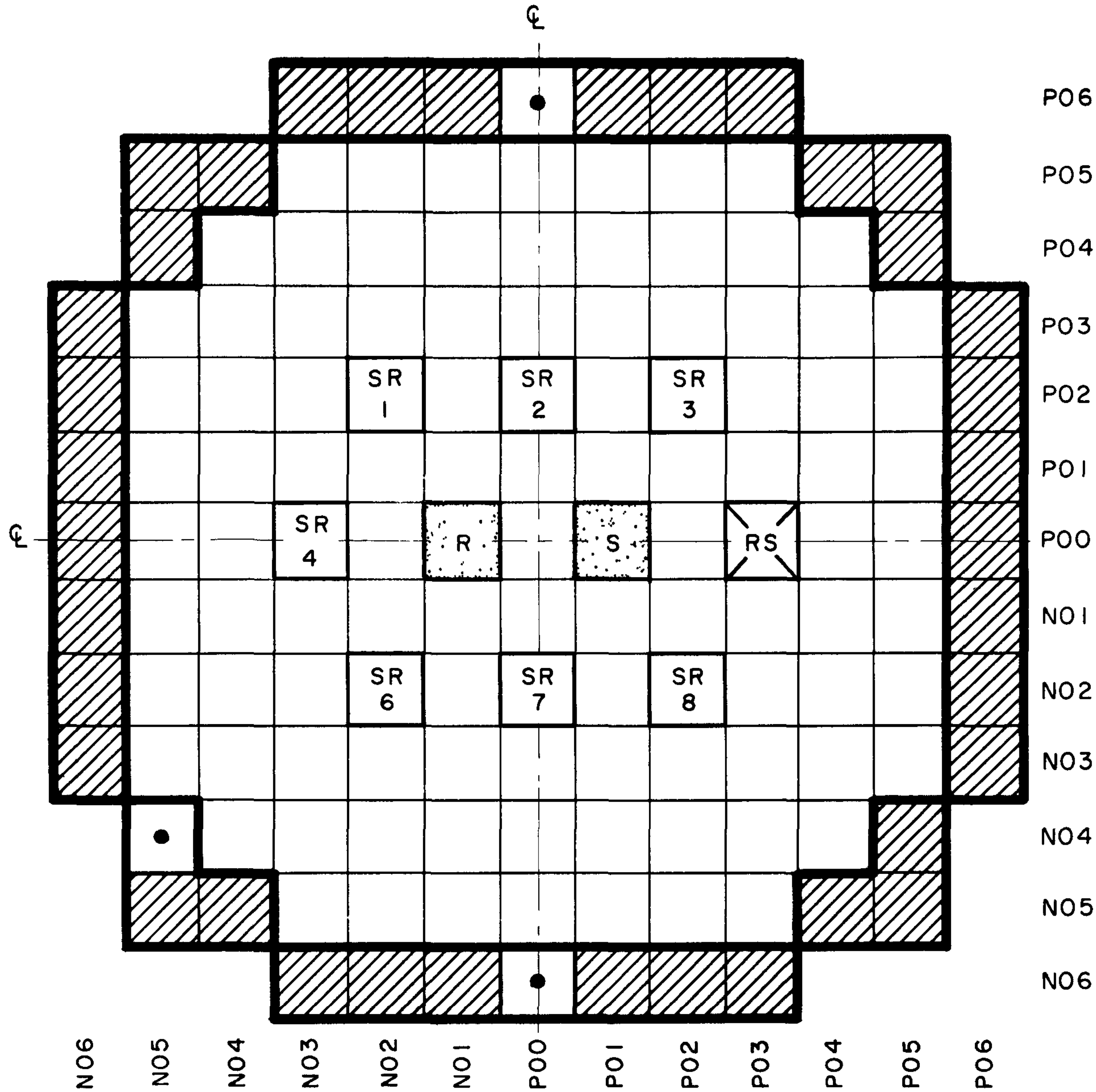
(d) The regulating rod was withdrawn to the same elevation that was used previously in making the base reactivity period measurement (Step (c) of Section III, A. 1), and the resulting positive period was measured along with the primary sodium flow rate, the reactor temperature, the regulating and shim rod positions, the shield plug and HDM positions, and the loading on the hold-down column.

(e) The regulating rod was reinserted, the reactor power was reduced, and the critical rod and period measurements of Steps (c) and (d) above were repeated to improve the statistical accuracy of the data.

(f) The reactor was shut down and Steps (a) through (e) were repeated for the remaining five movements of the HDM.

B. REACTOR PLANT CONDITIONS

The reactor fuel loading configuration during the test is shown in Figure 6. A total of 99 core fuel subassemblies were loaded into the core lattice. The excess reactivity (all safety and control rods fully withdrawn)



DESCRIPTION	QUANTITY
OPERATING CONTROL RODS	2
SR SAFETY RODS	7
CORE SUBASSEMBLIES (25 6 % ENRICHED U-10 W/O Mo ALLOY; ~ 4.74 kg U-235/SUBASSEMBLY)	99
DUMMY SUBASSEMBLY (NO FUEL-SODIUM FILLED) . . .	3
RS RETRACTABLE SOURCE	1
INNER RADIAL BLANKET SUBASSEMBLIES-DEPLETED U-3 W/O Mo ALLOY	37
TOTAL SUBASSEMBLIES .	149

FIG. 6 - CORE LOADING CONFIGURATION

with this loading was measured, and found to be approximately 59 cents* at 517 F with the antimony section of the retractable neutron source retracted 30 inches. With this loading, criticality could be achieved with the shim and regulating control rods located in the middle third of their total travel.

Whenever possible, the primary system was maintained at an isothermal temperature of 517 F during the test 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, which resulted from primary sodium pump operation, and the heat removal which resulted from the operation of the below-floor ventilation system. The primary sodium flow rate that was required to maintain a temperature equilibrium of 517 F was approximately 6.0×10^6 lb/hr. With this flow rate, the temperature drift rate was kept to within $\pm$ 0.25 F/hr. The auxiliary system, consisting of the overflow pumps and the primary system cold trap, was also operated when required to reduce the upward drift in temperature.

The critical reactor power maintained during the test varied between 400 and 800 watts. The power was purposely kept low to minimize the activation of the reactor components. When reactor period measurements were being made, the transient power was allowed to rise approximately one-half of a decade above the critical power before the regulating rod was reinserted and the power reduced. Because a retractable source was used during the test, source reactivity effects were negligible at all power levels, and it was not necessary to accurately reproduce the power for each critical or period measurement.

The low sodium flow rate trip setting of the reactor safety system was reduced during the test from its normal setting of 75 per cent of the 200-Mw(t) design flow to 40 per cent of the 200-Mw(t) design flow. This was done because the flow rate required for temperature equilibrium, 6.0×10^6 lb/hr or 68 per cent of the 200-Mw(t) flow rate, was less than the normal trip point setting. Another modification was made for the test; the scram levels for the intermediate and power range were set at flux levels corresponding to powers less than 1 Mw(t).

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* The reactivity conversions for the Fermi reactor are:

1 cent = 3.19 ih
1 ih = 2.08×10^{-5} $\Delta k/k$
β_{eff} = 0.00662

C. NEUTRON SOURCE AND INSTRUMENTATION

In place of safety rod No. 5, a retractable neutron source was located in the reactor during the test. A temporary, precision temperature readout station was set up in the reactor control room so that an accurate record of reactor temperature could be maintained. The positive period and power drift rate information were acquired using the data obtained from specially installed neutron detectors. The remaining test data, i.e., the primary sodium flow rates, the control rod and safety rod positions, the rotating shield plug and HDM positions, and the hold-down column loading, were obtained from the permanent plant instrumentation.

1. Neutron Source

Throughout the core reproducibility test a retractable antimony-beryllium (Sb-Be) neutron source was located in the reactor in place of safety rod No. 5 in core position P03-P00 (Figure 6).* The retractable radioactive antimony-124 portion of the source is a rod approximately 0.7 of an inch in diameter by 25 inches long. The antimony rod fits inside a hollow beryllium cylinder which is approximately 30 inches long and contains 3.4 kg of beryllium. The beryllium cylinder is in turn located inside a square, steel can which has the external dimensions of a normal lower safety rod guide tube. To retract the source from the core, the handling head of the antimony section is engaged with the gripper of the safety rod drive extension.

The presence of the retractable source during the test permitted accurate reactivity measurements to be made at low power, thus minimizing the activation of core components. The reactor could be started up safely with the antimony source rod fully inserted and, after criticality was attained at low power, the source could be withdrawn from the core to eliminate source reactivity effects in the subsequent reactivity measurements. Calibration measurements made at the time the retractable source was installed had shown that, with the source retracted 30 inches, source reactivity effects were negligible.[4]

2. Instrumentation

The instrumentation used to monitor the neutron ~~flux during~~ the test was essentially the same as that described in detail in APDA-NTS-1.[5] However, in this test no in-core instrumentation was used because the temporary

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* The coordinate system used to locate subassemblies in the core lattice is shown in Figure 6. 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.

instrument thimble which was normally installed for the low-power tests in place of safety rod No. 5 had been replaced by the retractable source. All of the nuclear instrumentation used in the test was temporary instrumentation, installed for the low-power test program. Briefly, it consisted of two high-sensitivity BF_3 proportional detector channels and six B-10 lined ion chamber channels. All of the detectors were located inside six neutron counter tubes embedded in the graphite shield that surrounds the reactor vessel (Figure 1). The two BF_3 detectors were connected to mechanical scalers located in the reactor control room. They provided the data from which the reactor periods were determined in the test; they were also used to supply both count rate and period signals to the source range safety system of the reactor. Five of the six B-10 lined ion chambers provided power level protection for the intermediate and power ranges. The intermediate range detectors also provided period protection. The sixth ion chamber provided a linear current signal to a Keithley micromicroammeter recorder located in the reactor control room. This recorder gave period information during the test and it was also used to measure any drift in power which took place during the critical rod position reactivity measurements.

The temperature of the primary system was monitored during the test by use of the normal plant temperature sensing elements. These sensing elements consist of iron-constantan thermocouples and platinum resistance temperature detectors. The thermocouples are installed on the fuel support plates located below the core and on the hold-down plate located above the core. They measure the temperature of the core inlet and outlet sodium, respectively. The resistance temperature detectors are located in the primary sodium piping leading to and from the reactor. They measure the temperature of the reactor inlet and outlet sodium. In the test, the data from all of these temperature sensors were relayed via special circuits to the 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. With the equipment used, temperatures could be read to an accuracy of $\pm$ 1 F.

The permanent plant instrumentation[2] was used to obtain the remaining data required, i.e., primary sodium flow rates, control rod and safety rod positions, rotating shield plug and hold-down mechanism positions, and the hold-down column spring loading. The primary sodium flow meters in the control room could be read to within $\pm 0.05 \times 10^6$ lb/hr/loop. The positions of the operating control rod and safety rod drives were read on Gilmore position indicators located in the reactor control room. The rod drives are equipped with digital readout, fine-position indication systems capable of showing the elevation of the drive extensions to within $\pm$ 0.03 inch. The position of the rotating shield plug was indicated by the azimuth position readout on the plug console. This indicator could be read to the nearest $\pm$ 0.1 degree. The position of the hold-down column was indicated by the hold-down vertical position indicator located on the HDM console. It could be read to the nearest ± 1/8 inch. The applied loading on the hold-down column was read from the spring compression indicator on the HDM console. This indicator could be read to the nearest ± 1/32 inch.

IV. METHOD OF ANALYSIS

A. DETERMINATION OF CORE REPRODUCIBILITY

The determination of the reactivity effect of hold-down mechanism movement (core reproducibility) was made using the critical rod position and positive period data obtained after each movement. The data were analyzed in the following way. First, the critical rod position and positive period data were converted to critical and period reactivities using the rod calibration curves and the inhour relationship for the reactor. These data were then corrected for any reactivity perturbations which existed between the measurements due to temperature drift, power drift or rod position error. Because the reactor periods were all measured with the operating control rods set at the same position (Section III,A), any change in the core configuration due to movement of the HDM could then be determined by noting whether the period and critical reactivities obtained before and after the movements were significantly different.

1. Relationship Between Critical Rod Position, Reactor Period and Reactivity

The critical rod positions were obtained from the Gilmore indicators in the reactor control room (Section III, C. 2). The critical rod position data were converted to reactivity data using the rod calibration curves. Because the shim rod was maintained at the same elevation during all critical measurements (Section III, A), the reactivity change due to HDM operation could be determined from just the change in the critical regulating rod position. The relationship between critical regulating rod position and reactor reactivity is shown in the rod calibration curve given in Figure 7.[6]

Three separate determinations of the reactor period were obtained. Reactor period information was obtained from the count rates of each of the two BF_3 proportional detector channels and from the ion chamber current trace of the Keithley micro-microammeter (Section III, C. 2). The count rate data from the BF_3 channels were plotted as a function of time to obtain the periods and, in the case of the Keithley recorder, the periods were obtained directly from its clock-timer which was set to trip on e-fold power increases. The three periods were averaged and these data converted to reactivity data using the inhour relationship for the reactor. This relationship is shown in Figure 8[7]. In the actual analysis, a detailed tabular listing of the data shown in Figure 8 was used so that small differences in the periods could be accurately related to reactivity.

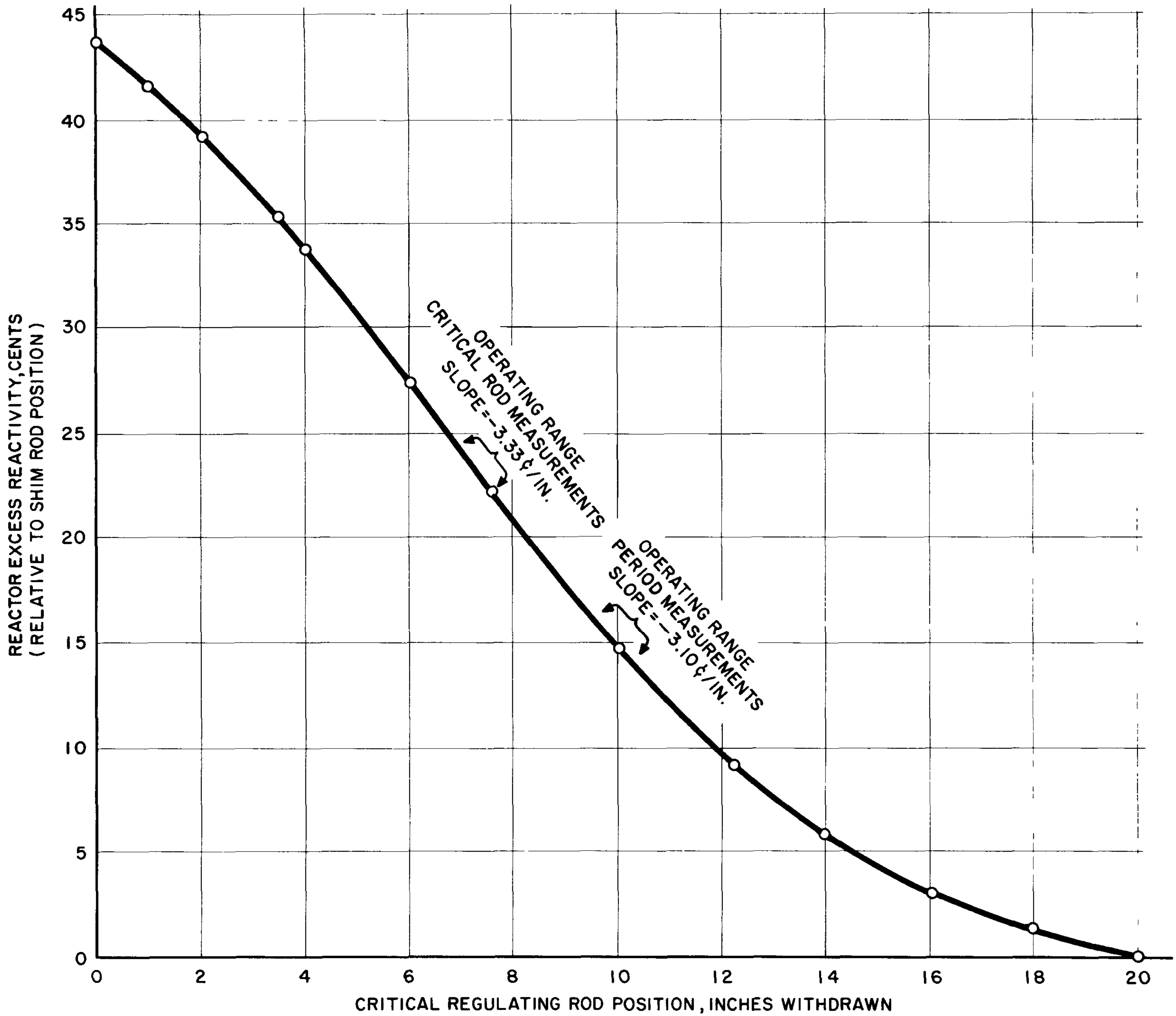

FIG. 7 - REACTIVITY VERSUS CRITICAL REGULATING ROD POSITION

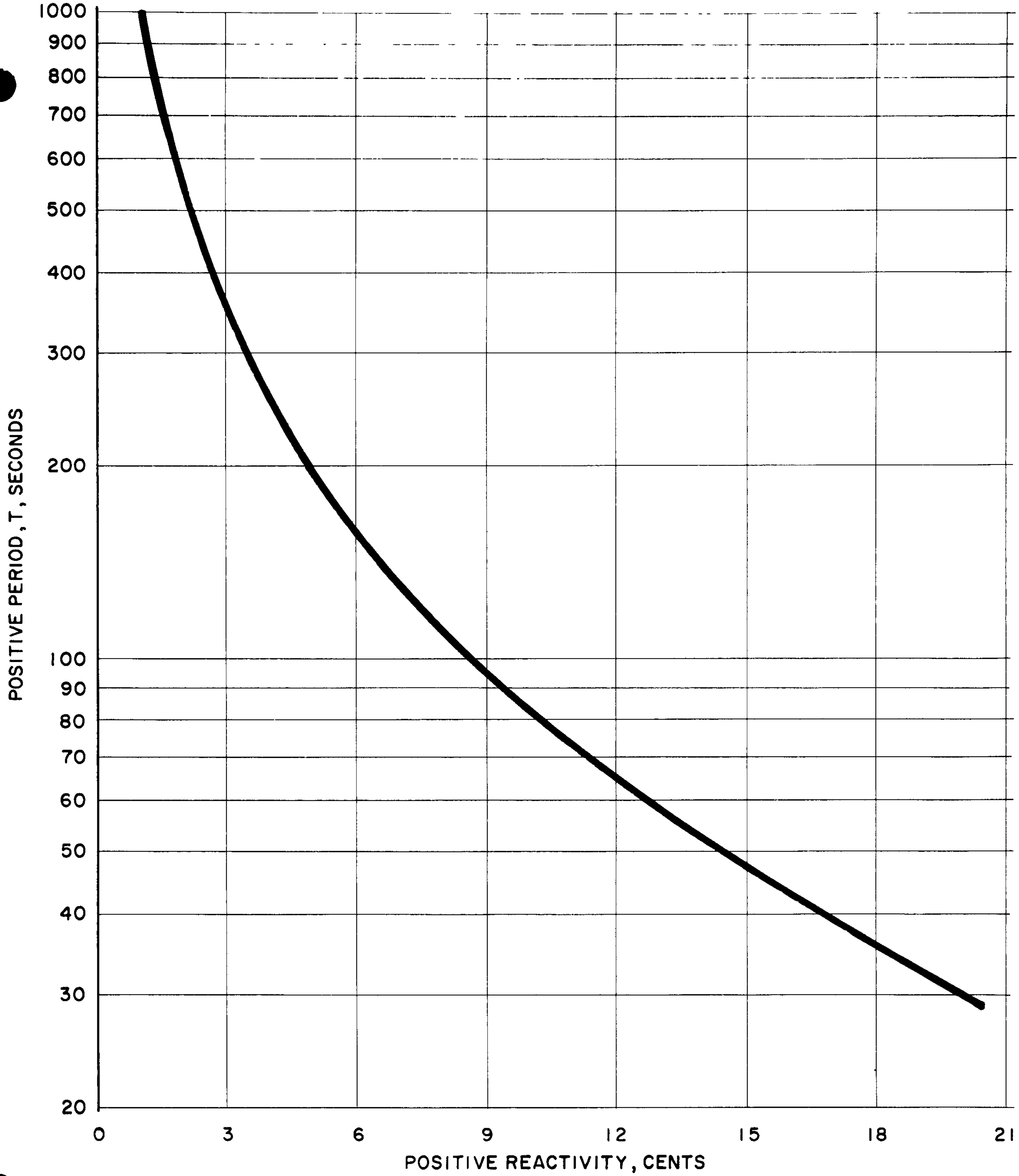

FIG. 8 - REACTIVITY VERSUS REACTOR PERIOD

2. Corrections to the Data

To determine core reproducibility, the critical rod and positive period reactivity data obtained after each HDM movement were compared to the critical rod and positive period data obtained after the other movements to establish whether any significant reactivity changes had taken place. To make a valid comparison, the data had to be corrected for spurious reactivity perturbations that occurred between measurements. The reactivity perturbations considered were those due to (a) temperature drift, (b) flux or power drift and (c) rod position error. In the case of the critical measurements all three perturbations had to be considered. However, for the period measurements only items (a) and (c) are important. No correction for source reactivity effects was needed in either case because of the retractable source.

a. Temperature Drift - Each time a critical rod and period reactivity measurement was made, the temperatures were slightly different because of the unavoidable temperature drift which occurred. Therefore, to make the data consistent, a correction was made to account for the reactivity feedback due to temperature drift. In applying this correction, the reactivities obtained after each HDM movement were corrected to the temperatures of the initial base critical and period reactivity measurements.

The temperature correction for a critical reactivity measurement was found as follows:

$$\delta R^{c}_{tij} = -0.26\ (t^{c}_{o1} - t^{c}_{ij}) \qquad (1)$$

where:

δR^{c}_{tij} = the reactivity correction for temperature drift for the j^{th} critical rod measurement made after the i^{th} HDM movement, cents

t^{c}_{o1} = the average isothermal reactor temperature at the time of the initial base critical reactivity measurement, F

t^{c}_{ij} = the average isothermal reactor temperature at the time of the j^{th} critical rod measurement made after the i^{th} HDM movement, F

-0.26 = the isothermal temperature coefficient of the reactor, cents per degree F[8]

Similarly, in the case of the period reactivity measurements, the temperature correction was:

$$\delta R^{p}_{tij} = -0.26\ (t^{p}_{o1} - t^{p}_{ij}) \qquad (2)$$

where all terms are defined as in Equation (1) except that the superscript "p" now refers to the period reactivity measurements.

To correct the critical and period reactivities for temperature, the values calculated from Equations (1) and (2) were added to the reactivity values actually measured.

b. Power Drift - When the critical rod reactivity measurements were made, the regulating rod was not always adjusted to precisely critical conditions. Consequently, when some of the critical measurements were made, the reactor was actually slightly subcritical or supercritical; this was indicated on the Keithley recorder trace as a downward or upward drift in power, respectively. To make all the critical reactivity data consistent, the data were corrected to the critical condition of zero drift. The correction used was:[7]

$$\delta R^{c}_{pij} = 0.18 \, D_{ij} \qquad (3)$$

where:

δR^{c}_{pij} = the reactivity correction for power drift for the j^{th} critical measurement made after the i^{th} HDM movement, cents

D_{ij} = the power drift rate measured on the Keithley recorder for the j^{th} critical measurement made after the i^{th} HDM movement, $\pm$ per cent drift per minute

0.18 = the correlation between excess reactivity and drift, cents/per cent drift/minute [7]

To correct the critical reactivities for drift, the values calculated from Equation (3) were added to the critical reactivities actually measured.

c. Rod Position Error - When the critical rod and positive period reactivity measurements were made after HDM movement, it was not always possible to reproduce exactly the reference position of the control rods used in making the base reactivity measurements. Consequently, for those measurements in which the positions were not exactly repeated, reactivity corrections had to be made for rod position error.

The correction for shim rod position error in the critical measurements was found as follows:

$$\delta R^{c}_{sij} = -3.30\,(P_{sij} - P_{sr}) \qquad (4)$$

where:

δR^{c}_{sij} = the reactivity correction for shim rod position error for the j^{th} critical measurement made after the i^{th} HDM movement, cents

P_{sij} = the shim rod position at the time of the j^{th} critical measurement made after the i^{th} HDM movement, inches of withdrawal

P_{sr} = the reference shim rod position, 5 inches of withdrawal

-3.30 = the slope of the shim rod calibration curve in the region of its reference position, cents per inch of withdrawal

Two corrections for rod position error had to be considered for the period reactivity measurements; the shim rod correction given by Equation (4) above, and a similar correction for deviations of the regulating rod from its reference position. The regulating rod position error correction was:

$$\delta R^{p}_{rij} = -3.10\,(P_{rij} - P_{rr}) \qquad (5)$$

where all terms are defined as in Equation (4), except that the superscript "p" now refers to the period measurements and the subscript "r" refers to the regulating rod.

To correct the critical and period reactivities for rod position error the values calculated from Equations (4) and (5) were added to the critical rod and period reactivities actually measured in the test.

Equations (6) and (7) summarize the corrections made to the critical rod and positive period reactivities actually measured, (R^{c}_{ij} and R^{p}_{ij}) to account for temperature drift, power drift, and rod position error:

$$R^{c}_{ij}\,(\text{corrected}) = R^{c}_{ij}\,(\text{measured}) + \delta R^{c}_{tij} + \delta R^{c}_{pij} + \delta R^{c}_{sij} \qquad (6)$$

$$R^{p}_{ij}\,(\text{corrected}) = R^{p}_{ij}\,(\text{measured}) + \delta R^{p}_{tij} + \delta R^{p}_{sij} + \delta R^{p}_{rij} \qquad (7)$$

3. Data Reduction and Analysis

To determine core reproducibility, the test data were analyzed as follows. First, the critical rod and period reactivities (corrected values) obtained after each HDM movement were averaged to determine the average critical and period reactivities of all the measurements, including the base measurement. Then the deviation from the average was found for each individual critical and period measurement. If the deviations were within the limits of the statistical variation expected, based on experimental error, it could be concluded that no change in the core configuration had occured and that the core was reproducible.

a. Average Critical and Period Reactivities - The average critical and period reactivities of all the measurements were calculated as follows:

$$\overline{R^c} = 1/14 \sum_{j=1}^{2} \sum_{i=0}^{6} R^c_{ij} \quad (8)$$

$$\overline{R^p} = 1/14 \sum_{j=1}^{2} \sum_{i=0}^{6} R^p_{ij} \quad (9)$$

where:

$\overline{R^c}$ = the average critical reactivity, cents

$\overline{R^p}$ = the average period reactivity, cents

R^c_{ij} = the corrected critical reactivity (Equation 6) of the j^{th} critical measurement made after the i^{th} HDM movement (i = 0 refers to the base measurement), cents

R^p_{ij} = the corrected period reactivity (Equation 7) of the j^{th} period measurement made after the i^{th} HDM movement, cents

b. Deviations from Average Reactivities - The deviation of each individual critical and period reactivity from the average reactivity was calculated as follows:

$$\Delta R^c_{ij} = R^c_{ij} - \overline{R^c} \quad (10)$$

$$\Delta R^p_{ij} = R_{ij} - \overline{R^p} \quad (11)$$

where:

ΔR^c_{ij} = the deviation from the average critical reactivity of the j^{th} critical measurement made after the i^{th} HDM movement, cents

ΔR^{p}_{ij} = the deviation from the average period reactivity of the j^{th} period measurement made after the i^{th} HDM movement, cents

c. Estimated Experimental Error and Core Reproducibility - If the deviations of the individual critical and period measurements from the average reactivities were within the limits of the statistical variation expected, based on experimental error, it could then be concluded that no change in the core configuration had occurred because of HDM movement, and that the core was reproducible.

The experimental error in the core reproducibility measurements depended on the accuracy with which the critical rod and positive period reactivities could be measured.

In Reference 3 the uncertainties in the basic measurements are estimated to be as follows:

Rod position	$\pm$ 0.03 in.
Reactor period	$\pm$ 1 sec
Temperature drift	$\pm$ 1 F
Power drift	$\pm$ 0.2%/min

When these are combined, the uncertainties in the critical rod and positive period determinations of core reproducibility (Equations (10) & (11) are $\pm$ 0.35 cents and $\pm$ 0.25 cents, respectively. Therefore, within the limitations of the test, the conditions for core reproducibility were:

$$\Delta R^{c}_{ij} \leq \pm 0.35 \text{ cents}$$

$$\Delta R^{p}_{ij} \leq \pm 0.25 \text{ cents.}$$

The values for experimental error shown above represent the smallest reactivity changes due to core nonreproducibility that could be measured in the test. The reactivity change for a $\pm$ 2 mil change in the average core diameter was calculated and found to be $\mp$ 0.56 cents[9]. Therefore, the accuracy of the test was sufficient to detect variations in the average core diameter of approximately $\pm$ 1 mil.

The data obtained from the tight-core test, by means of mechanical measurements conducted in air at ambient temperatures with dummy subassemblies in the reactor, indicated that repeated lowering and raising of the HDM could result in a maximum change in the average core diameter of approximately $\pm$ 1 mil[1].

B. DETERMINATION OF EXPERIMENTAL ERROR

The estimated uncertainties in the critical rod and positive period reactivity measurements given above were based upon estimated inaccuracies in the measurement of rod position, reactor period, temperature drift and power drift. From the test data, a check on the accuracy of the estimated experimental error could be obtained indirectly by assuming that the core configuration was highly reproducible and remained unchanged throughout the test. As will be seen later in Section V, this assumption appears to be valid based on the experimental data. In this case, the apparent reactivity changes measured give an indication of the experimental error of measurement.

V. EXPERIMENTAL RESULTS

A. CORE REPRODUCIBILITY MEASUREMENTS

The results of the core reproducibility measurements are summarized in Tables I through III. Tables I and II list the pertinent critical rod and positive period data, respectively, for each of the hold-down mechanism movements made during the test. The basic critical rod position and positive period data obtained are given in the tables as well as the resulting uncorrected critical and period reactivities. Also listed are the corrections for temperature drift, power drift, and rod position error that were applied to the uncorrected reactivities. The last column of Tables I and II lists the final corrected critical and period reactivity values for each HDM movement.

Table III summarizes the corrected reactivity results given in Tables I and II and it shows the reactivity deviations for each HDM movement compared to the average critical and period reactivities. The reactivity deviations given in Table III are presented graphically in Figure 9. Table III and Figure 9 also give the estimated measurement errors. As can be seen, the spread in the reactivity deviations is less in all cases than the estimated error of measurement. Therefore, it can be concluded that the core configuration is reproducible to within ± 0.5 mil on the average core radius (Section IV, A.3C).

B. EXPERIMENTAL ERROR

Based on the test results, it appears reasonable to assume that the core is highly reproducible. Assuming this to be true, the reactivity deviations that were measured are apparent changes only, and represent the experimental errors of measurement. From Table III, therefore, the experimental errors for critical rod and positive period reactivity measurements are approximately ± 0.25 cents and ± 0.18 cents, respectively. Although these values are about 30 per cent less than the predicted errors of ± 0.35 cents and ± 0.25 cents (Section IV, A.4), they are in agreement within the limitations of the test data which are based on a relatively small number of measurements.

TABLE I - CRITICAL DATA FROM CORE REPRODUCIBILITY TEST

No. of HDM Movement, i	Type of HDM Movement	Measurement No., j	Basic Data: Critical Shim Rod Position, P_s, Inches Withdrawn	Basic Data: Critical Regulating Position, P_r, Inches Withdrawn	Basic Data: Power Drift Rate, D, Per Cent Min[a]	Basic Data: Average Temperature, t^c, F[b]	Uncorrected Critical Reactivity from Regulating Rod Calibration Curve, R^c, Cents	Reactivity Corrections: Temperature Drift, δR_t^c, Cents	Reactivity Corrections: Power Drift, δR_p^c, Cents	Reactivity Corrections: Shim Rod Position, δR_s^c, Cents	Corrected Critical Reactivity on Regulating Rod, R^c, Cents
0	None (Arbitrary Base)	1	5.00[c]	7.24	0	517.14[d]	23.25	0	0	0	23.25
		2	5.00	7.23	0	517.12	23.28	-0.01	0	0	23.27
1	Raised, rotated, and returned to original position	1	5.00	7.28	0.04	518.27	23.12	0.30	0.01	0	23.43
		2	5.00	7.26	0.15	517.86	23.18	0.19	0.03	0	23.40
2	Raised, rotated, and returned to original position	1	5.05	7.13	0	517.84	23.62	0.18	0	-0.16	23.64
		2	5.05	7.12	0.50	516.83	23.65	-0.08	0.09	-0.16	23.50
3	Raised, rotated, and returned to original position	1	5.00	7.16	-0.07	517.00	23.52	-0.04	-0.02	0	23.46
		2	5.00	7.21	0.10	517.25	23.35	0.03	0.02	0	23.40
4	Raised, rotated, and returned to original position	1	5.00	7.20	0.20	517.54	23.38	0.11	0.04	0	23.53
		2	5.00	7.22	0	517.79	23.32	0.17	0	0	23.49
5	Raised, rotated, and returned to original position	1	5.00	7.21	0.22	517.64	23.35	0.13	0.04	0	23.52
		2	5.00	7.21	0	517.86	23.35	0.19	0	0	23.54
6	Raised and lowered only	1	5.00	7.20	1.00	516.77	23.38	-0.10	0.18	0	23.46
		2	5.00	7.13	0.08	516.40	23.62	-0.19	0.02	0	23.45

a. Obtained from Keithley recorder chart. In most instances the measurements were made over 5-minute time intervals.

b. Average of the thermocouple and resistance temperature detector readings.

c. Reference shim rod position, P_{sr}, for rod position error reactivity corrections.

d. Reference temperature, t_{01}^c, for temperature drift reactivity corrections.

TABLE II - PERIOD DATA FROM CORE REPRODUCIBILITY TEST

No. of HDM Movement, i	Type of HDM Movement	Measurement No., j	Basic Data: Shim Rod Position, P_s, Inches Withdrawn	Basic Data: Regulating Rod Position, P_r, Inches Withdrawn	Basic Data: Average Temperature, t^p, F [a]	Basic Data: Average Period, T, Seconds [b]	Uncorrected Period Reactivity, R^p, Cents	Reactivity Corrections: Temperature Drift, δR_t^p, Cents	Reactivity Corrections: Shim Rod Position δR_s^p, Cents [c]	Corrected Period Reactivity, R^p, Cents
0	None (Arbitrary Base)	1	5.00 [d]	10.00 [e]	517.12 [f]	103.0	8.51	0	0	8.51
		2	5.00	10.00	517.19	103.4	8.49	0.02	0	8.51
1	Raised, Rotated, and Returned to Original Position	1	5.00	10.00	517.86	104.8	8.40	0.19	0	8.59
		2	5.00	10.00	517.45	104.0	8.45	0.08	0	8.53
2	Raised, Rotated, and Returned to Original Position	1	5.05	10.00	517.84	100.8	8.66	0.19	-0.16	8.69
		2	5.05	10.00	516.83	100.0	8.71	-0.08	-0.16	8.47
3	Raised, Rotated, and Returned to Original Position	1	5.00	10.00	516.98	100 5	8.68	-0.04	0	8.64
		2	5.00	10.00	517.23	102.4	8.55	0.03	0	8.58
4	Raised, Rotated, and Returned to Original Position	1	5.00	10.00	517.54	102.3	8.56	0.11	0	8.67
		2	5.00	10.00	517.44	103.0	8.51	0.08	0	8.59
5	Raised, Rotated, and Returned to Original Position	1	5.00	10.00	517.64	101.5	8.61	0.14	0	8.75
		2	5.00	10.00	517.86	101.7	8.60	0.19	0	8.79
6	Raised and Lowered Only	1	5.00	10.00	516.77	99.9	8.72	-0.09	0	8.63
		2	5.00	10.00	516.40	99.4	8.75	-0.19	0	8.56

a. Average of the thermocouple and resistance temperature detector readings.

b. Average of the data from the ion chamber and two source range channels.

c. The regulating rod position error reactivity correction, δR_r^p, is zero in all cases because its reference withdrawal position (10 inches) was always reproduced exactly.

d. Reference shim rod position, P_{sr}, for shim rod position error reactivity corrections.

e. Reference regulating rod position, P_{rr}, for regulating rod position error reactivity corrections.

f. Reference temperature, t_{01}^p, for temperature drift reactivity corrections.

TABLE III - REACTIVITY EFFECTS DUE TO MOVEMENT OF THE HOLD-DOWN MECHANISM

No. of HDM Movement, i	Type of HDM Movement	Measurement No., j	Reactivity Deviations of Individual Measurements Compared to Average Reactivities: Critical Rod Measurements: Corrected Critical Reactivity, R^c, Cents	Average Critical Reactivity, $\overline{R^c}$, Cents	Deviation From Average Critical Reactivity, ΔR^c, Cents	Estimated Experimental Error, Cents	Positive Period Measurements: Corrected Period Reactivity, R^p, Cents	Average Period Reactivity, $\overline{R^p}$, Cents	Deviation From Average Period Reactivity, ΔR^p, Cents	Estimated Experimental Error, Cents	Conclusions
0	None (Arbitrary Base)	1	23.25		-0.20		8.51		-0.10		
		2	23.27		-0.18		8.51		-0.10		
1	Raised, Rotated and Returned to Original Position	1	23.43		-0.02		8.59		-0.02		
		2	23.40		-0.05		8.53		-0.08		
2	Raised, Rotated and Returned to Original Position	1	23.64		0.19		8.69		0.08		
		2	23.50		0.05		8.47		-0.14		
3	Raised, Rotated and Returned to Original Position	1	23.46		0.01		8.64		0.03		
		2	23.40	23.45	-0.05	±0.35	8.58	8.61	-0.03	±0.25	No Measurable Effect Due to HDM Operation
4	Raised, Rotated and Returned to Original Position	1	23.53		0.08		8.67		0.06		
		2	23.49		0.04		8.59		-0.02		
5	Raised, Rotated and Returned to Original Position	1	23.52		0.07		8.75		0.14		
		2	23.54		0.09		8.79		0.18		
6	Raised and Lowered Only	1	23.46		0.01		8.63		0.02		
		2	23.45		0.00		8.56		-0.05		

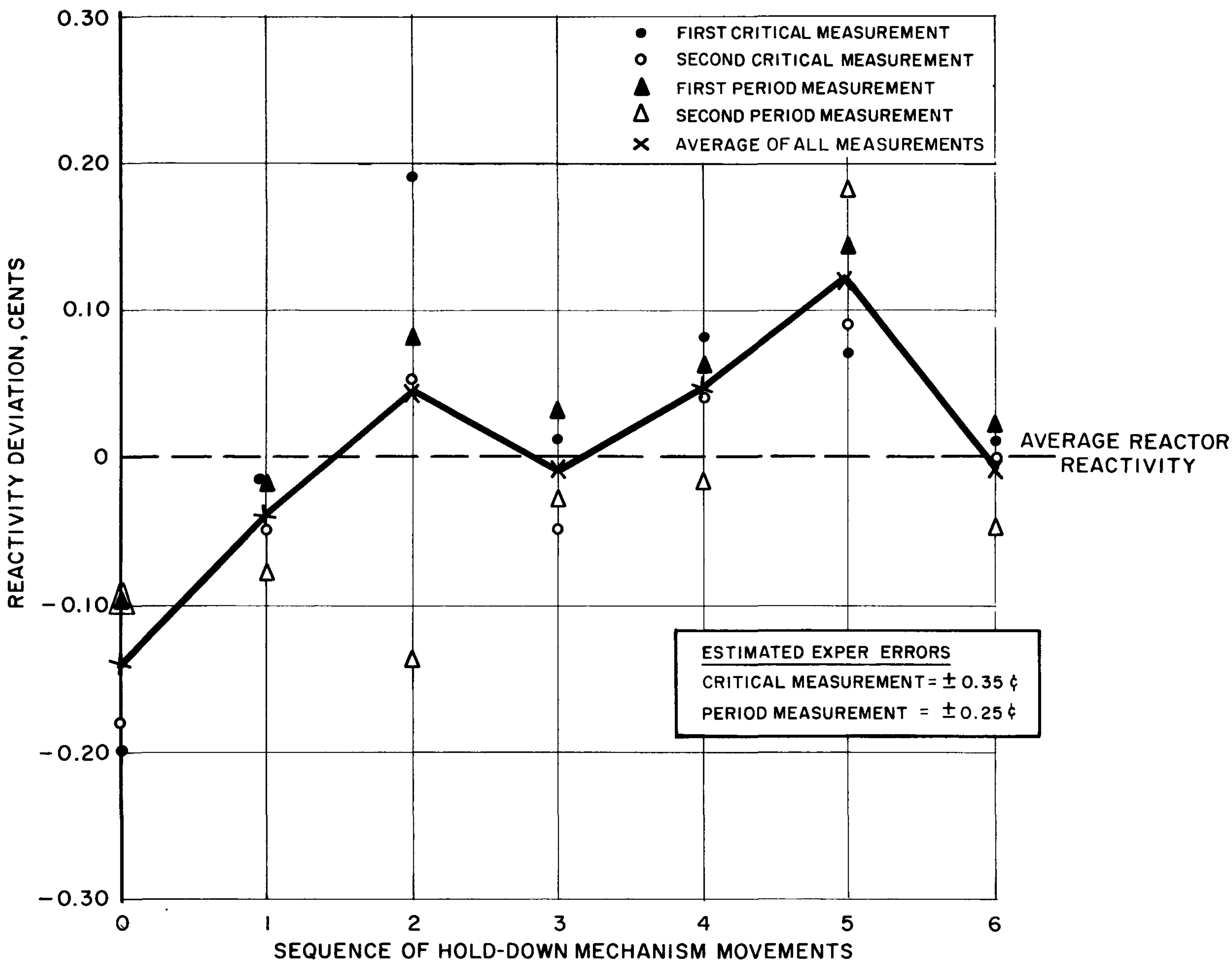

FIG. 9 -REACTIVITY VARIATION WITH HOLD-DOWN MOVEMENT

VI. CONCLUSIONS

Reactivity measurements made in the Enrico Fermi reactor, after a series of hold-down mechanism movements, show that no significant experimental errors due to HDM movement will be introduced in those nuclear tests requiring operation of the HDM between reactivity measurements. The test results show that the reactivity change, if any, is within the experimental error of $\pm$ 0.35 cents. This corresponds to a maximum change in the average core diameter of about $\pm$ 1 mil. The core reproducibility test results, obtained by nuclear measurements made under actual reactor operating conditions, are consistent with the results of the earlier mechanical measurements made in the tight-core test under preoperational reactor conditions. In the latter test, it was found that the core was tight to within $\pm$ 1 mil on the average core diameter.

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