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AEROJET-GENERAL NUCLEONICS INDUSTRIAL REACTOR (AGNIR) REACTOR PHYSICS TESTS

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By

R. L. Tomlinson

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Division

AEROJET-GENERAL NUCLEONICS

A DIVISION OF AEROJET—GENERAL CORPORATION

GENERAL TIRE

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ABSTRACT

The Aerojet-General Nucleonics Industrial Reactor (AGNIR) achieved initial criticality on 9 July 1965. Following initial criticality, a series of neutronics and power calibration tests were performed to characterize the reactor from both the physics and thermodynamics standpoints. A description of the conduct and significant results of this test program is presented herein.

*Published by Aerojet-General Nucleonics, San Ramon, Calif.

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AEROJET-GENERAL NUCLEONICS INDUSTRIAL REACTOR (AGNIR) REACTOR PHYSICS TESTS

I. INTRODUCTION

The Aerojet-General Nucleonics Industrial Reactor (AGNIR) achieved initial criticality at San Ramon, California, on 9 July 1965. It was the twentieth reactor to be built and operated at the San Ramon site. The previous nineteen were AGN-201 and -211 research and training reactors which were sold commercially to research and educational institutions in the U.S. and Europe. One 20 watt(t) AGN-201 reactor was in use at San Ramon for over eight years until the AGNIR became available for company research activities.

The AGNIR is a 250 kw(t) pool-type reactor; it is fueled with uranium-zirconium hydride; and is water-moderated and water-cooled. The reactor is licensed for general purpose neutron irradiations and isotope production. The open-core design and the 10-ft-diameter, 23-ft-deep water pool was designed to simplify the installation of special purpose irradiation loops. Both wet and dry irradiation facilities are provided within the reactor in addition to special laboratory space for the setup of electronic gear adjacent to the reactor. In-pool storage is provided for 21 irradiated fuel or dummy element irradiation capsules.

The reactor is operated from a control console which permits the operator to fully view all operations performed at the top of the reactor pool. The facility is served by a 3-ton bridge crane; a mechanically positioned, large component irradiation box can be actuated from the top of the reactor pool.

The reactor core consists of zirconium-hydride fuel moderator elements surrounded by graphite-filled reflector elements. The inherent safety of this core design simplifies the procedure for obtaining licenses for experiments.

Reactor control is maintained by three boron carbide control rods. In-core irradiation facilities include a seven-element central exposure capability; two 3-element exposure facilities; a glory hole; and multipurpose dummy element irradiation capsules.

The facility consists of a high-bay metal-framed building 40 by 80 ft, the low-bay portion of which is occupied by a general purpose laboratory, a control room, and a change room. Six shielded pits are provided in the facility for the storage of radioactive components, and a hot cell, which is licensed for 500 curie of Co-60, is also located with the reactor building. Non-radioactive storage is provided above the low-bay area within access of the three-ton bridge crane.

The initial physics tests on the reactor are reported herein. A cut-away drawing of the AGNIR installation is shown in Figure 1; and a drawing of the AGNIR core is shown in Figure 2. The facility was described earlier (Ref. 1) as were the procedures used in performing the above-mentioned physics tests (Ref. 2).

II. SUMMARY AND CONCLUSIONS

The initial criticality for the AGNIR was achieved with 63 aluminum-clad TRIGA Mark I fuel elements. These fuel elements contained a total of 2265 gm of U-235 in the form of uranium-zirconium hydride. The isothermal temperature coefficient for the system was found to have an average value between 60 and $125^{\circ}F$ of $-0.15¢/^{\circ}F$. All in-core void measurements indicated negative effects. The power coefficient was measured to be -0.47¢/kw, resulting in a $1.17 initial reactivity deficit at 250 kw in addition to xenon, samarium, and fuel burnup effects. The total worth of the control and safety rod system was measured to be -$8.51. No data were obtained during these tests that measurably differ from that presented in the AGNIR Hazards Summary Report (Ref. 1).

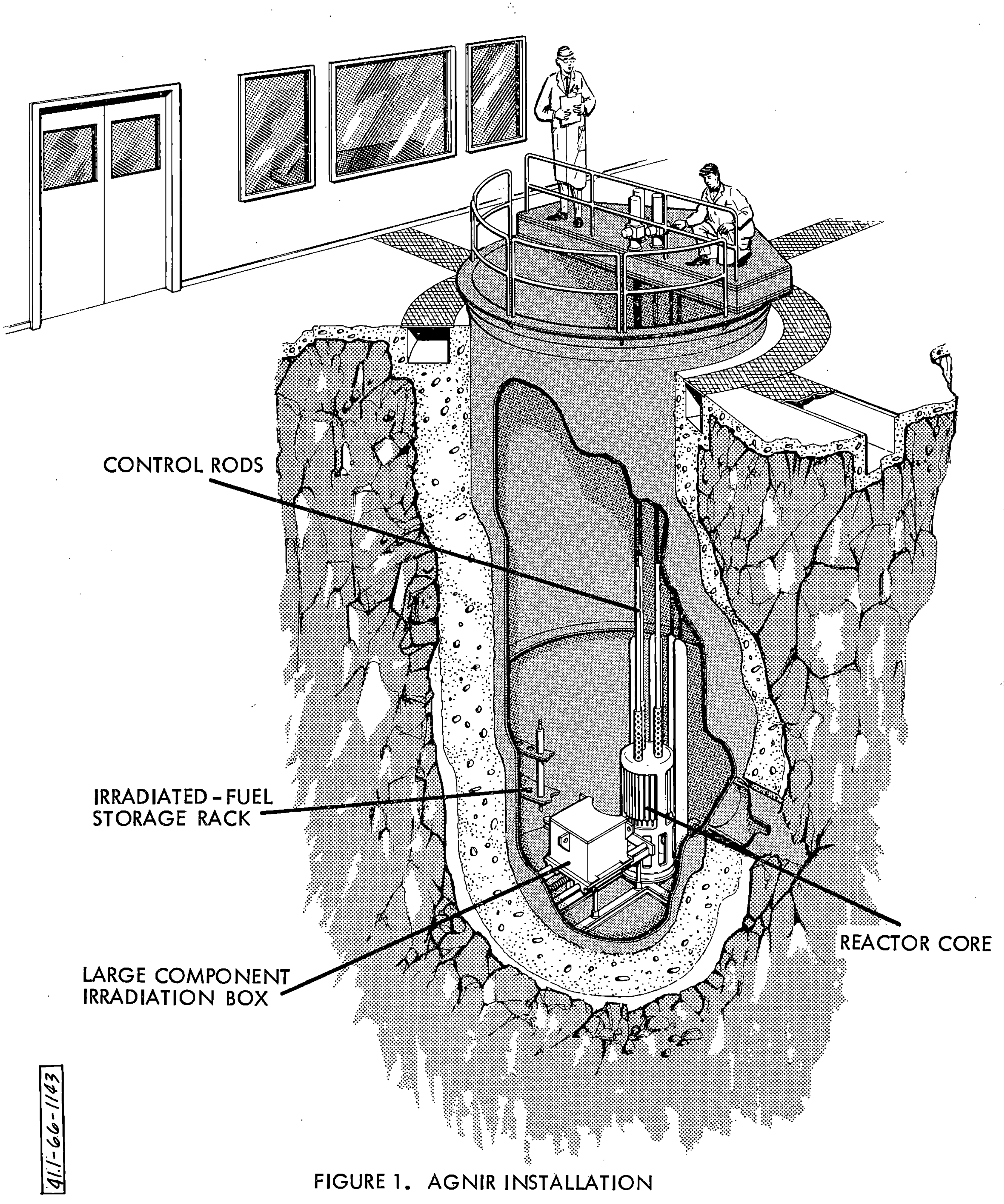

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FIGURE 1. AGNIR INSTALLATION

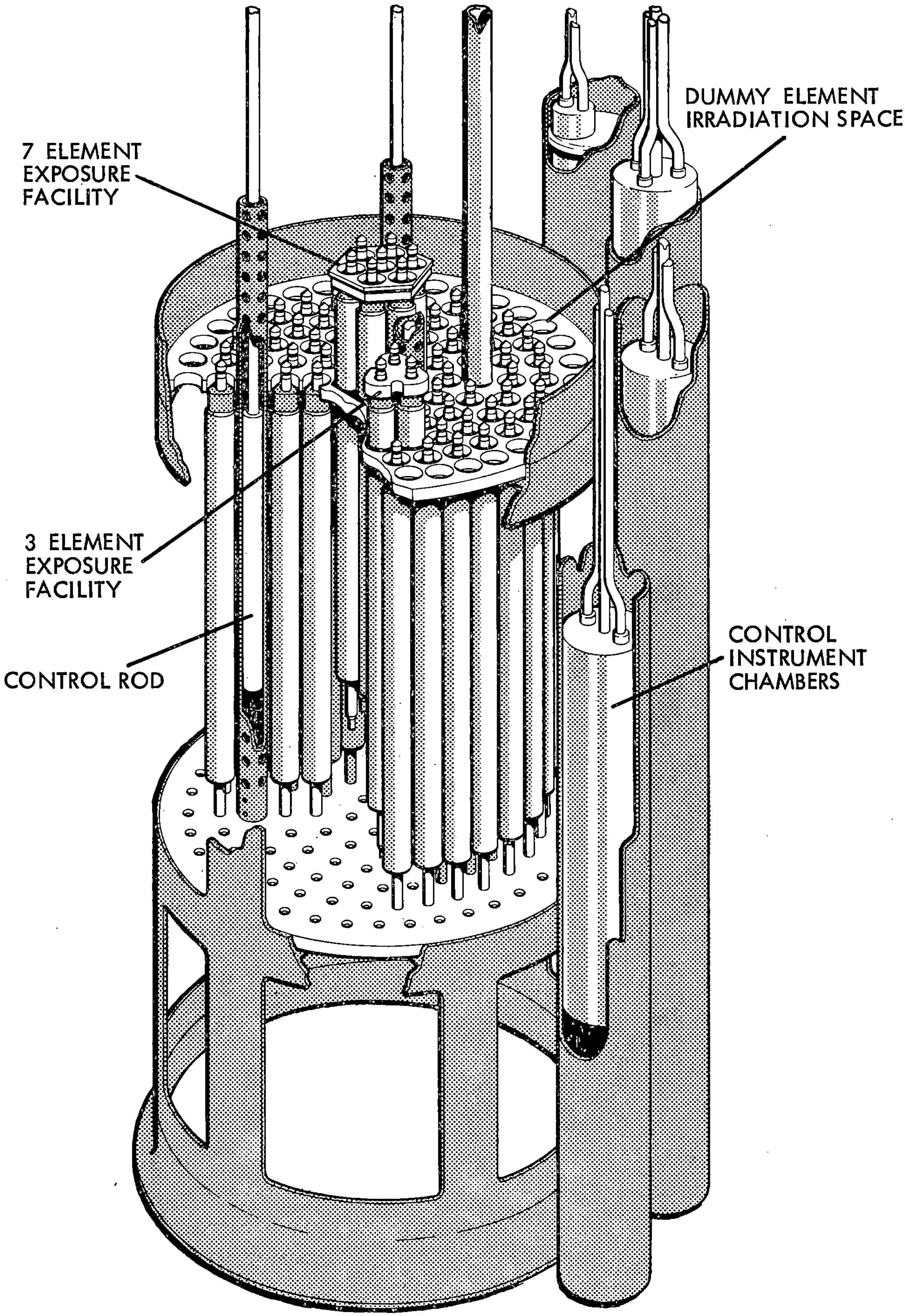

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FIGURE 2. AGNIR CORE

III. CONTROL AND SAFETY ROD SCRAM TESTS

The experimental tests performed prior to the initial reactor criticality, and the four measurements subsequently performed as part of the quarterly maintenance checks, indicate that the control rod drop times fall well within the Technical Specifications of the reactor license. The Technical Specifications state that the total rod drop time, including magnet separation time, shall not exceed 600 milliseconds. For the three control/safety rods the magnet separation varied from 50 to 60 msec, while the total drop time varied from 410 to 430 msec. A special relay rack panel was installed in the control room to facilitate the easy measurement of the rod drop time with the aid of a sweep oscilloscope and a series of microswitches. The panel also has provisions for controlling a BF_3 pulse counting assembly that was used for control rod calibrations using the rod-drop technique, described in Section VI.

IV. FUEL LOADING

A. INITIAL FUEL LOADING

The initial fuel loading followed the reference procedures (Ref.2); the fuel load consisted of 63 aluminum-clad TRIGA Mark I fuel elements and 23 graphite-filled reflector elements. The loading was purposely skewed toward the control instrumentation to provide the maximum signal to the reactor instrumentation during the initial critical experiment. The initial loading configuration is shown in Figure 3A.

The nuclear instrumentation used during the initial critical experiment consisted of the normal four channels of reactor control instrumentation; i.e., one BF_3 pulse channel; one gamma-compensated ion chamber intermediate channel; and two uncompensated ion chambers used as power channels. With no appreciable gamma background on the fuel, all four channels were on scale providing useful information. In addition, two additional BF_3 pulse channels and one uncompensated ion chamber were used during the critical experiment for a total of seven usable channels of nuclear instrumentation. A plot of the multiplication versus fuel mass for the initial fuel loading (Figure 4) reveals that the ion chamber data proved more reliable than the pulse counter data for this initial fuel loading. Criticality was achieved for the configuration within 35 grams of the value found in the initial criticality calculation.

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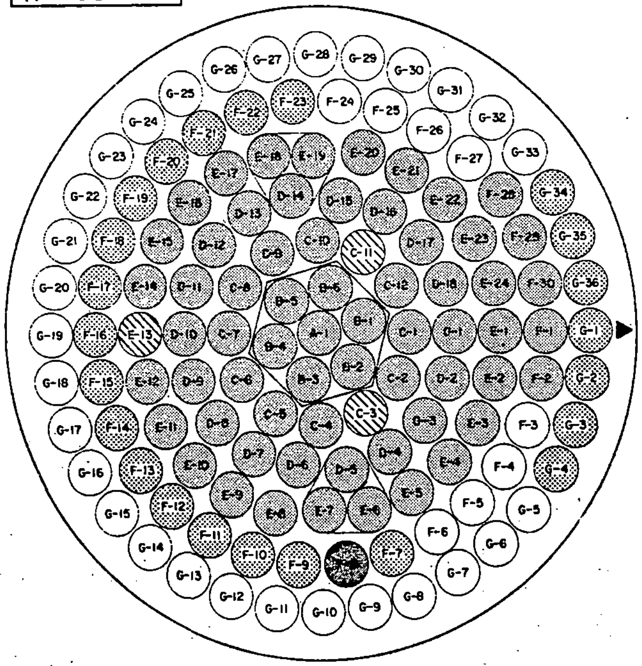
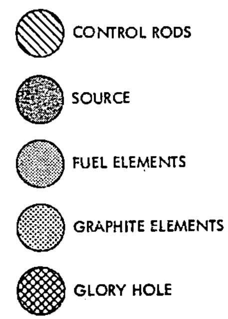
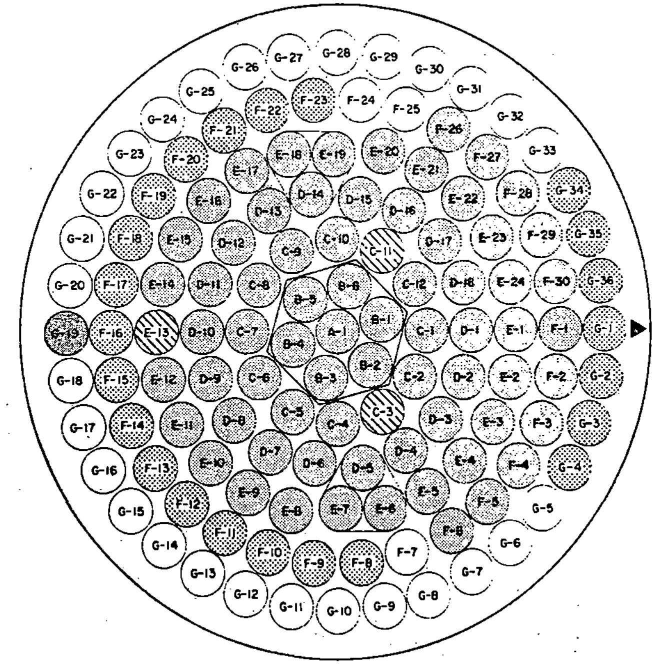


AGNIR CORE LOADING FOR CRITICAL + 20.7¢ EXCESS COLD CLEAN
(SKEWED LOADING PATTERN)

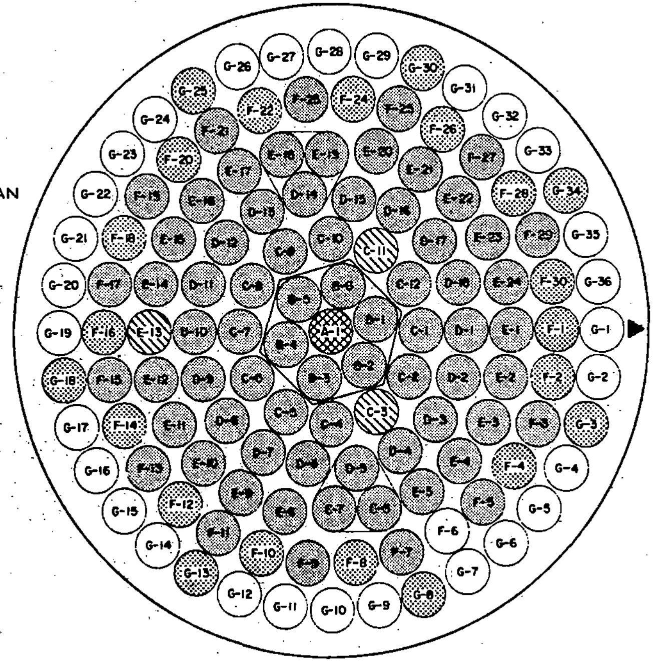
FIGURE 3A.





AGNIR CORE LOADING FOR $2.70 EXCESS COLD CLEAN
(SKEWED LOADING PATTERN)

FIGURE 3B.



AGNIR CORE LOADING FOR $1.80 EXCESS COLD CLEAN
(SYMMETRIC LOADING PATTERN)

FIGURE 3C.

FIGURE 3. AGNIR CORE LOADING PATTERNS

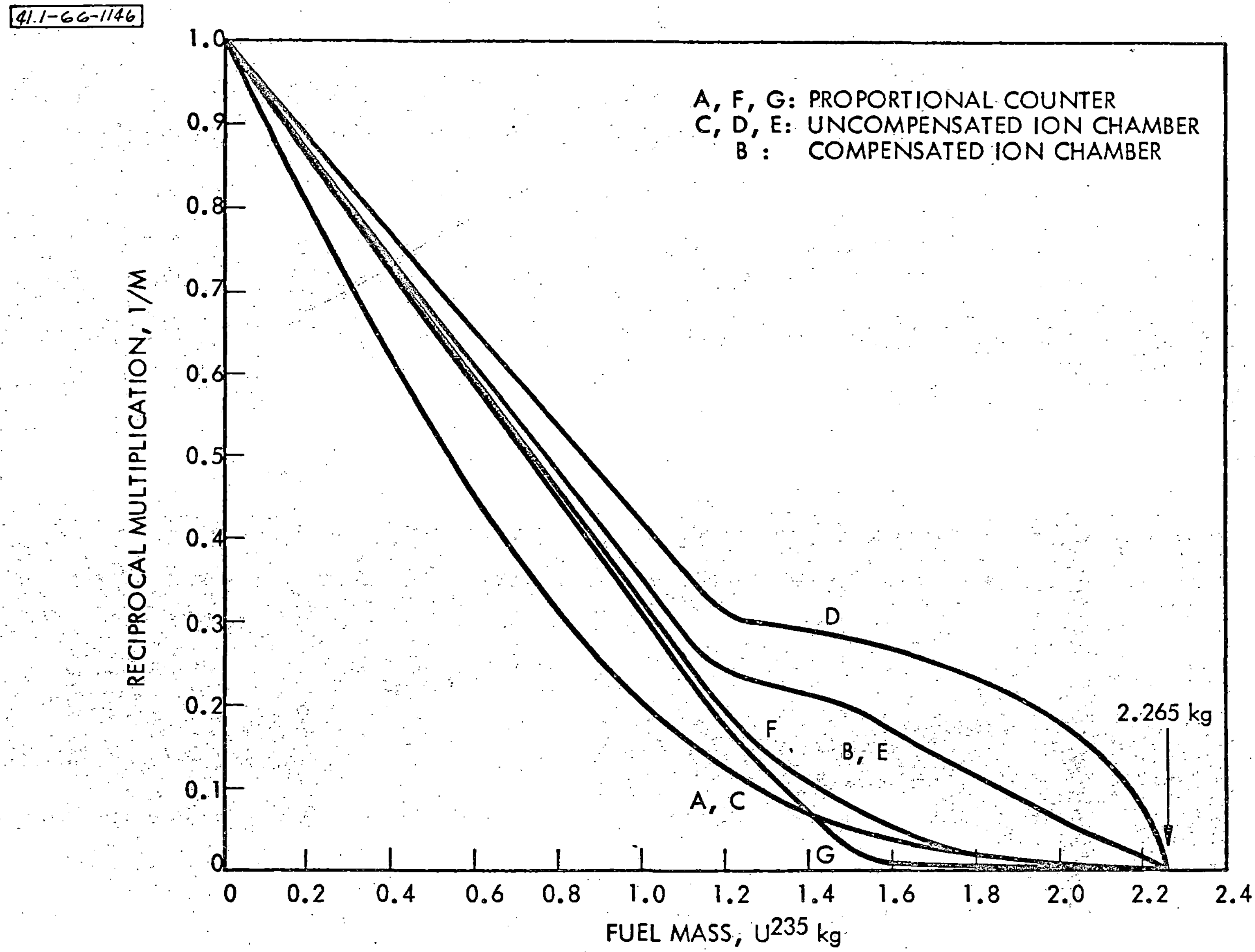


FIGURE 4. AGNIR INITIAL APPROACH TO CRITICALITY

The fuel loading proceeded until a total of 69 fuel elements and 23 graphite elements were loaded into the AGNIR core for a total cold, clean excess of \$2.70 (Figure 3B). The initial control rod calibrations were performed during this loading. The final fuel loading for this configuration is shown in Figure 3B. Preliminary core component reactivity measurements were made with this configuration.

B. SECOND FUEL LOADING

On completion of the preliminary physics tests the AGNIR core loading was adjusted to a nearly symmetric pattern with the "glory hole," a dry exposure tube, located at the geometric center of the reactor (Figure 3C). With 71 TRIGA Mark I fuel elements and 23 graphite elements, the reactor had a cold, clean excess reactivity of \$1.80. The control rod calibrations, core component reactivity measurements, neutron flux traverses, and power calibrations were performed with this basic core configuration.

V. ISOTHERMAL TEMPERATURE COEFFICIENT

The water-filled pool, which serves as a radiation shield and coolant reservoir for the AGNIR, contains approximately 13,000 gallons of water. The water tank was used as a low-grade calorimeter for two thermal measurements: 1) power calibration of the reactor (see Section VII), and 2) the isothermal temperature coefficient and cooling characteristics of the reactor pool tank.

Nineteen 220-volt immersion heaters, with a total measured power rating of 23.9 ± 0.1 kw, were inserted into the reactor grid using the fuel element positions, while water was continuously circulated through a purification loop at the rate of ≈ 6 gpm. While maintaining the reactor critical, the water temperature was monitored at five locations within the reactor pool tank. During the tests, the water temperature was varied from 69° to $125^{\circ}F$. The control rods were calibrated, using both period and rod-drop techniques (see Section VI), prior to measuring the temperature coefficient. As the water temperature of the pool tank is changed, the actual position of the poison section of the control and safety rods differs from the control/safety rod position indicators, because of thermal expansion of the rods. The discrepancy is appreciable since the submerged portion of the control/safety rods is 20.5 ± 0.5 ft during normal reactor operation, the uncertainty in length being due to the

allowable 1 ft variation in the water level within the reactor pool tank. The average value of the isothermal temperature coefficient from 60^{o} to 130^{o}F is -0.15¢/^{o}F (Figure 5). The insertion of control rod poison as a function of bulk water temperature due to the linear expansion of the aluminum hanger rods accounts for the entire coefficient within the accuracy of the experimental measurements.

VI. REACTIVITY MEASUREMENTS

A. TECHNIQUES EMPLOYED

A series of reactivity measurements were performed, using positive period and rod-drop techniques. The circuitry used in performing these measurements is similar to that used at other reactor installations; however, an AGN-developed neutronics code* was used in reducing the data from the rod-drop measurements.

The range of positive periods measured, using this technique, varied between 100 and 10 seconds, which corresponds to excess reactivities from 10 to 40 cents. The reference procedures (Ref. 2) were used during the measurements. The In-Hour Equation used in the period measurements is plotted in Figure 6.

B. CONTROL AND SAFETY ROD CALIBRATIONS

The large reactivity worth of the AGNIR control and safety rod system ($8.51 total) does not allow complete positive period calibration of the shim and safety rods (approximately $3.80 and $3.75, respectively), due to the $3.00 license limitation and the safety interlock on the safety rod. The safety rod is maintained in the "full-out" position during reactor operation; therefore, total worth measurements on all rods were obtained, using rod-drop techniques. Intermediate points on the shim and regulating rods were also obtained with rod-drop techniques and were found to be in good agreement with the period measurements. The calibration curves obtained using these techniques are presented in Figures 7 and 8.

In all reactivity measurements, the accurate determination of criticality is very important. To assist in this determination, an expanded scale was placed on the Channel 4 linear power recorder. Using this recorder,

*Internal Communication: T.P. Wilcox, DROP - An IBM Code to Solve for Reactor Power Levels After a Step Change in System Reactivity, AN-COMP-134

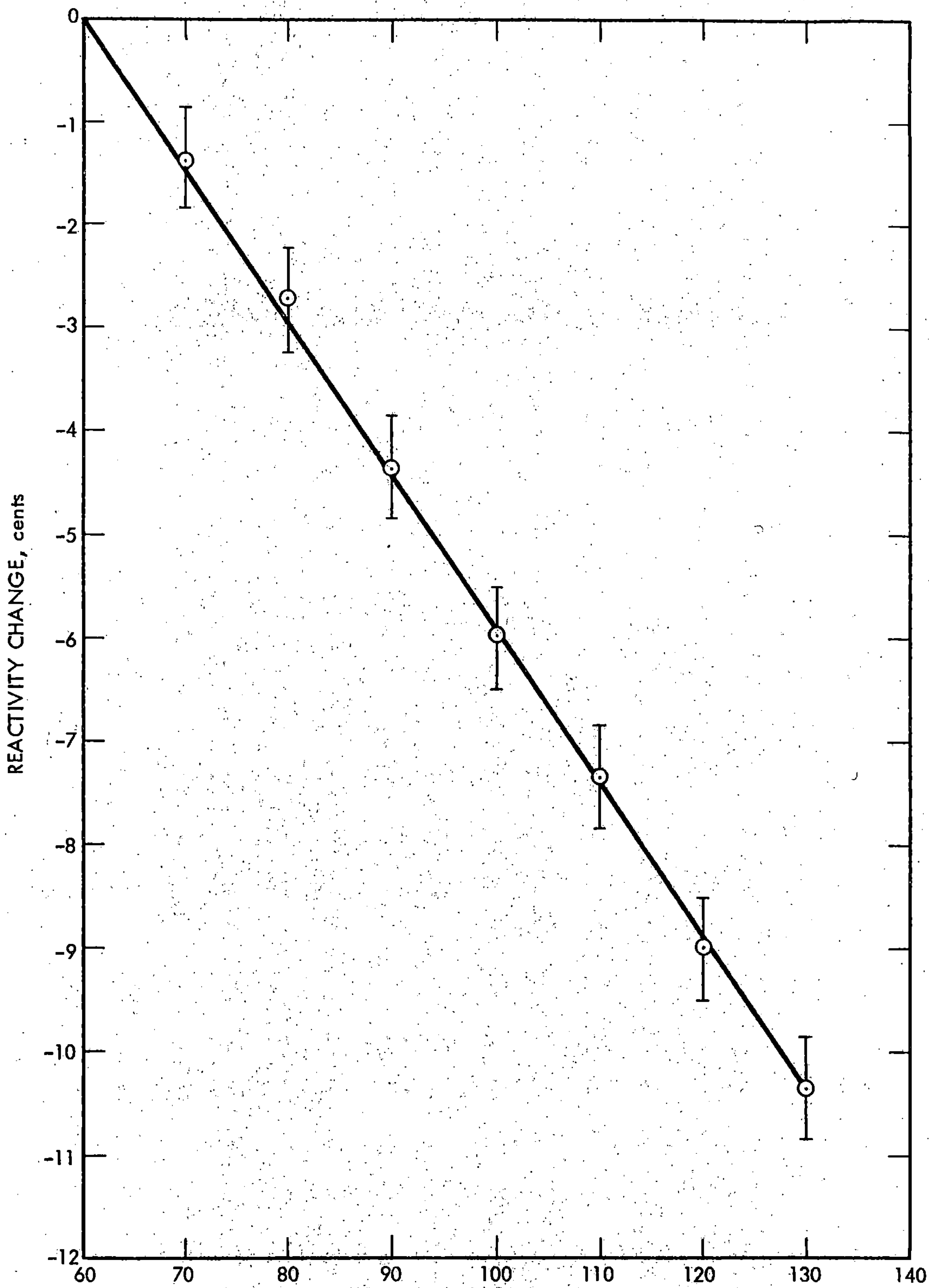


FIGURE 5. AGNIR ISOTHERMAL TEMPERATURE COEFFICIENT

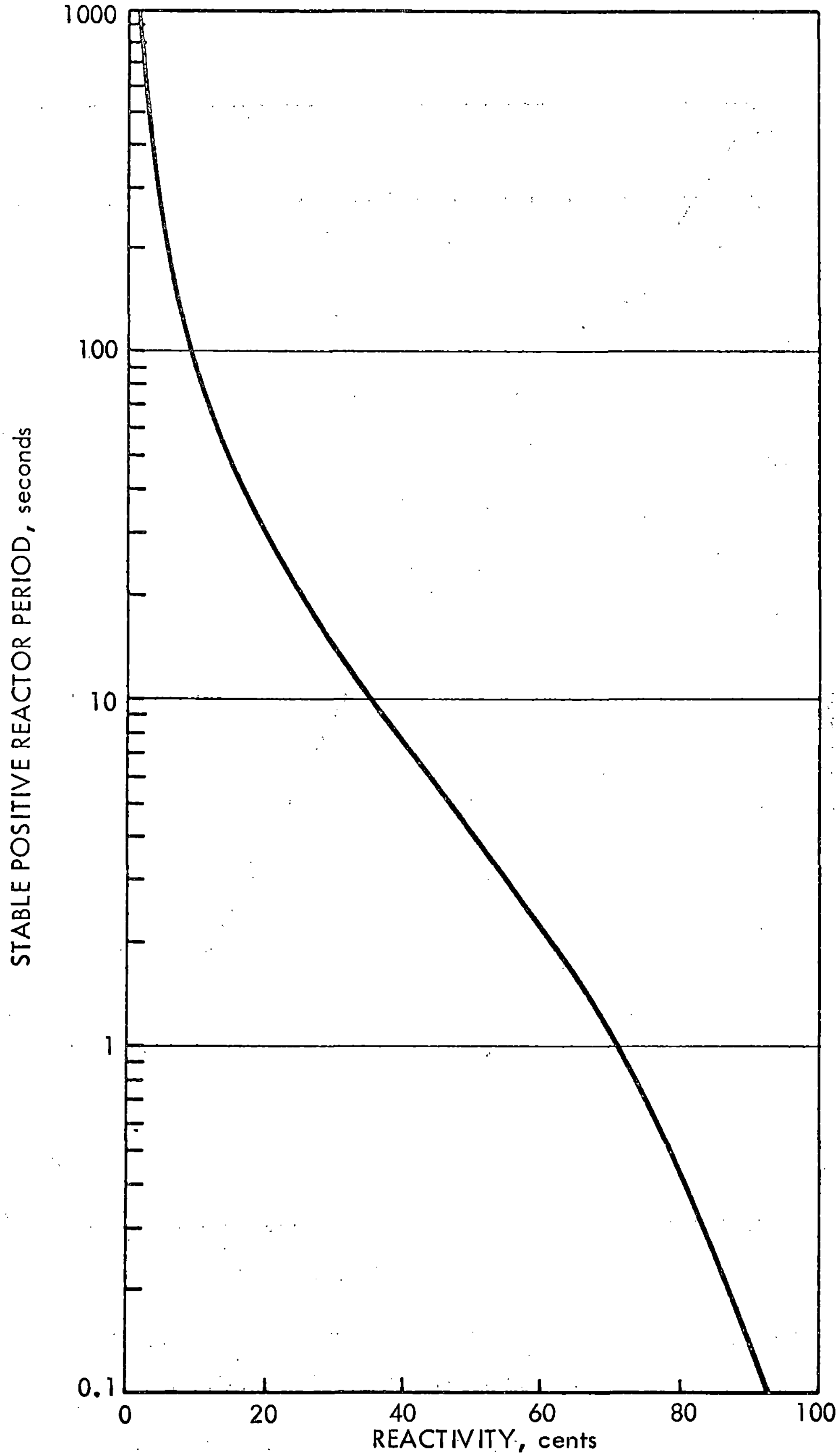


FIGURE 6. AGNIR IN-HOUR EQUATION

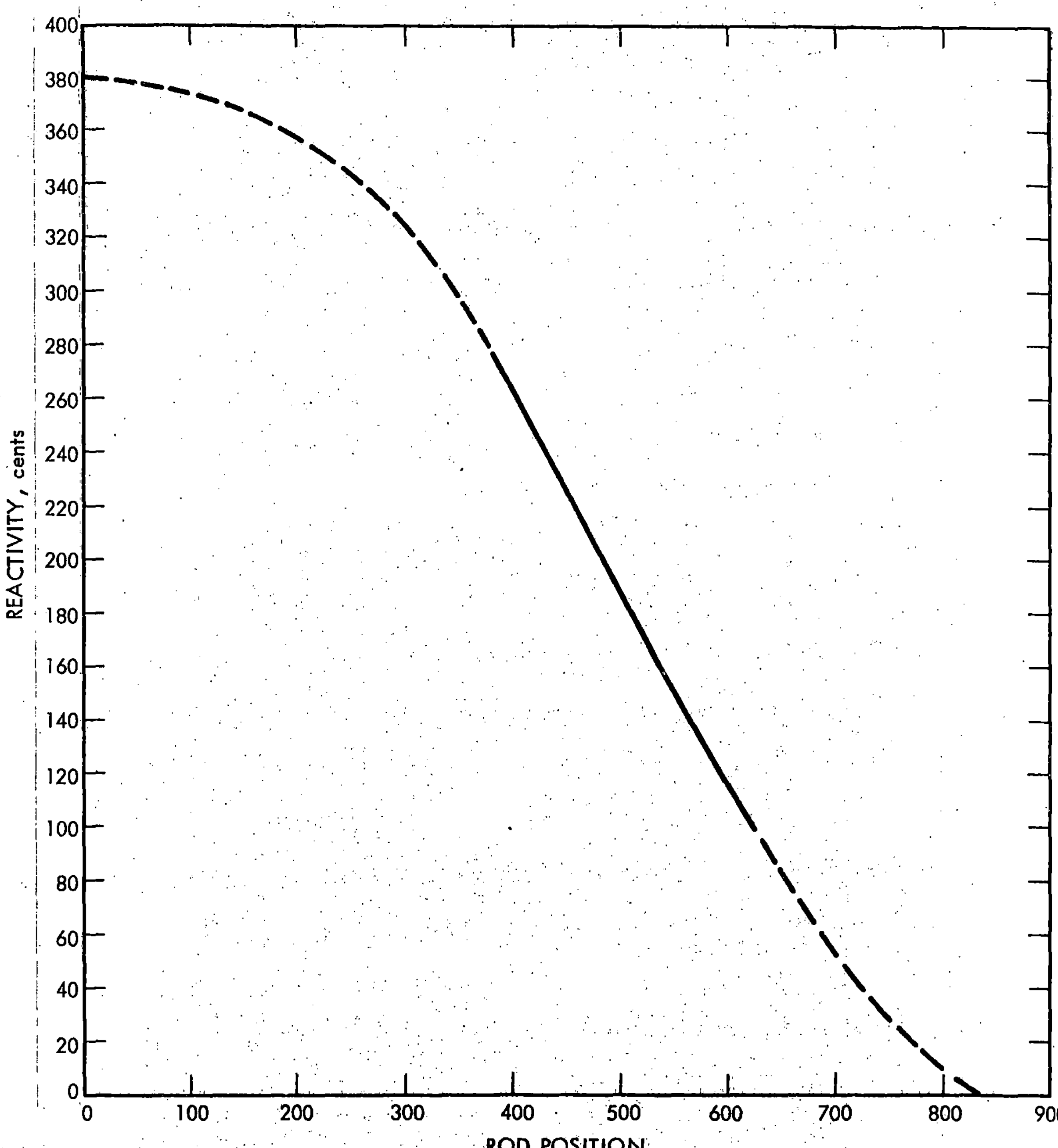


FIGURE 7. AGNIR SHIM ROD REACTIVITY CALIBRATION

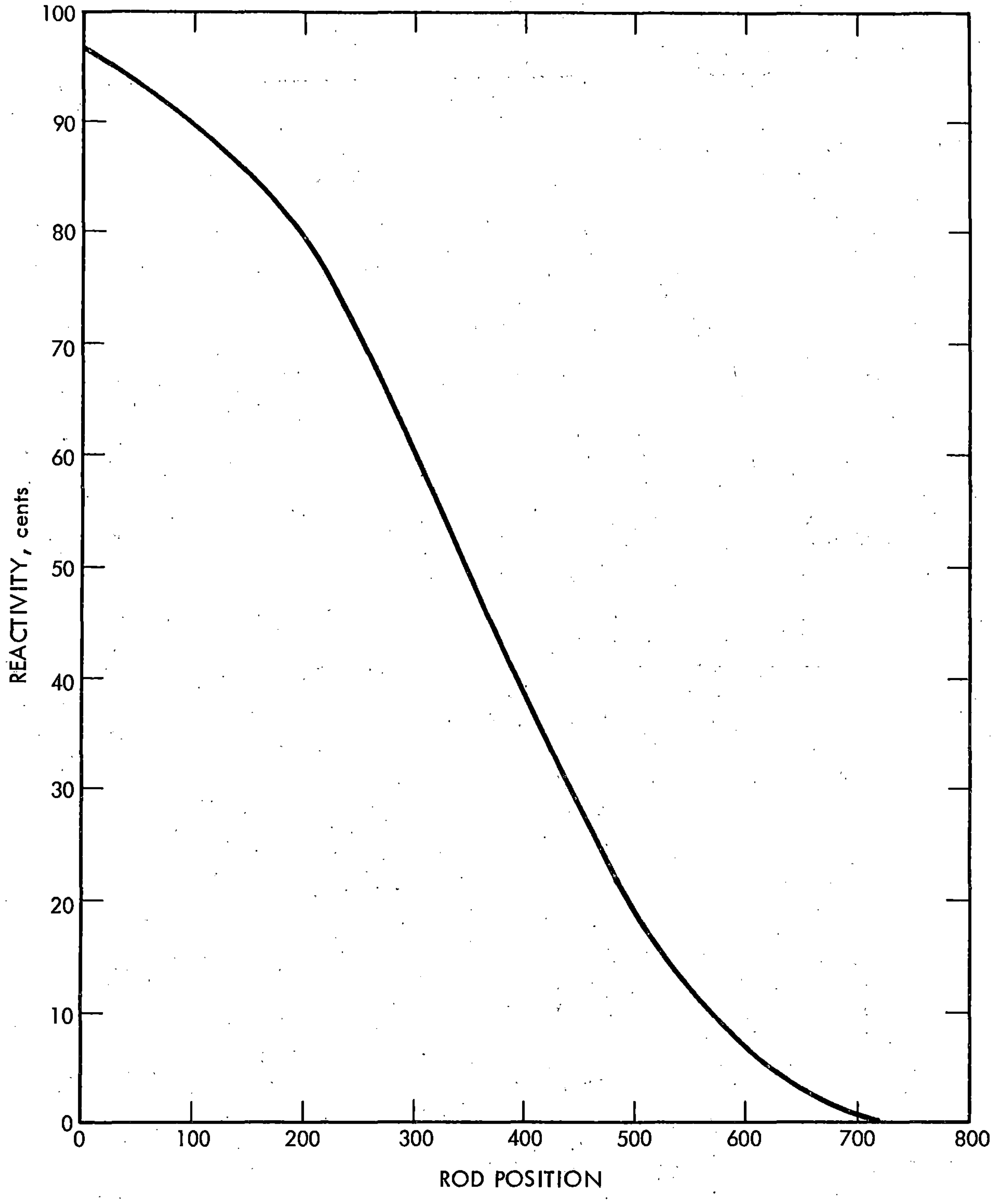


FIGURE 8. AGNIR REGULATING ROD REACTIVITY CALIBRATION

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with its full-range zero suppression and 100-to-1 amplification, minute drifts in power can be readily detected and exact criticality accurately determined.

C. FUEL AND REFLECTOR ELEMENT REACTIVITY MEASUREMENTS

The reactivity worth of the AGNIR fuel elements, dry glory hole, and dummy element irradiation capsule were evaluated as a function of ring position, starting at the geometric center of the reactor grid plate. The fuel measurements and dry glory hole measurements both were made with reference to water. The actual worth measurements are plotted as a function of ring position in Figure 9.

It can be seen that a fuel element in the center of the loading, ring A, is worth less than that in rings B and C, which are almost identical in worth. Since the AGNIR grid structure is basically a TRIGA grid with a few minor modifications, this effect is not what might be expected, a priori; however, in most TRIGA reactors the central core position is occupied with a pulse rod or a nonmovable glory hole and are therefore not available for the placement of fuel. The TRIGA grid is undermoderated in the center and overmoderated at the edge. Starting at the center of the core, the hydrogen/uranium (235) ratio increases approximately linearly with radius. Multigroup neutron transport calculations (Ref. 3, 4) performed on the actual AGNIR core loading indicate a definite depression of thermal neutron flux in the center of the core with a fuel element in the central location. With the central fuel position flooded with water, the standard loading pattern for TRIGA reactors, a normal thermal neutron distribution across the core is obtained (Figure 10). Therefore, the shape of the fuel element reactivity curves shown in Figures 9 and 10 are what would be expected from an analytical basis for the AGNIR with and without a fuel element in the central position.

Graphite reflector elements were evaluated in the F and G rings of the AGNIR core. The average value for these elements were found to be 9 cents for the F ring, and 4 cents and for the G ring.

D. GLORY HOLE MEASUREMENTS

A special dry glory hole is available for various radiation experiments. This glory hole is equipped with an internal shield plug that is used to reduce the radiation streaming in the vicinity of the control rod

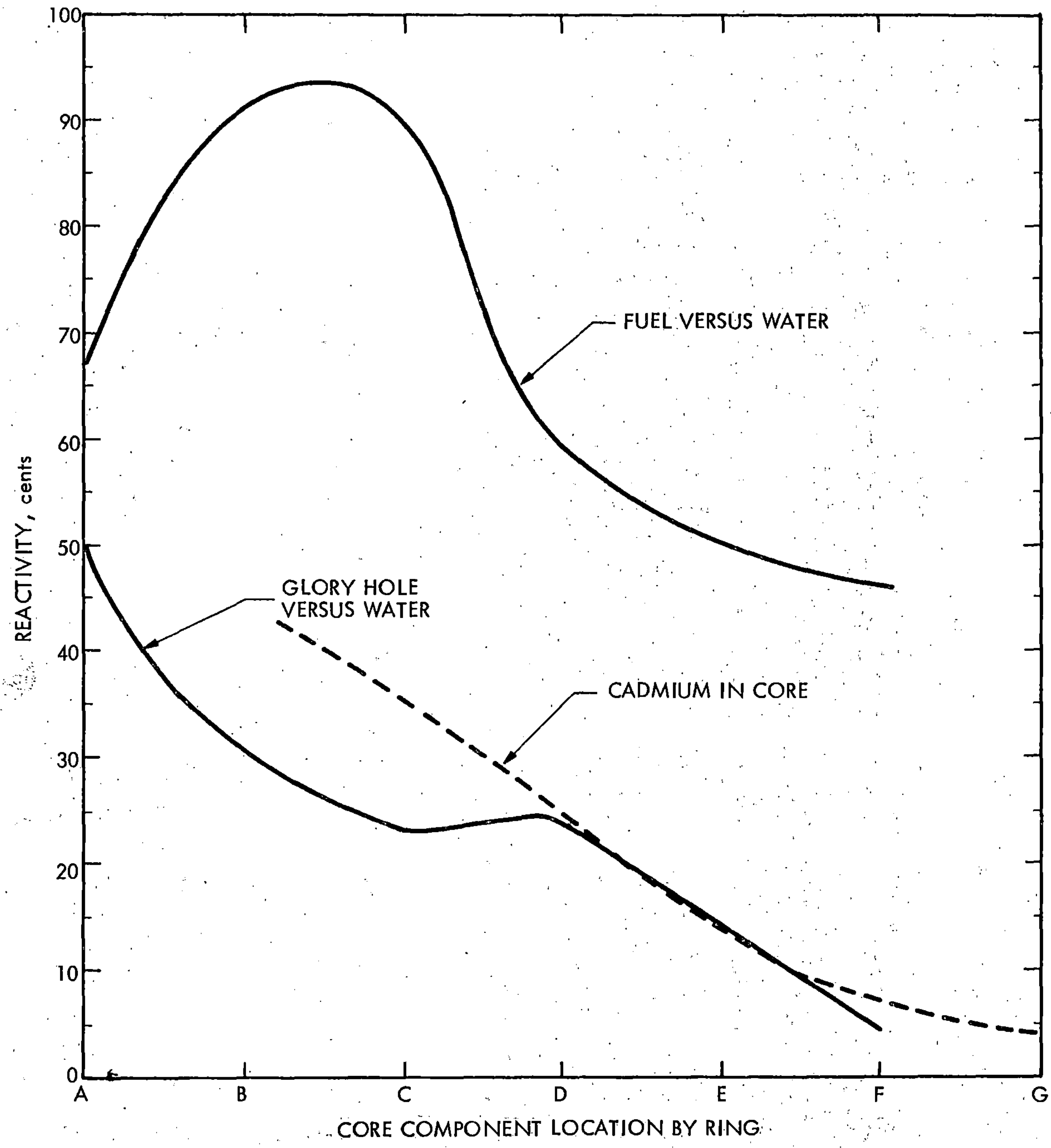

FIGURE 9. AGNIR CORE COMPONENT REACTIVITY WORTH AS A FUNCTION OF CORE POSITION

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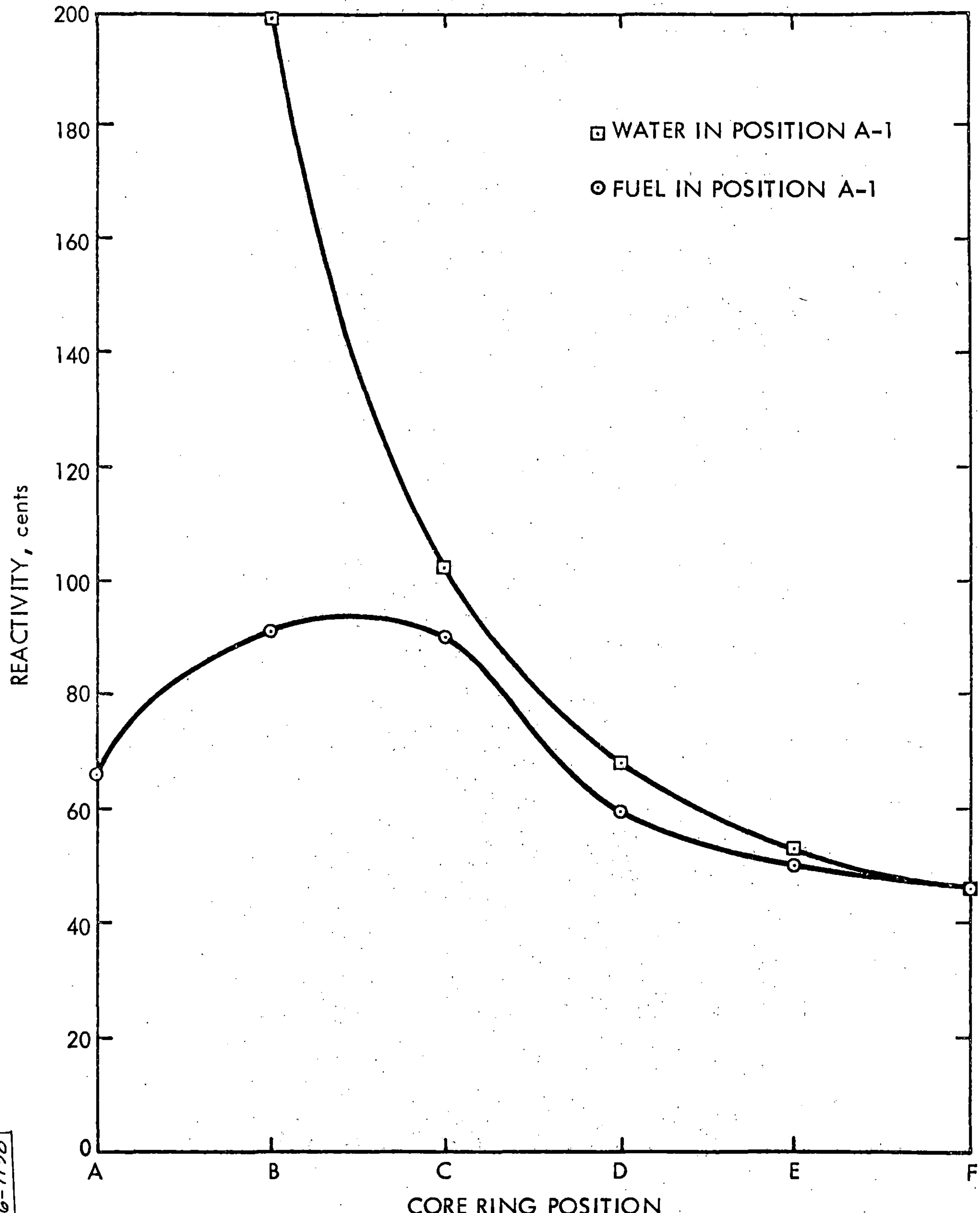

FIGURE 10. FUEL ELEMENT WORTH VERSUS WATER IN THE AGNIR CORE

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drives at the top of the AGNIR pool. The glory hole can be positioned in selected locations in each of the seven rings of the reactor core. The reactivity of water versus the voided glory hole for these locations are shown in Figure 9.

E. DUMMY ELEMENT IRRADIATION CAPSULE MEASUREMENTS

To facilitate special short irradiations of a general nature, an irradiation capsule was designed that could be adapted for a variety of irradiations (Figure 11). It can be located in most fuel element positions and has provisions for bringing instrumented tubes to the surface. A shielded transfer cask is available for transporting the capsule within the AGNIR building to the hot cell area for remote disassembly. The worth of the dummy irradiation capsule versus water in the reactor core was found to be identical in reactivity with the glory hole within the experimental error of the measurements.

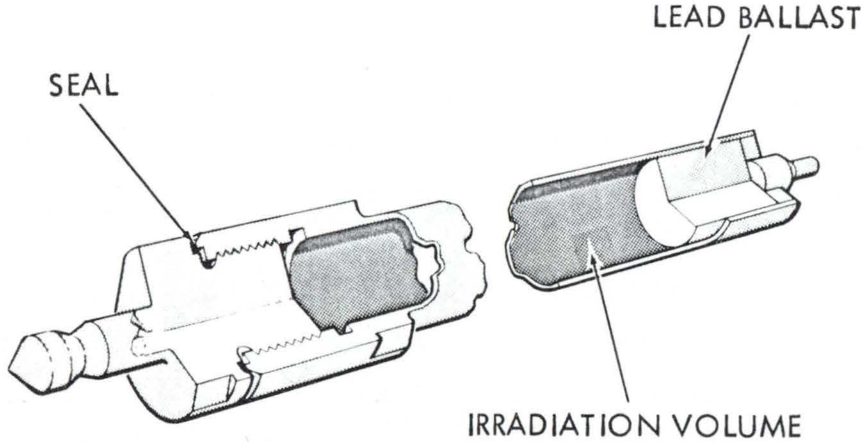

FIGURE 11. AGNIR DUMMY ELEMENT IRRADIATION CAPSULE

F. FLUX WIRE HOLDER MEASUREMENTS

The AGNIR core was designed to allow flux traverses to be readily performed. A total of 22 holes, 0.313 in. in diameter, penetrate the upper and lower reactor grid plates to allow the use of flux measuring wires, or 0.25-in.-diameter (or smaller) neutron-sensitive chambers to be placed in the reactor core. Special aluminum holders for flux measuring wires have been fabricated for use in these holes. The reactivity of these holders, with respect to water, is so low as not to be a consideration in any flux measurements; however, special cadmium tubing used with many flux wire measurements (0.050-in. ID by 0.090-in. OD) has an appreciable effect on the reactivity of the AGNIR. Cadmium tubes, with a length of 26 in. and a weight of 6.63 gm, were inserted in the flux wire holders and their reactivity worth determined. These data are plotted in Figure 9 as a function of core position.

G. THERMAL COLUMN MEASUREMENTS

The AGNIR thermal column consists of a large block of graphite containing five rows of 1.5-in. diameter holes arranged at increasing radii from the core. The rows are placed 6 in. apart, and each row contains seven irradiation positions (Figure 12). Flux wire holder positions are located near the centerline of each row to facilitate performing neutron flux traverses of the thermal column assembly. Four slotted beams, two on each side, are provided to allow experiments to be attached directly to the thermal column. Extensions of these beams allow experiments to be placed immediately adjacent to the reactor core. The assembly is located adjacent to the reactor core on tapered pins and remotely bolted to the bottom of the reactor pool tank. Installation and removal of the whole assembly is accomplished with the facility crane and remote handling tools on a routine basis. Figure 12 also shows a 6-in. dry irradiation tube in one of the rear positions of the thermal column.

When the thermal column was installed, the worth of the column was measured to be less than one cent positive with respect to water, due to the 2-in. gap between the reactor core structure and the thermal column which effectively separates the reactivity effects of the thermal column from that of the reactor core. Neutron flux traverses performed in the thermal column are described in Section IX.

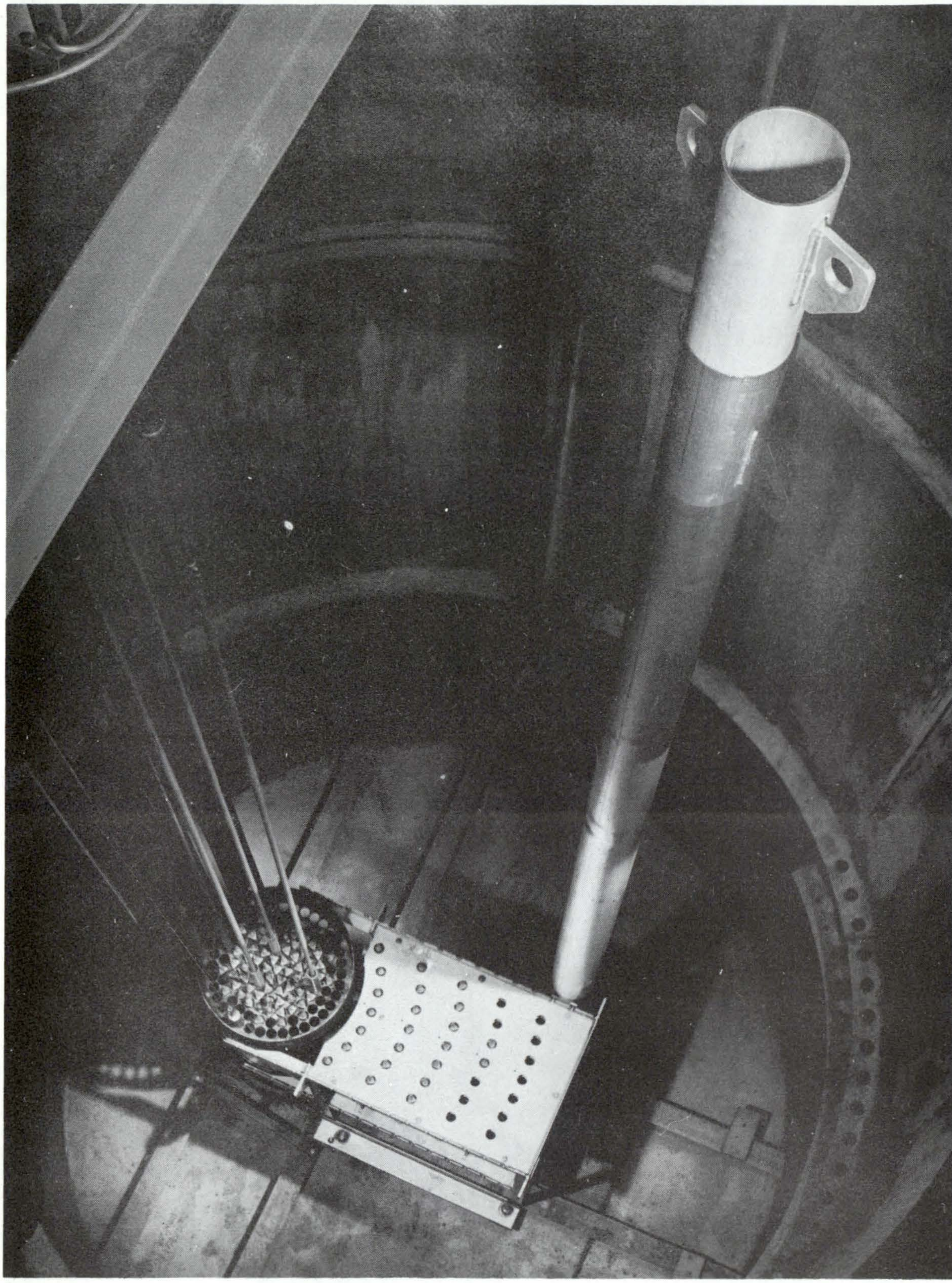

FIGURE 12. DRY IRRADIATION TUBE ON THERMAL COLUMN

H. LARGE COMPONENT IRRADIATION BOX

The large component irradiation box (Figure 13) consists of an aluminum box with an internal volume of 8 cu ft. The walls of the box are relatively thin to eliminate excessive parasitic neutron absorption. The box is pressurized with CO_2 to 0.5 psi above the water pressure with the aid of a relief valve attached to the top of the box. The CO_2 is supplied through aluminum and plastic tubing from a supply at the top of the reactor pool. Another tube is available for bringing electrical leads to the top of the pool if required for any experiment. The box is weighted with lead to eliminate buoyancy. The box is remotely installed and bolted to a movable table at the bottom of the AGNIR pool. Similarly, the movable table is remotely positioned on tapered locating pins and bolted to the bottom of the AGNIR pool.

When the void box was installed, a reactivity loss of 9 cents was measured for the voided box with respect to water. The box is designed to handle the irradiation of components and subsystems up to 2 ft in diameter.

I. XENON POISON EFFECTS

Since AGNIR operates at an average thermal neutron flux of about 4×10^{12} n/cm^2-sec and peaks at about 10^{13}n/cm^2-sec at the center of the reactor core, the effects of xenon poisoning on the operation are appreciable. A test was run on the cold, clean reactor core to determine more specifically the magnitude of these effects. The reactor was held at a constant power level of 250 kw and a constant pool temperature of 85°F for 50 hours during the test. Using the control rod calibrations, the effect of xenon poisoning as a function of operating time was determined (Figure 14). Similarly, the poison worth of xenon was measured following shutdown by making criticality determinations at low power level and correcting for the power coefficient (Figure 15) and isothermal temperature coefficient effects (Figure 5). The results of these data are also plotted in Figure 14.

VII. POWER CALIBRATIONS

An accurate method of reactor power level determination for pool-type reactors is electrical heat substitution (Ref. 5). The reactor pool tank (containing 13,000 gallons of water) was determined to be a fair calorimeter between 70 and 95°F. As previously discussed in Section IV, nineteen 220-volt immersion heaters (with a total measured power rating of 23.9 ± 0.1 kw) were

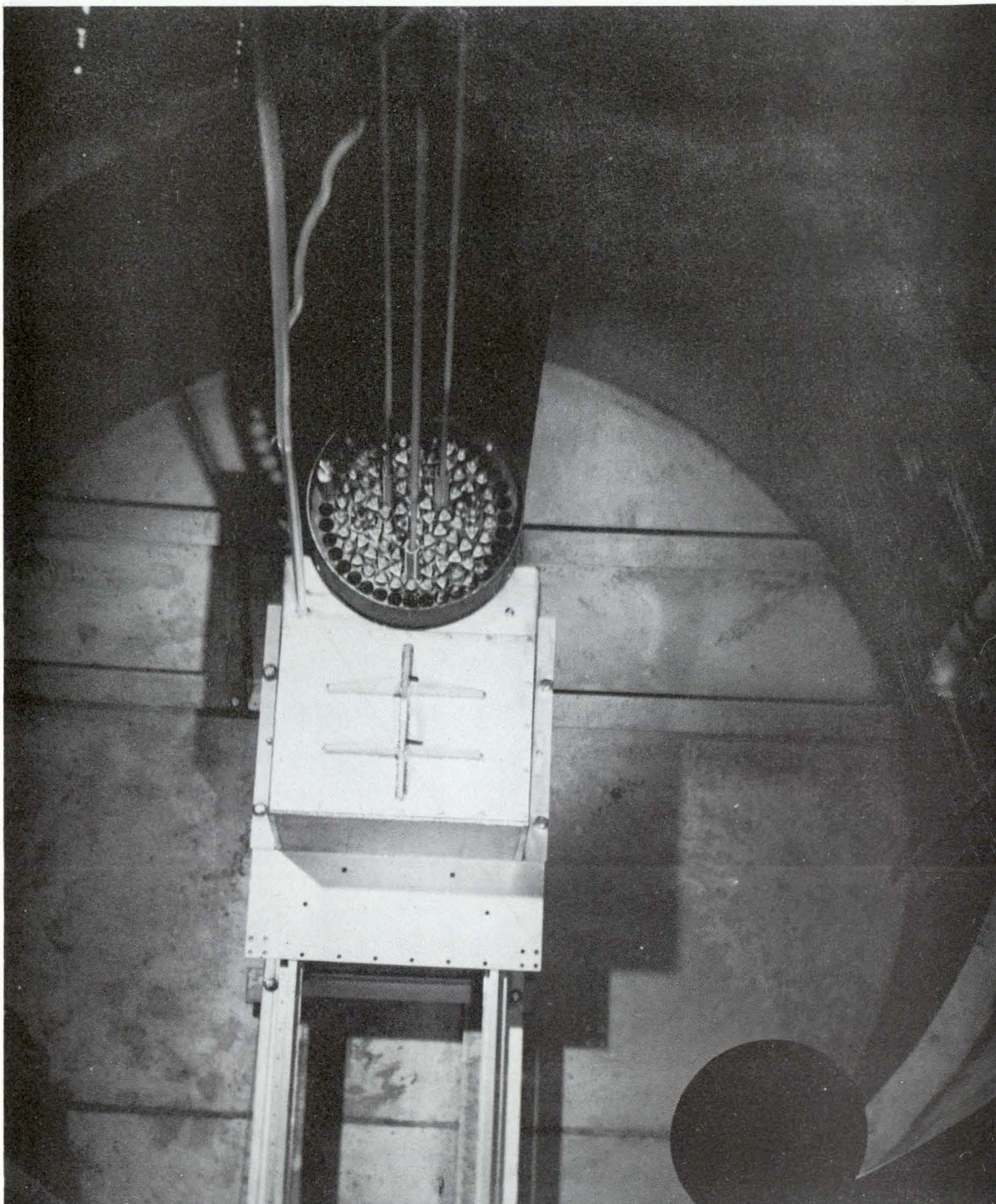

FIGURE 13. LARGE COMPONENT IRRADIATION BOX

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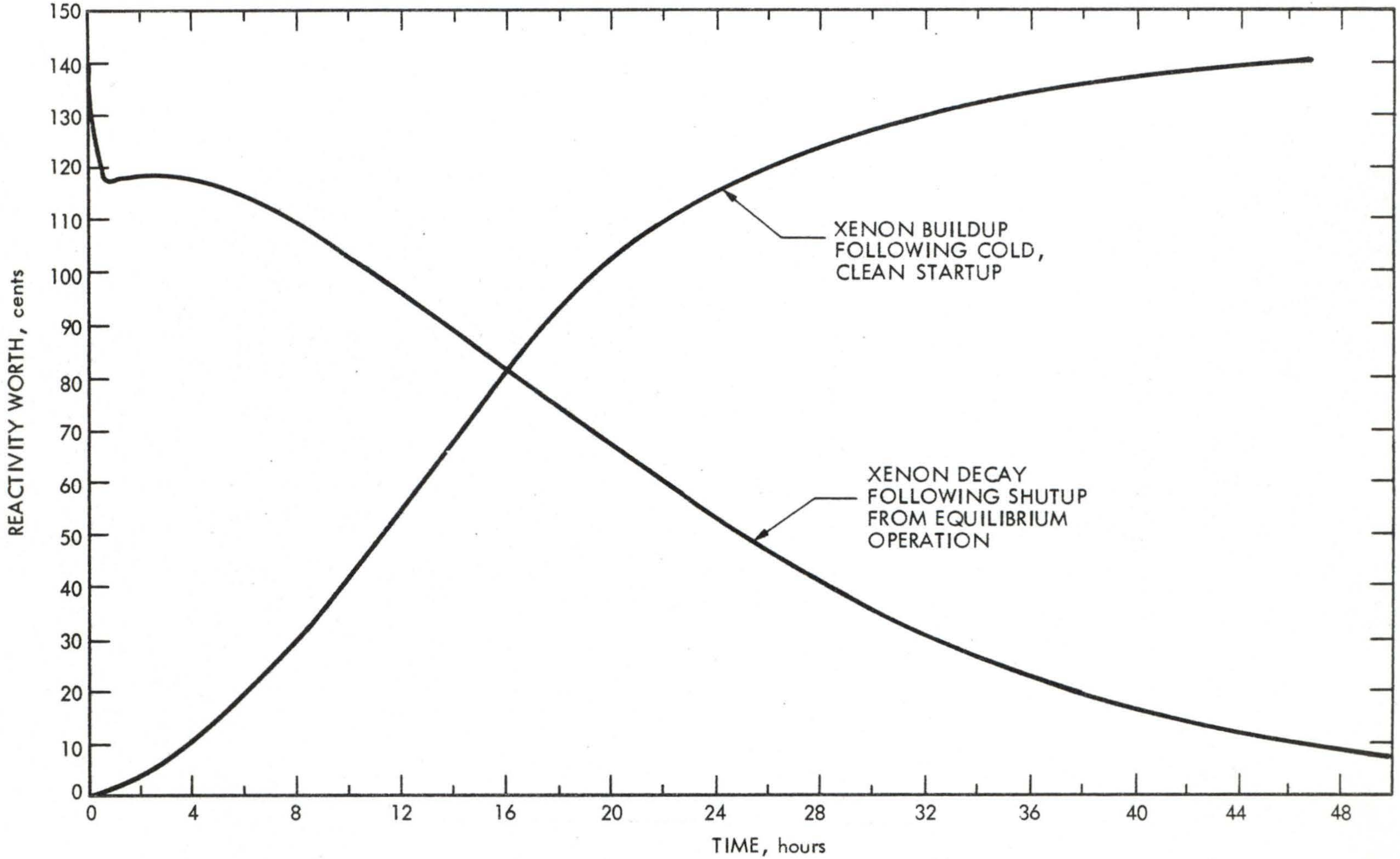

FIGURE 14. XENON POISON EFFECTS IN AGNIR VERSUS TIME

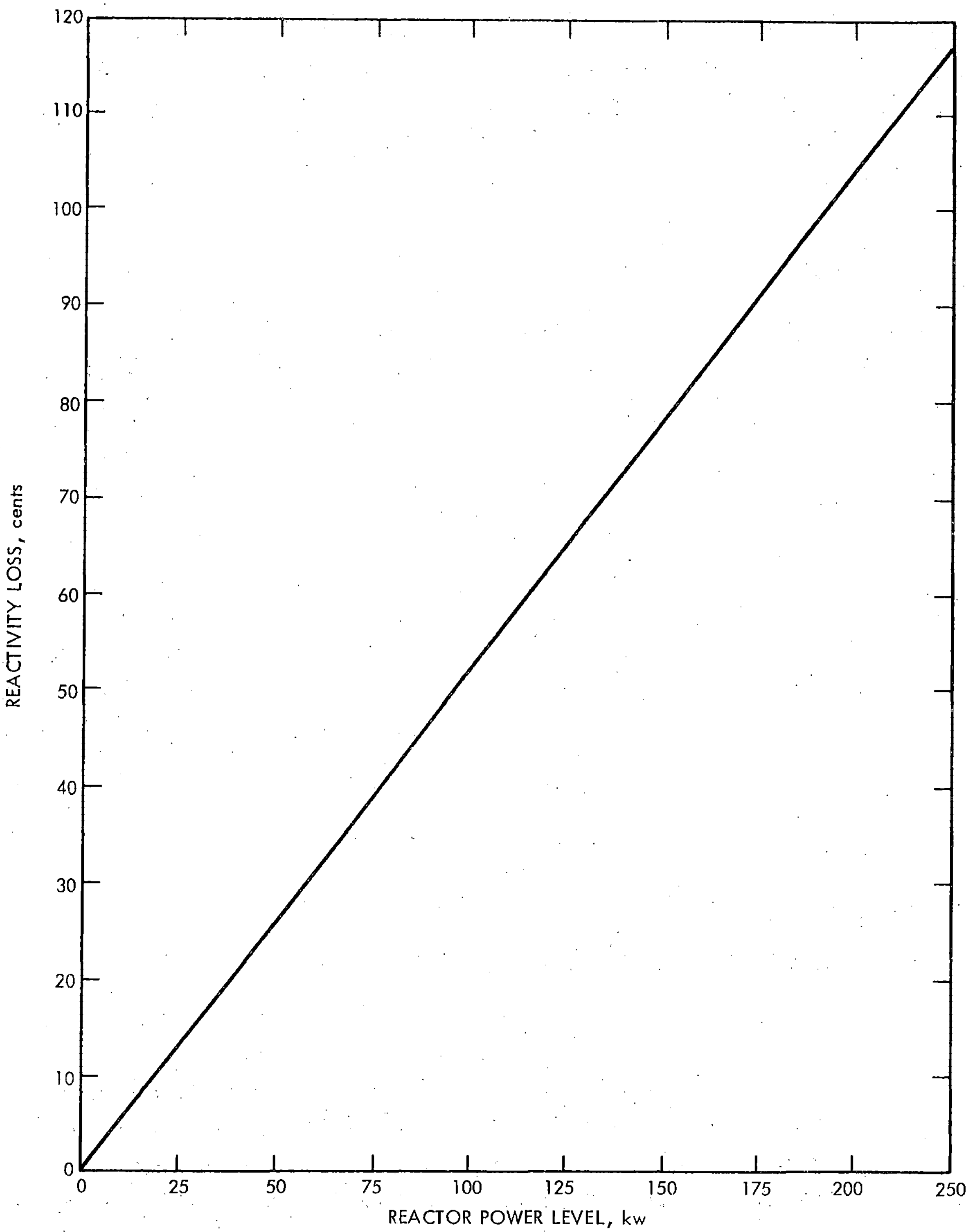

FIGURE 15. AGNIR POWER COEFFICIENT OF REACTIVITY

inserted into the reactor grid, using the fuel element positions, while the water was continuously circulated through a purification loop at ≈ 6 gpm. Since the inlet to the purification loop is near the top of the reactor pool tank and the discharge near the bottom, this flow slowly stirs the pool water, thereby reducing temperature stratification within the tank. The water temperature was monitored at five locations within the reactor pool tank. Plots of the heating and cooling characteristics of the pool water tank are shown in Figures 16 and 17. Once the 23.9 kw electrical heating curve was obtained, the reactor was flux-mapped at low power* and the corresponding readings of the Channels 3 and 4 ion chambers were made. The flux traverses were made at an estimated power level of 160 w, based on thermal flux integration techniques. Using this estimated power as a basis, a scale factor was applied to the ion chamber readings corresponding to a power level of 23.9 kw. A 24-hr nuclear heating run was performed at these ion chamber readings. The actual power level was found to be 34.32 ± 0.93 kw, based on the previously performed electrical heating data; therefore, the initial flux mapping was performed at 230 watts instead of the estimated 160 watts (Figure 17).

Subsequent nuclear heating runs were performed at 200 kw and 250 kw (Figure 16). Due to the increased heating rate over the initial calibration runs, the heating curves at these power levels are practically linear and do not show the effects of water evaporation that occurs at the lower heating rates. At pool temperatures of 70°F, the water evaporation was found to be about 0.5 gallons/hr; while at 125°F, the rate increased to 5 gallons/hr. The cooling curve in Figure 16 clearly shows the operating limitations of the AGNIR without its 250-kw heat exchanger.

VIII POWER COEFFICIENT MEASUREMENT

The power coefficient (i.e., the reactivity loss as a function of reactor power) was measured at constant water temperature without xenon in the core. Using the control rod calibration curves, the reactor power was increased in 25-kw steps above delayed critical and the reactivity loss determined. A plot of the data is shown in Figure 15. The measured average reactivity coefficient was found to be approximately -0.47¢/kw, for a total reactivity loss at 250 kw of $1.17.

*Internal Communication: V.R. Forgue, Gold Wire Flux Mapping of AGNIR, AGN Chem Tech Memo No. 887, October 1965.

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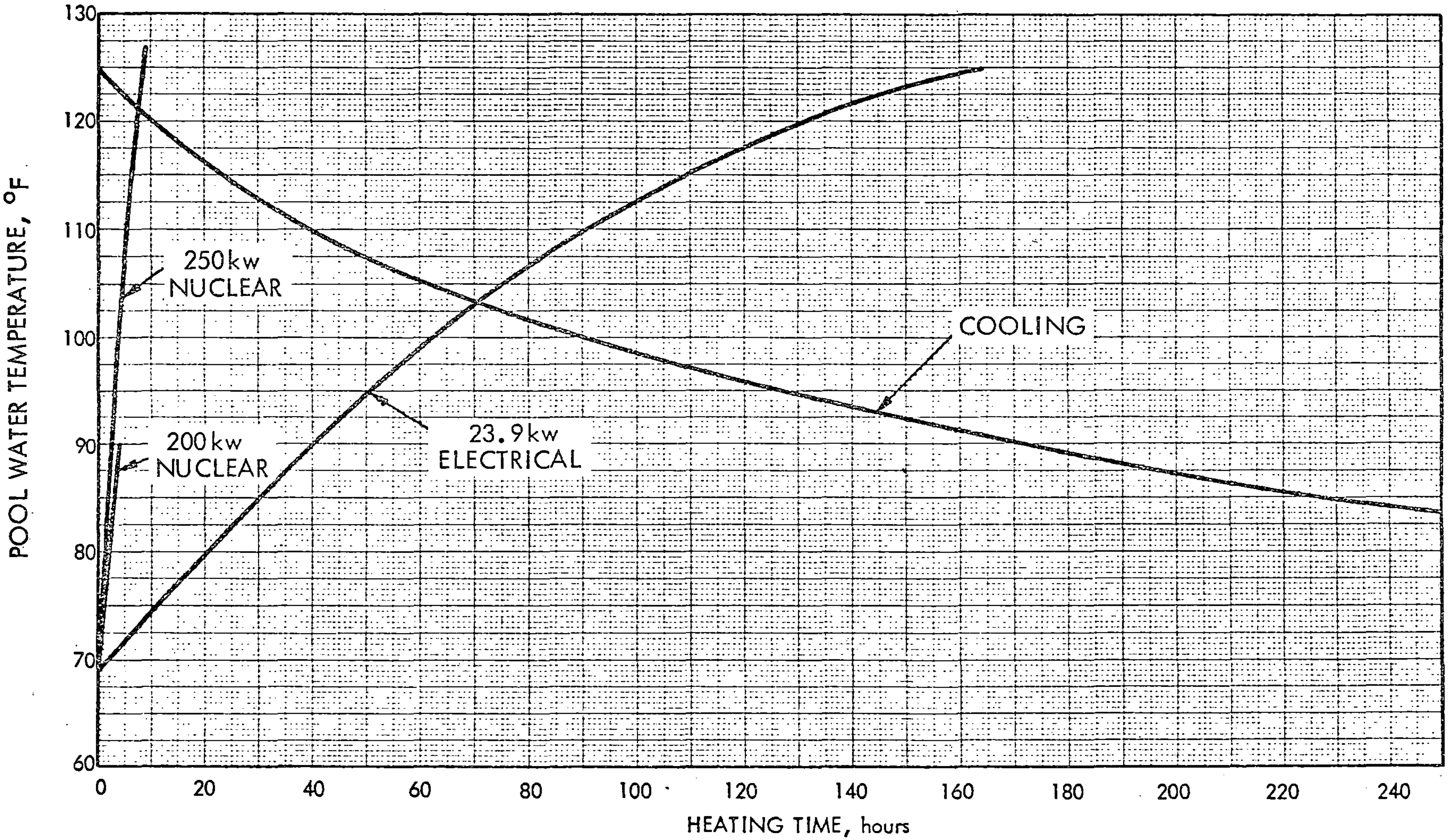

FIGURE 16. AGNIR POOL WATER HEATING AND COOLING DATA (WITHOUT HEAT EXCHANGER)

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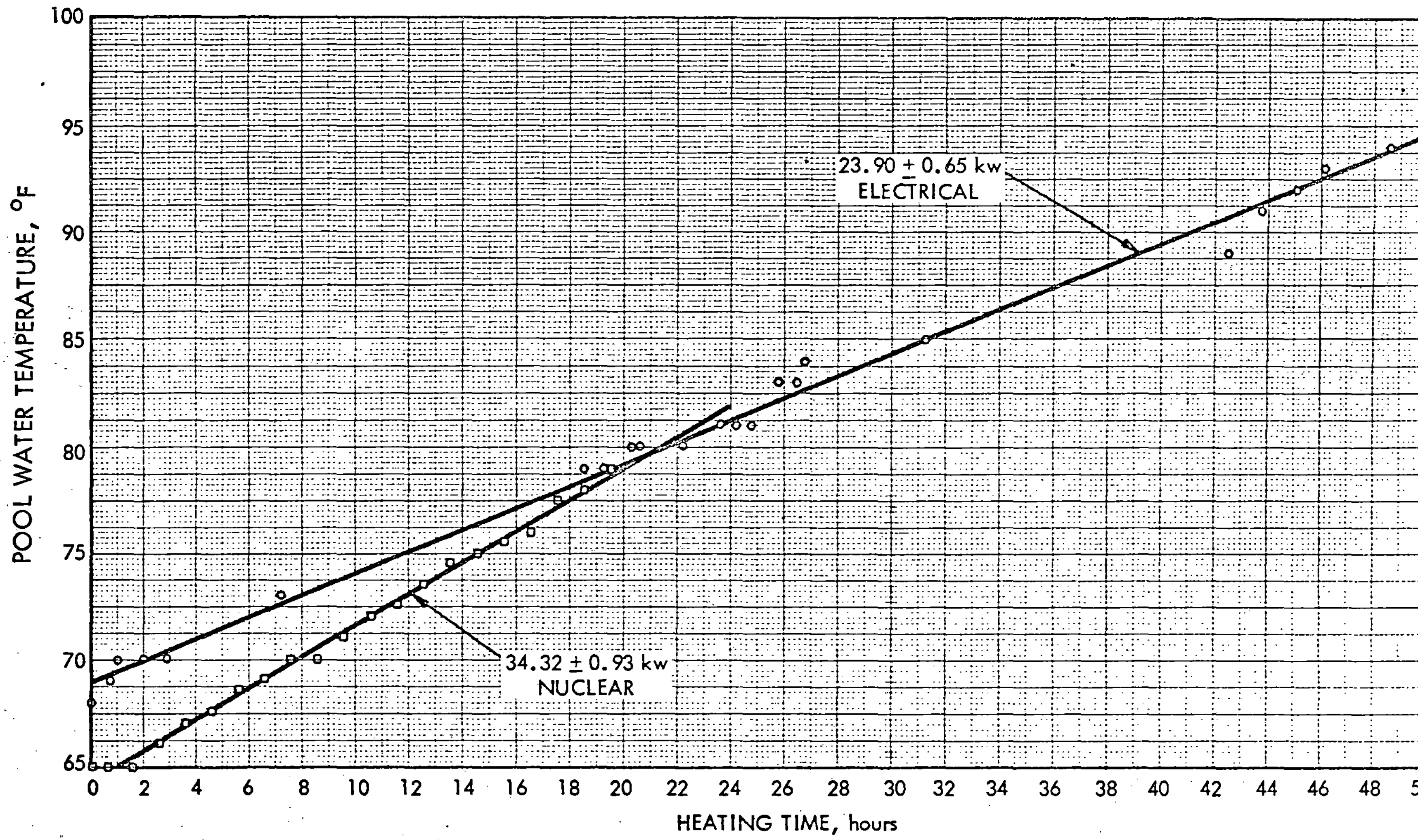


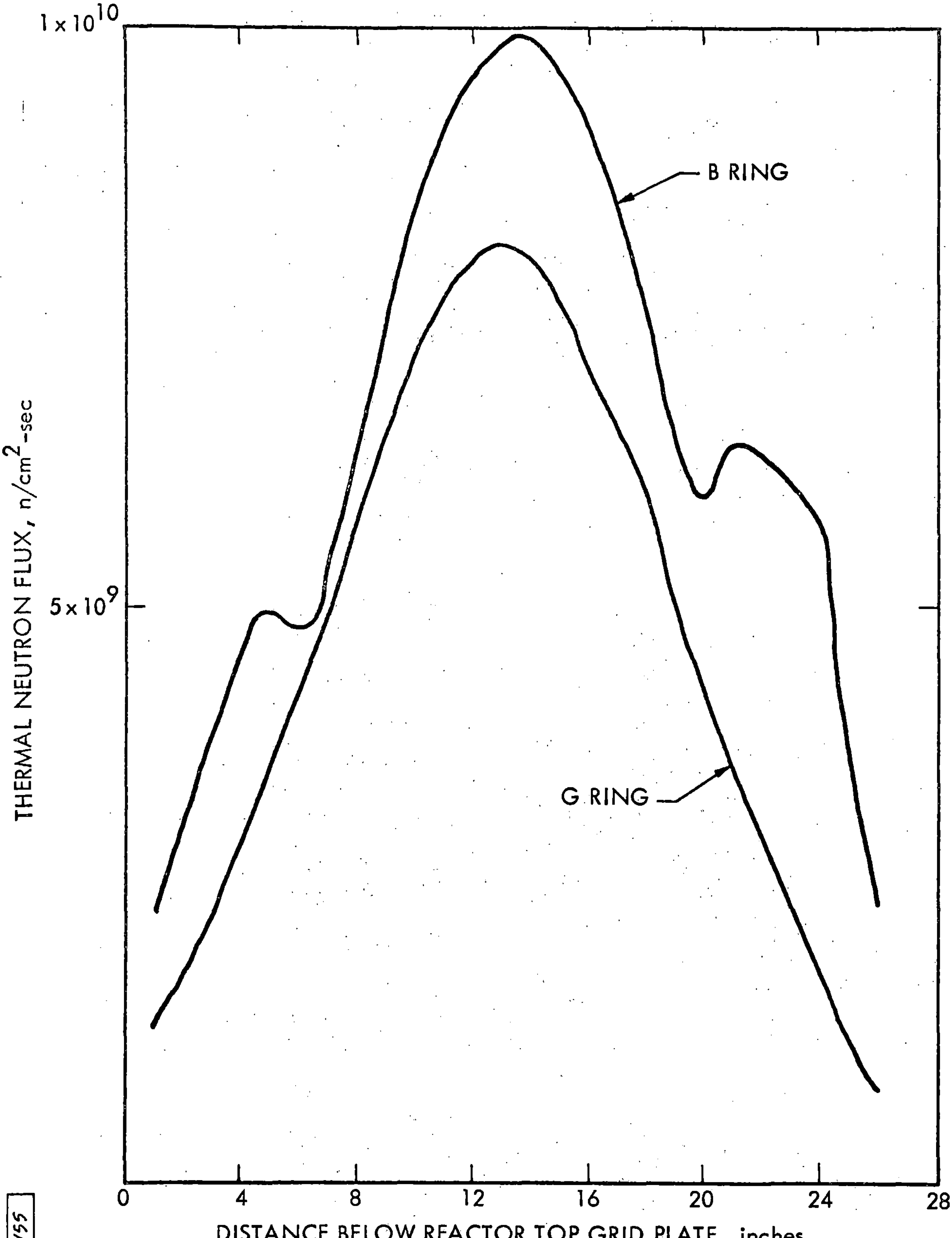
FIGURE 17. AGNIR CALORIMETRIC POWER CALIBRATION

IX. NEUTRON FLUX TRAVERSES

The thermal neutron flux mapping of the AGNIR core and thermal column was performed using 0.010 in. diameter gold wires inserted into the AGNIR flux wire holders and irradiated in the AGNIR core and thermal column, using the 28 flux wire positions (22 in the core and 6 in the thermal column - see Section VI-F). Epicadmium measurements were made, using 0.050 in. ID by 0.090 in. OD cadmium tubes with the 0.010 in. gold wires running axially down the tubes. The 26-in. long gold wires were cut into 2-in. increments and wrapped around a dowel to form an 0.32 in. diameter ring and counted on a scintillation counter that had been previously standardized with 0.002 in. by 0.50 in. diameter gold foils by reference to a National Bureau of Standards calibrated neutron flux. In regions of the AGNIR core where the neutron flux changes rapidly with position, 1/2-in. long wires were used. The 0.010 in. gold wire and the standard 0.002 in., 0.5-in. diameter gold foils were cross-calibrated, using the AGN 201M reactor (basic AGN-201 reactor modified for 20-watt operation). A typical axial thermal flux plot performed in the B and G rings of the AGNIR is shown in Figure 18. The B ring represents the flux plot at the center of the core, while the G ring represents the flux distribution in the reflector region. Figure 19 shows the thermal neutron distribution radially across the AGNIR core at the center-line of the fuel. Figure 20 shows the thermal neutron distribution radially across the centerline of the AGNIR core and thermal column. The details of the thermal neutron flux measurements were documented earlier*.

*Internal Communications: V.R. Forgue, Gold Wire Flux Mapping of AGNIR, AGN Chem Tech Memo No. 887, October 1965.

V.R. Forgue, Flux Traverse in AGNIR Thermal Column, AGN Chem Tech Memo No. 952, March 1966.



4.1-66-1155

FIGURE 18. AXIAL THERMAL NEUTRON DISTRIBUTION IN THE AGNIR CORE AT A POWER LEVEL OF 230 WATTS

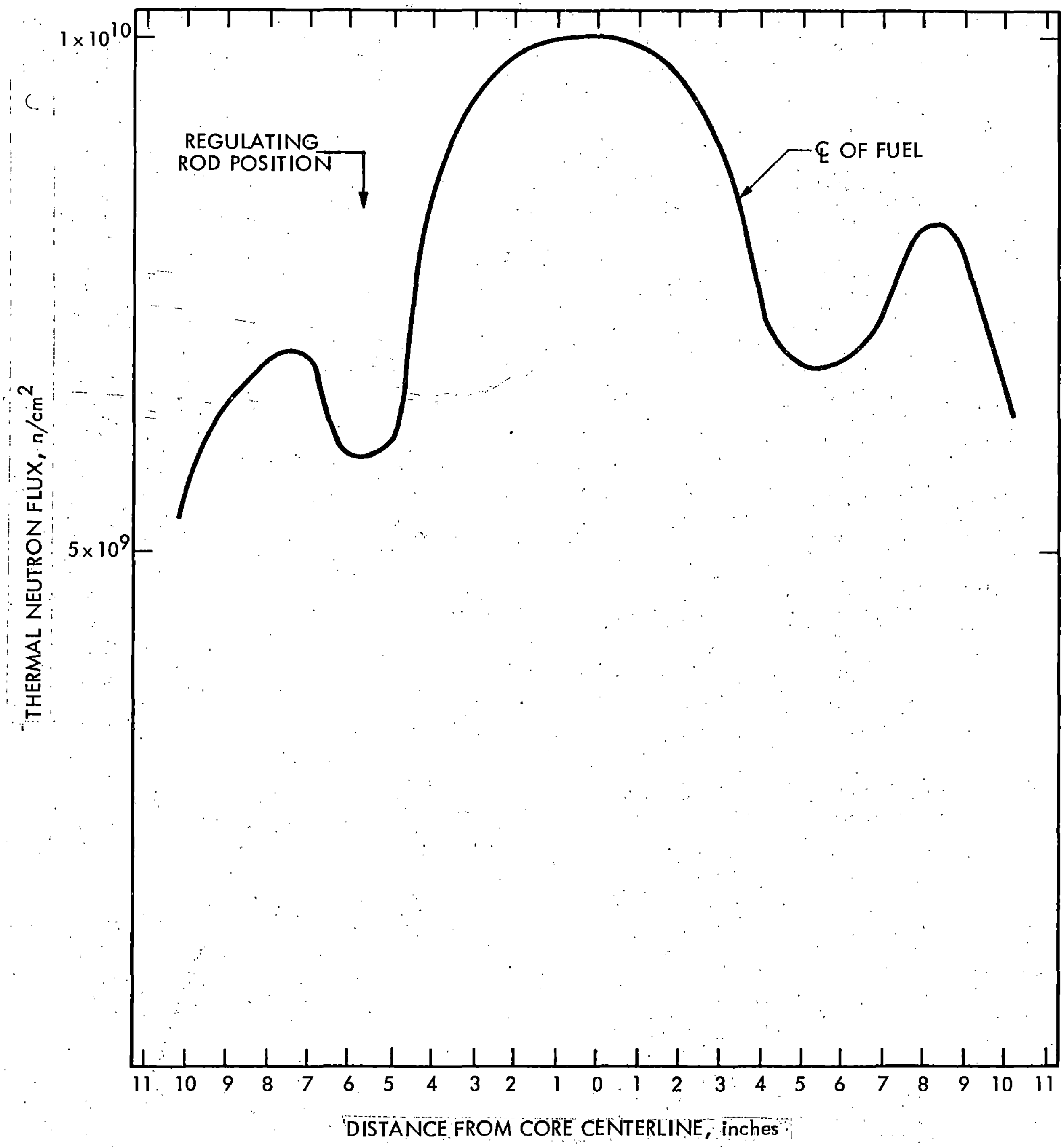


FIGURE 19. RADIAL THERMAL NEUTRON DISTRIBUTION IN THE AGNIR CORE (230 WATTS)

41.1-66-1156

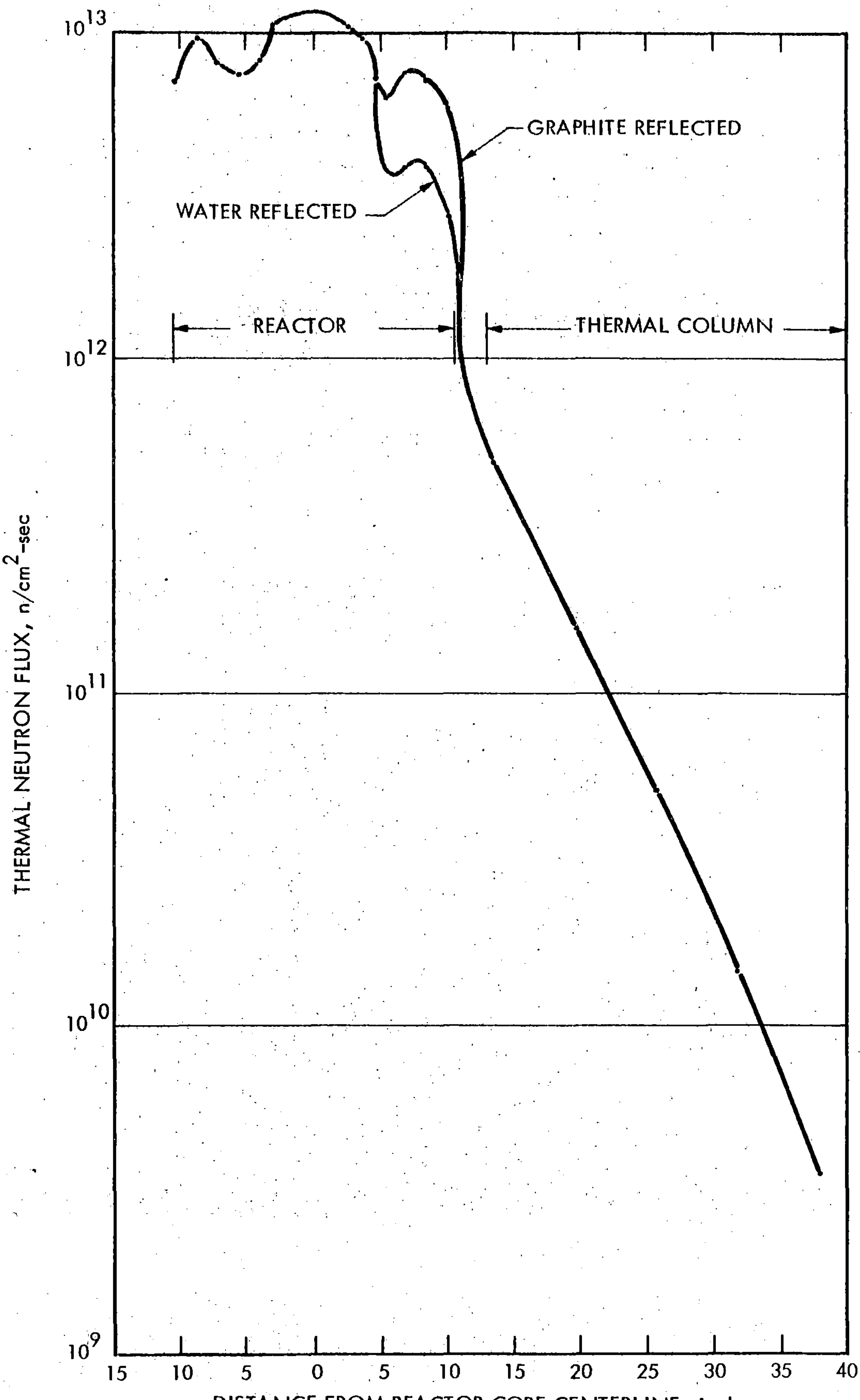


FIGURE 20. RADIAL THERMAL NEUTRON DISTRIBUTION IN AGNIR CORE AND THERMAL COLUMN

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