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STARTUP TEST TECHNIQUES FOR HTGRS

by

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1. INTRODUCTION

Startup test techniques that have been used to verify reactor physics calculations for High Temperature Gas-Cooled Reactors (HTGRs) will be discussed. These test techniques are different from those used with Light Water Reactors (LWRs) because of specific differences between the HTGR and the LWR. Some of the HTGR characteristics that influence the startup test techniques will be evident in the following brief description of the Fort St. Vrain (FSV) HTGR core design.

The FSV HTGR fuel element is a right hexagonal graphite block, 32 inches high and 14 inches across hexagonal flats, drilled axially with fuel and coolant holes. The fuel is enriched uranium and thorium in the form of small particles coated with carbon and silicon, bonded together in a graphite matrix to form fuel rods approximately one-half inch in diameter and two inches long which are stacked in the fuel holes of the graphite fuel element. The fuel elements are stacked in columns six elements high with 37 refueling regions containing seven columns each. The central column of each region contains holes for a pair of control rods and a hole for emergency shutdown use into which boronated graphite balls can be dropped. Figure 1 shows these fuel elements. Figure 2 shows a plan view of the core. The active core dimensions are 19.5 ft. diameter by 15.6 ft. high. The active core is surrounded by a graphite reflector approximately three foot thick. Above each of the 37 refueling regions is a penetration through the prestressed concrete reactor vessel (PCRV) into which the 37 control rod drive mechanisms are inserted and through which the region can be refueled with the control rod drive mechanism removed.

HEX-BLOCK FUEL ELEMENT

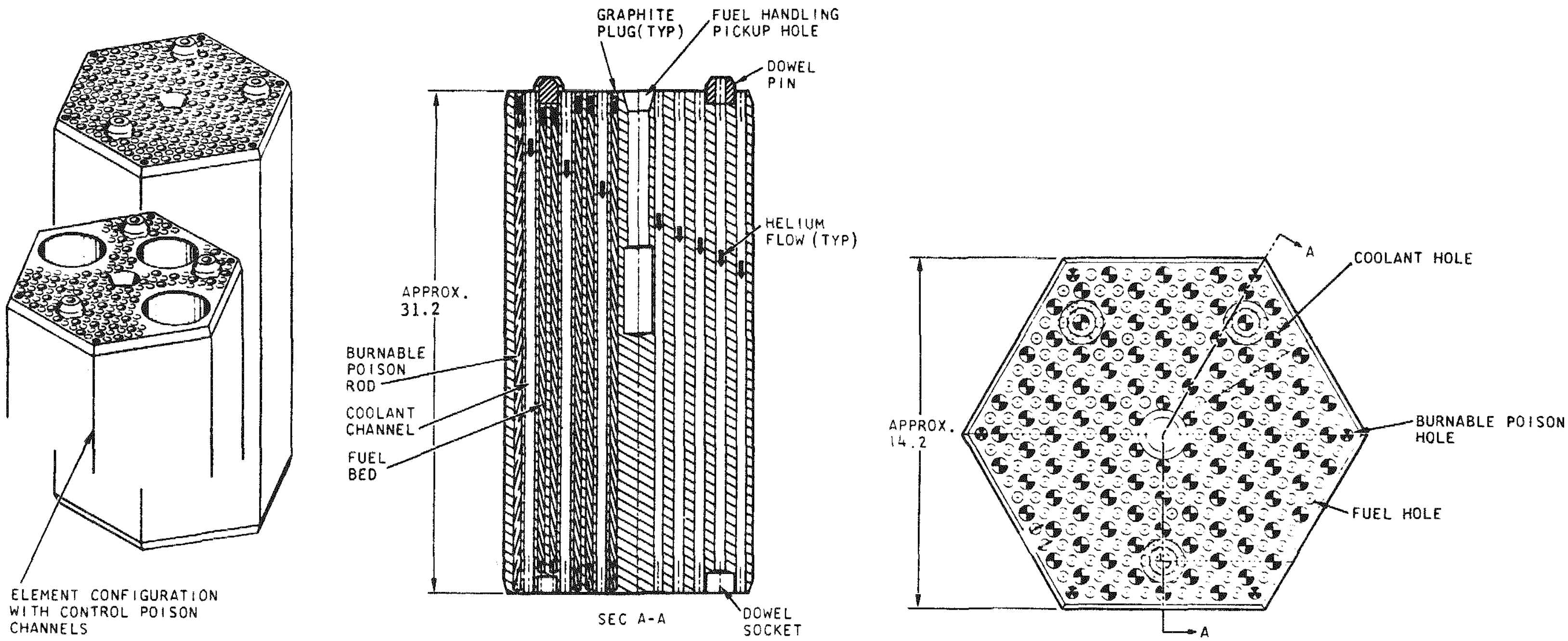

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Fig. 1 Fort St. Vrain graphite fuel element

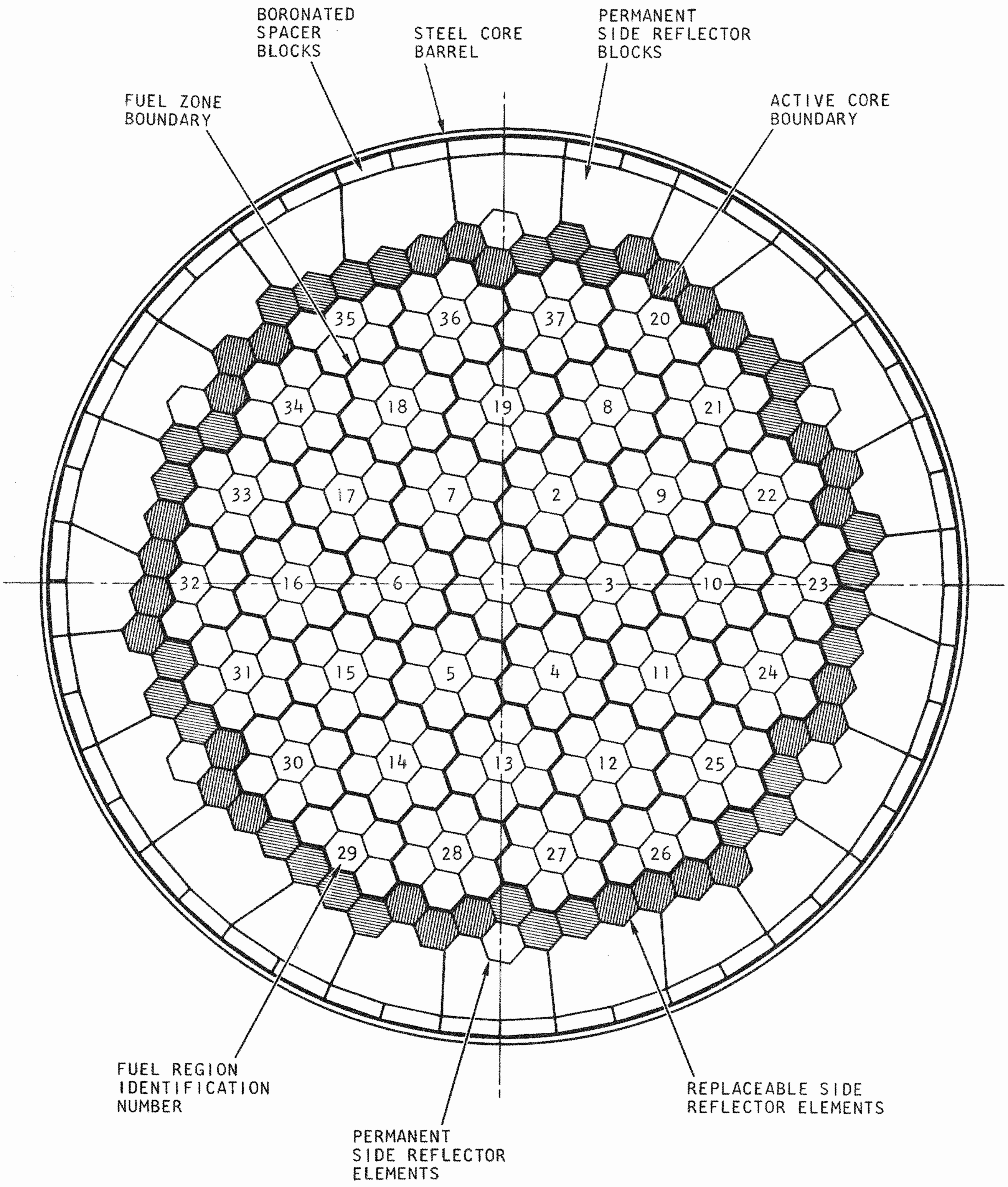

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Fig. 2 Fort St. Vrain core plan view

Each of the 37 control rod drive mechanisms contains a flow control valve (orifice) by which the helium flow to each of the 37 core regions can be remotely adjusted. Figure 3 shows a view on top of the core with flow control valves. Figure 4 shows the overall arrangement of the core and the PCRV internals.

The core is designed to operate at an average fuel temperature of 1500°F with an average helium gas outlet temperature of 1450°F giving steam conditions at the input to the turbine generator of 1000°F and 2400 psig. The net operating efficiency is about 38%. The design power is 842 megawatts thermal and 338 megawatts electrical net plant output.

The startup test techniques to be discussed have been and/or are being applied to the startup of the Fort St. Vrain Nuclear Generating Station operated by the Public Service Company of Colorado. These techniques will be used generally for HTGRs. Some of these techniques were developed and used by General Atomic Company for the startup of the Peach Bottom Atomic Power Unit #1 which was operated by the Philadelphia Electric Company until its recent decommissioning.

The startup tests are all designed to provide measured values for core characteristics relating to the safe operation of the plant and to provide an evaluation of the calculational methods used to predict these values. Specifically the tests, for which techniques are to be discussed here, are the following:

a) initial loading of fuel elements;
b) core shutdown margin with all fuel loaded and control rods inserted;
c) flux distributions at zero power;
d) control rod reactivity worths at various power levels;
e) temperature coefficient of reactivity;
f) xenon reactivity worth and stability of the core to xenon oscillations.

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Fig. 3 View of control rod drive and orifice assemblies above the fully loaded core

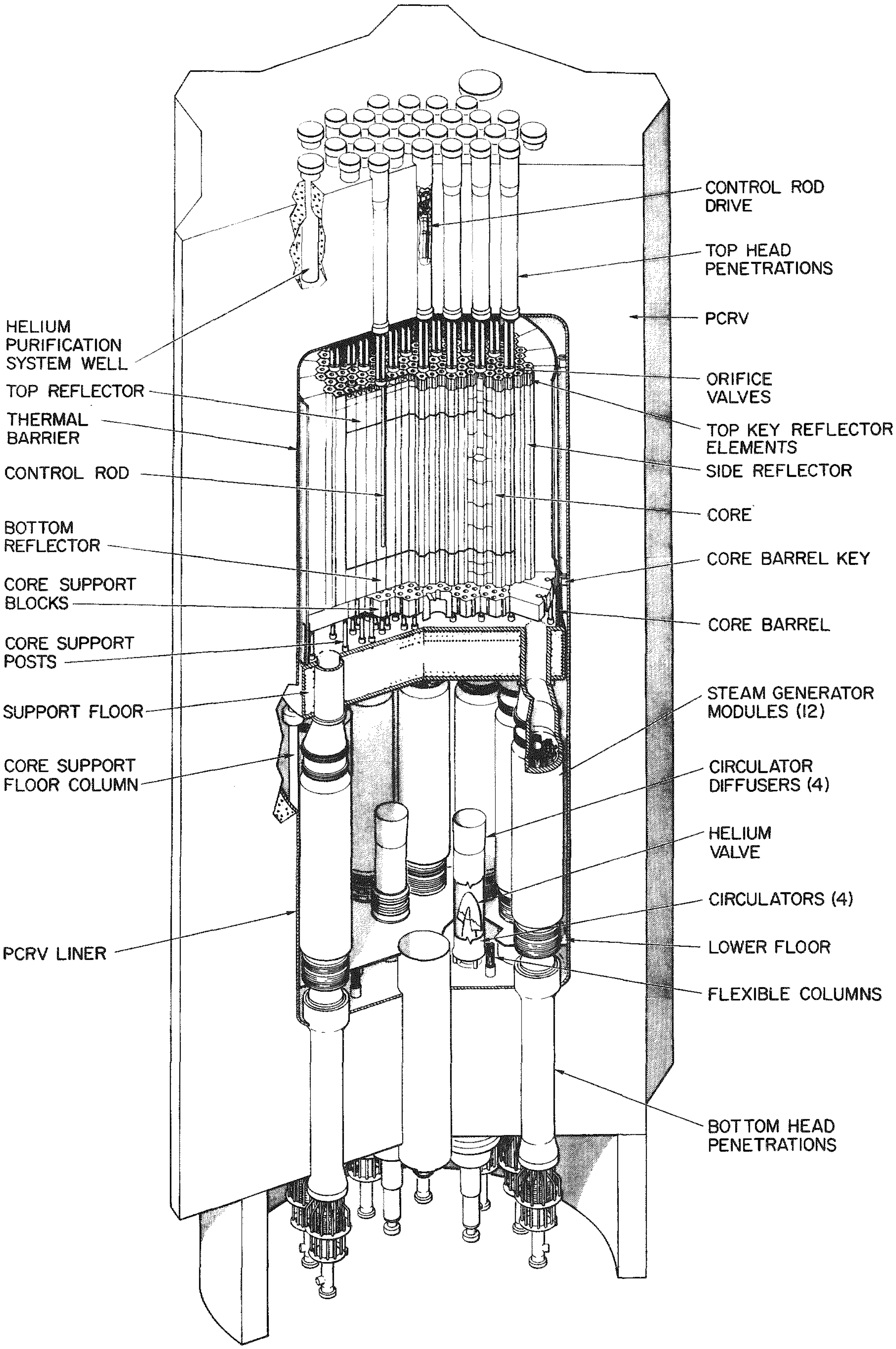

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Fig. 4 Primary reactor system of Fort St. Vrain HTGR

2. INITIAL FUEL LOADING

The fuel loading procedure is designed to take into account the fact that both fuel and moderator (graphite are being added to the core simultaneously. Neutron monitoring techniques are designed to insure a large margin of subcritical reactivity at all times.

Prior to initial loading of the fuel, the bottom and most of the side reflector graphite blocks are in place. For various reasons, including operational considerations, core multiplication prediction and monitoring considerations, it is desirable to load the core initially by layer rather than by region. For refueling, a refueling machine is available to completely unload any one of the 37 refueling regions. The use of the machine to load the core layer by layer would be very time consuming since it would involve moving the machine to each of the 37 regions for each layer to be loaded.

A very time-efficient method for initial loading of the core was developed and used effectively at Fort St. Vrain. This method makes use of specially designed hoists for use on the refueling floor over the PCRV penetrations with which fuel elements can be lowered into the core one at a time. Personnel within the PCRV guide the fuel blocks into their proper location within the region for the layer being loaded. The loading of an entire core layer of blocks is completed prior to loading the next layer.

Three of the normal control rods and drive mechanisms were used in three regions near the center of the core and were available for scram insertion into the core. Temporary neutron absorber rods were installed in all three control element holes in the central block of each of the other regions as the loading progressed. These temporary absorber rods provided significantly more negative reactivity than the regular control rod system and assured that the core remained subcritical during the entire loading period. After the core was loaded and the shutdown margin determined, these temporary absorber rods were replaced by the normal control rod system.

To assure a safe loading procedure, the reactivity status of the core was continuously monitored by at least two channels of in-core nuclear instrumentation. Additional in-core detectors supplied input to the plant protective system. A small neutron source was located at the center of the bottom layer of fuel.

Specific loading steps were determined for which the number of elements to be loaded was less than one-half (but not more than a limiting number) the additional elements required to reach the linear extrapolated inverse multiplication value of 0.04 using inverse multiplication from scalar counts of the in-core detectors. The source-detector arrangement was such that the inverse multiplication curve was calculated to be concave upwards so that this extrapolation would be conservative. In addition, count rate data were obtained for each element loaded and restrictions placed on this count rate prior to approval to load the next element.

A fuel element being prepared for insertion into the PCRV is shown in Figure 5.

The control room console for monitoring the count rate from the in-core detectors during fuel loading at Fort St. Vrain is shown in Figure 6.

The total numberof fuel and reflector elements loaded for Fort St. Vrain was 2774. The loading was accomplished in 20 days.

A summary of the significant features of the technique for initial fuel loading is given in Table 1.

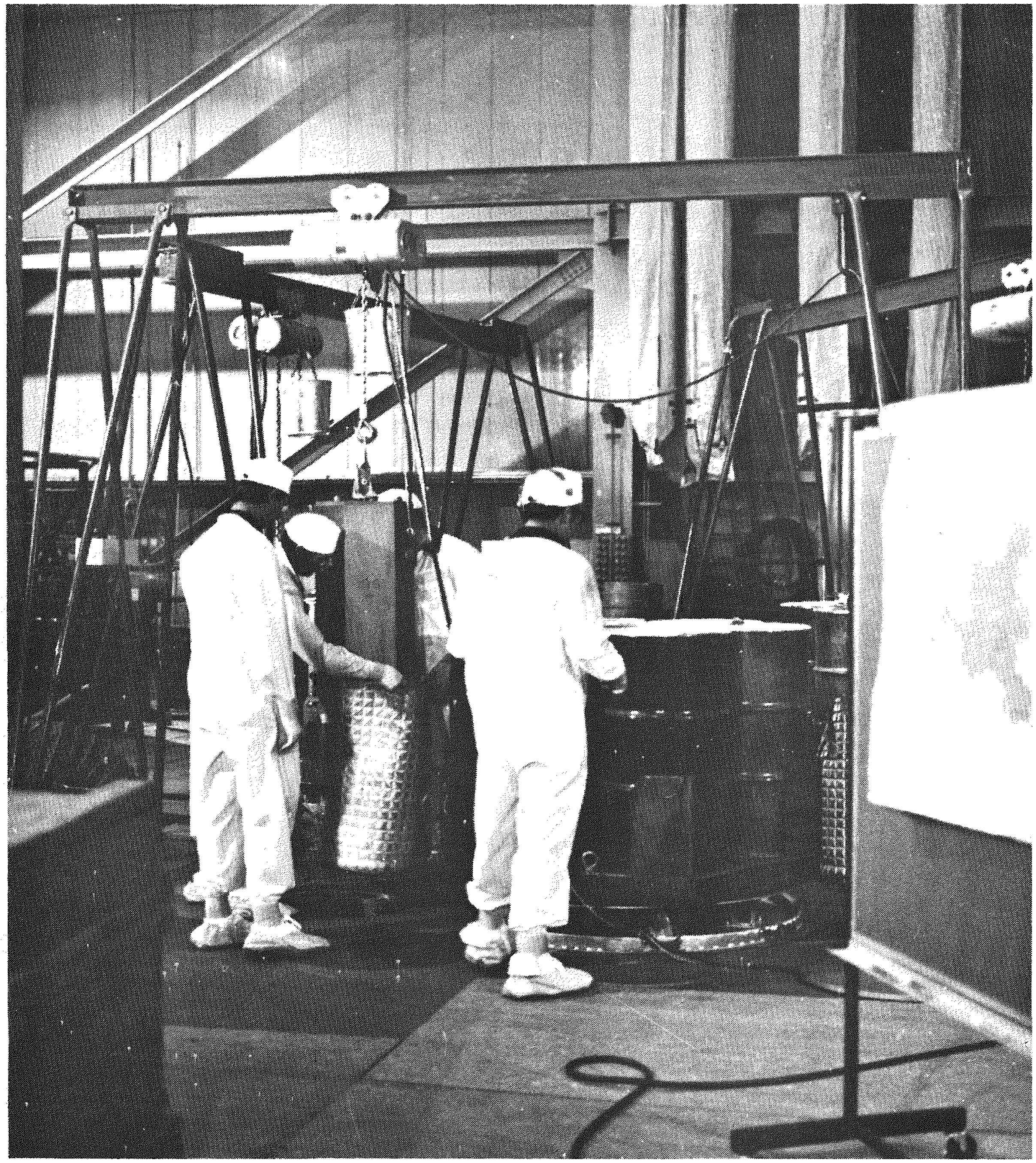

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Fig. 5 Fuel block on hoist with padded bag being installed prior to insertion into core

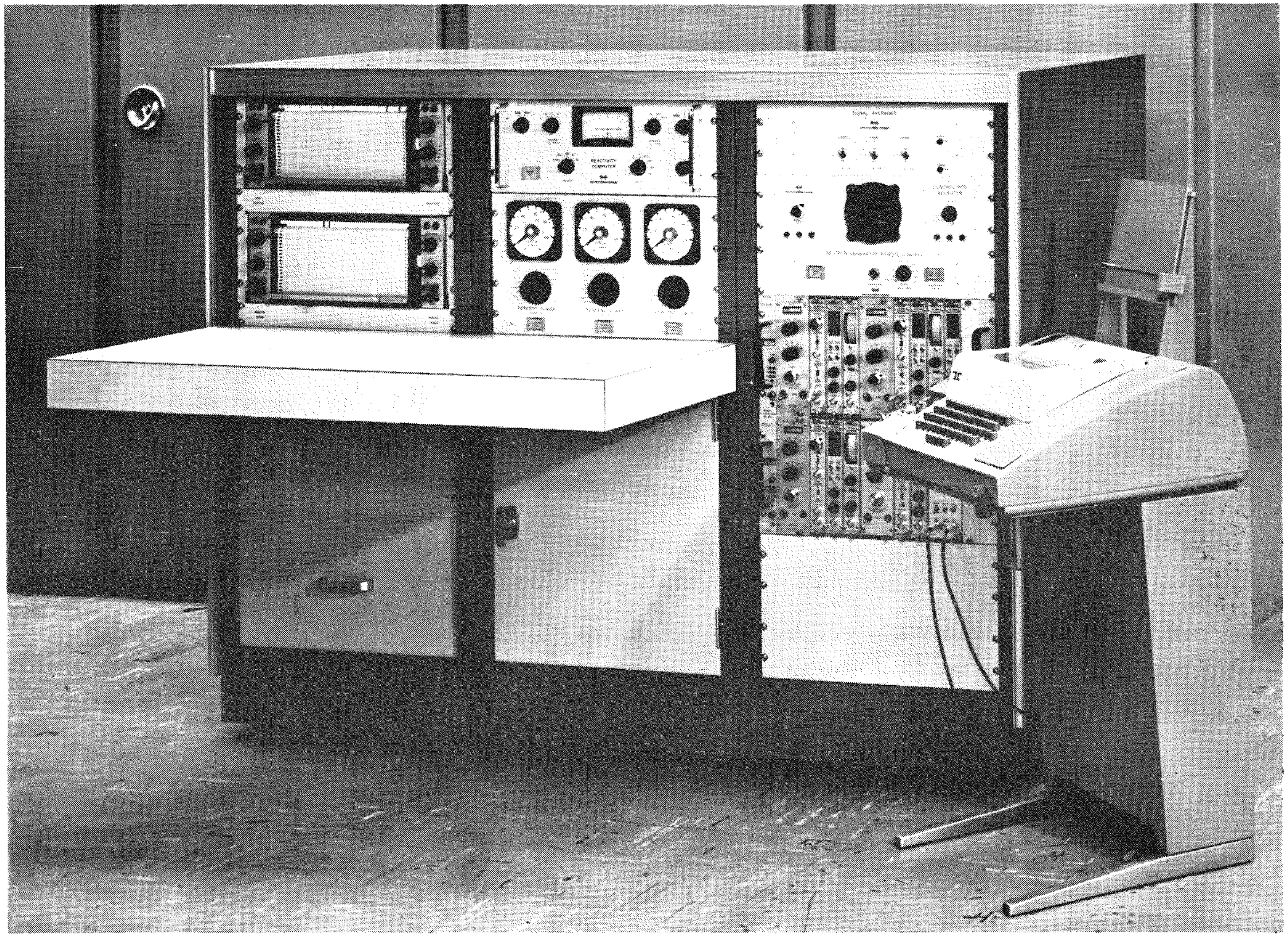

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Fig. 6 Front view of monitoring console with teletype

Table 1

Summary of Significant Features of the Technique for Initial Fuel Loading

- Loading performed in air environment with personnel access to core for placement and removal of temporary in-core instrumentation.
- Special hoists for lowering elements through open penetrations.
- Personnel inside PCRV to guide placement of elements.
- Stringent element accountability and inspection at each step.
- All control from the control room with communication system to refueling floor and to interior of PCRV.
- Loading by layer.
- Temporary small in-core source (no personnel exposure hazard).
- Temporary high sensitivity in-core detectors for monitoring multiplication.
- Temporary high sensitivity in-core detectors for plant protective system.
- Special instrument console in control room to monitor count rates.
- Three normal control rod drives capable of scram action.
- Use of temporary absorber rods in all three holes of the control elements.
- Loading limited by inverse multiplication.

3. PULSED NEUTRON MEASUREMENTS OF SHUTDOWN MARGIN

After initial loading of the core, it is desirable to measure the shutdown margin prior to proceeding to take the core critical. In addition, with the method of fuel loading used in which temporary absorber rods replaced control rods in all but three regions of the core, it is desirable to measure the shutdown margin prior to proceeding to replace the temporary absorbers with the normal control rod system.

The technique developed for use with both the Peach Bottom and the Fort St. Vrain HTGRs was that which made use of a pulsed neutron source, a sealed accelerator manufactured by KAMAN NUCLEAR CORPORATION. This source gives about 10^8 neutrons per pulse and was approximately 3.6 inches in diameter and 24 inches long. With these dimensions, the source was placed within the active core region. Figure 7 shows the pulsed source and its power supply. Cables to the control room permitted remote triggering of the source and control over the operation of the source.

Three in-core neutron detectors were used to measure the neutron dieaway following each neutron source pulse. A small steady state neutron source (same as used in initial core loading) was used in the core when not pulsing and, by means of a special drive mechanism, this source could be removed from the core region during the pulsing.

Multi-channel time analysis was achieved by using the Control Data CDC-1700 computer at the FSV site which is nominally used as a data logger.

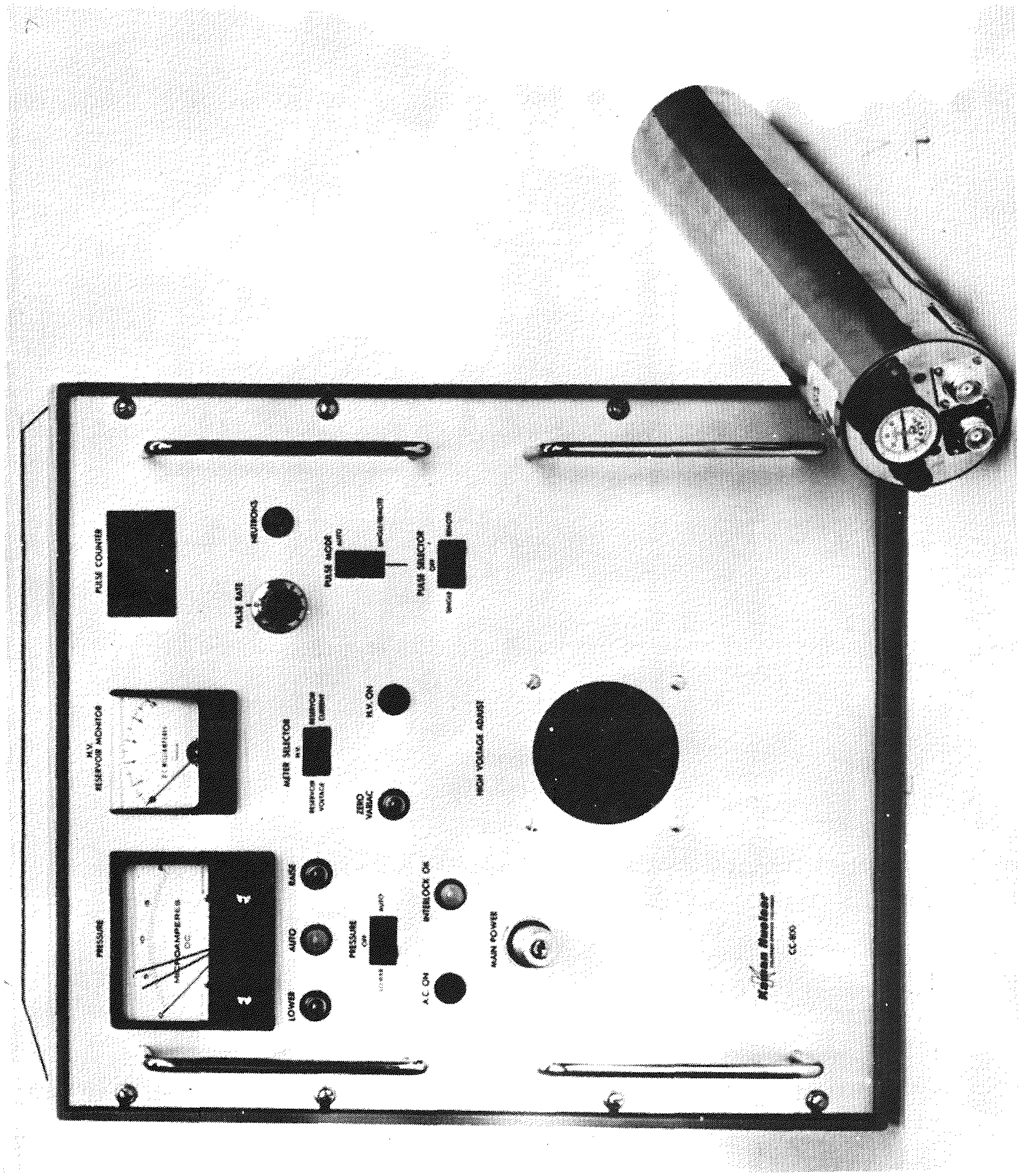

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Fig. 7 Sealed accelerator pulsed neutron source and control console

This same computer was also programmed to do the necessary data analysis including least squares fitting, such that an immediate analysis of the results was available.

A series of calculations was performed prior to the experiments in which the modal effects were analyzed and in-core locations for the source and detector were determined to give maximum response of the detectors to the fundamental mode dieaway. Three detectors were actually used so that the predicted detector location could be bracketed, thus allowing for some uncertainty in the predicted position.

In addition to the measurement with all control rods inserted, many other subcritical configurations were also measured, including the highest worth control rod withdrawn, groups of control rods withdrawn in the normal sequence used to approach critical and several configurations near critical.

A measurement consists of positioning the pulsed source and three detectors at the predicted locations in the core, setting up the desired subcritical control rod configuration, remotely removing the steady state in-core neutron source and then repetitively pulsing the accelerator source at a predetermined rate for a sufficient time to obtain satisfactory statistics on the counts stored in the multichannel analyzer. A time of four hours or less was sufficient to obtain satisfactory data. Measurements were made for core k-effective values from 0.90 to 0.995.

The analysis of the data was performed immediately after the completion of the pulsing using a program on the CDC-1700 computer. A more detailed and sophisticated analysis was performed later at General Atomic. The analysis done immediately after the experiment was very valuable in determining the adequacy of the measurement and when sufficient data had been taken and generally agreed very well with the later more detailed analysis.

The relationship of the decay constant of the fundamental mode in the core to the subcritical reactivity of the core requires knowledge of the neutron generation (lifetime) time in the core. A technique (called multiplication ratio technique) involving the pulsing of two configurations very near critical was developed to provide a measurement of the neutron lifetime (generation time) near critical. By comparing this measurement of lifetime with that calculated for this configuration a correction factor (if any) could be determined to be applied to the calculated lifetime for those other configurations further subcritical for which the measured lifetime was not available. In some configurations (with a k-effective greater than 0.97) the so-called extrapolated area-ratio analysis was also used to obtain the neutron lifetime from the measurements.

A summary of the significant features of the technique for pulsed neutron measurements is given in Table 2.

Table 2

Summary of Significant Features of the Technique
For Pulsed Neutron Measurements

- Core in an air environment.
- Personnel access to core for placement and removal of temporary in-core instrumentation.
- Small sealed accelerator neutron source which can be placed within core.
- Temporary high sensitivity in-core detectors.
- Digital computer for multichannel time analyzer.
- Digital computer for on-line data analysis.
- Special triggering circuit for pulsing the neutron source.
- Pre-measurement modal calculations to predict optimum source and detector locations.
- Ability to remotely remove steady state neutron source from the core during pulsing.
- Measurement at a k-effective of 0.90 can be made in approximately four hours.
- Measurement of neutron lifetime by a multiplication ratio technique very near critical or from extrapolated area ratio analysis further from critical.

4. AXIAL FLUX DISTRIBUTION MEASUREMENTS

The FSV HTGR has no in-core power monitoring instrumentation because of its relatively small core size. As a result, the axial power distribution is not explicitly obtained during power operation. However, the radial power distribution during operation is obtained by monitoring the helium inlet and outlet temperatures for each of the 37 refueling regions. The design of large HTGRs includes in-core power monitoring instrumentation.

For FSV, it was decided that a verification of the calculated axial flux distribution at zero power would add confidence to the calculated axial distribution during operation. For this reason, the axial flux distribution was measured in a limited number of regions. The regions measured represented rodded, unrodded, partially rodded and unrodded adjacent to partially rodded regions to provide a variety of cases for testing the calculations.

The technique used for these measurements involved remotely traversing temporary in-core neutron detectors axially in selected regions with the reactor critical at zero power in an air environment. A separate detector at a fixed location in the core was used to normalize any power level changes during the traversing. The detectors used were BF_3 proportional counters, the same ones used for the temporary in-core detectors during initial core loading and pulsed neutron measurements.

Special detector drive mechanisms were designed which could be temporarily attached to control rod drive assembly housings inside the PCRV in the plenum space above the core. These drive mechanisms could be remotely operated from the control room and could traverse a detector the full length of the reserve shutdown hole in the selected region of the core. This detector drive mechanism in no way interferred with the normal operation of the control rod drive mechanism. Figure 8 shows some of the special detector drives temporarily attached to some of the control rod drive housings inside the PCRV.

The steady state neutron source was attached to a drive mechanism similar to that for the detectors and was withdrawn from the active core region when the reactor was critical to permit operating at as low a power as possible, consistent with a reasonable counting rate from the in-core detectors. Count loss corrections would need to be evaluated at counting rates above 10^5 counts per second.

A typical result of these measurements is shown in Figure 9.

A summary of the significant features of the technique for zero power axial flux distribution measurements is given in Table 3.

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Fig. 8 View above the core showing special in-core-detector drive mechanisms

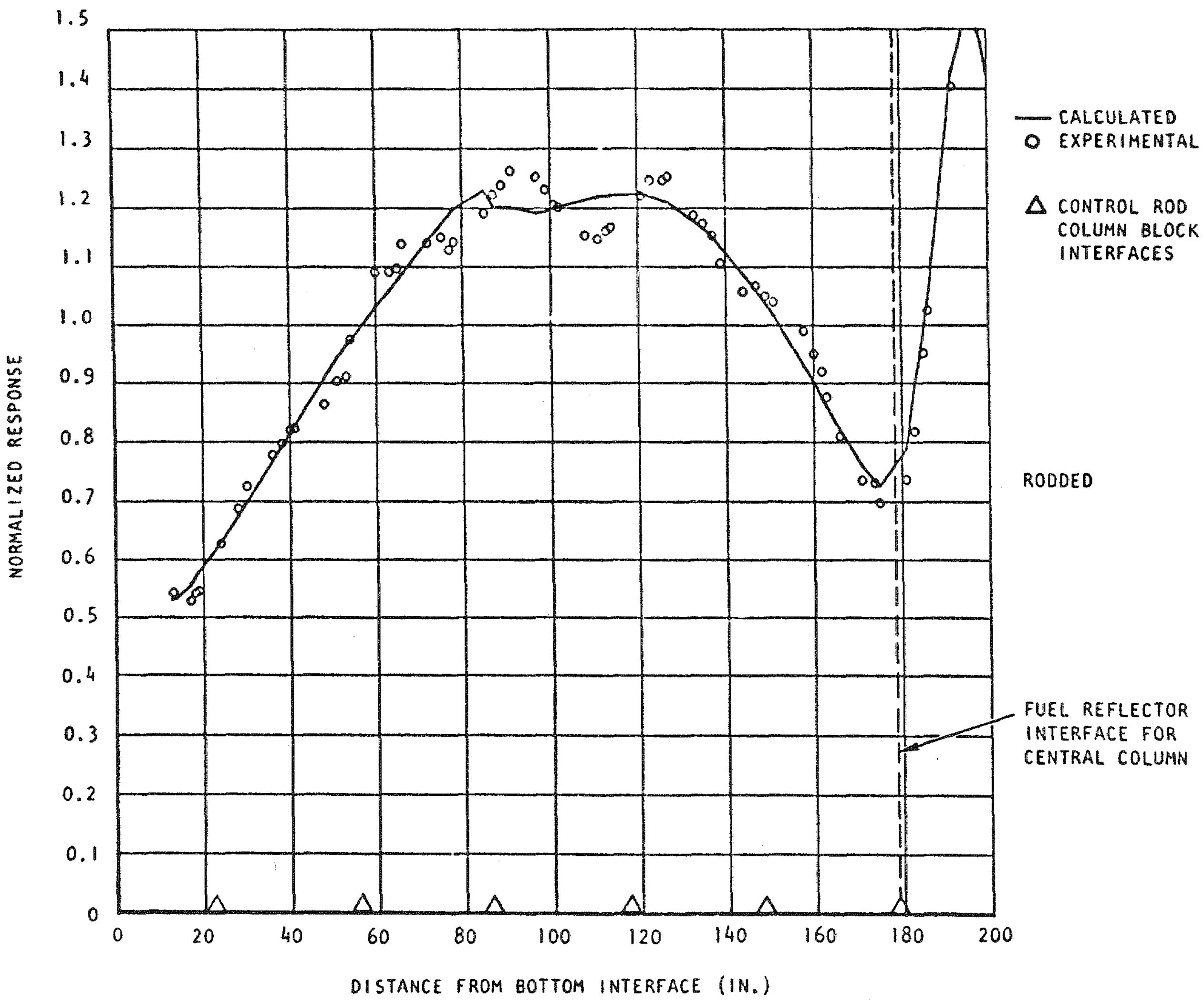

Fig. 9 Axial flux distribution for region 16

Table 3

Summary of Significant Features of Technique For Axial Flux Distribution Measurements

- Core in an air environment with personnel access to core for placement and removal of temporary in-core instrumentation.

- Special temporary in-core detector drive mechanisms to remotely traverse detectors axially in selected core regions.

- Detector traversing performed from control room.

- Fixed neutron detector for normalization.

- Source removal when critical to maintain low power levels.

5. CONTROL ROD REACTIVITY WORTH

Control rod reactivity worth measurements are necessary in order to evaluate reactivity changes in the core. In the HTGR, control rods are operated in banks of three rod pairs in 120° symmetry. A predetermined bank withdrawal sequence is used. In normal operation all rods are either fully inserted or fully withdrawn except for a single bank of three rods pairs being operated as the shim group and the central rod pair operated as the regulating rod.

In the HTGR, differential control rod worth measurements (reactivity change per unit position change) are made at many positions during the withdrawal of the rods and from the differential worth curve, an integral worth vs. position curve is obtained. These measurements are made at all powers up to and including full power. The technique is designed such that temperature feedback effects at power have a negligible effect on the rod worth measurement. This technique has been used for measurements in the Peach Bottom HTGR and the Fort St. Vrain HTGR.

An analog reactivity computer is used for the measurements. The input to the reactivity computer is the average output of three wide-range linear (10 decade) nuclear channels. The three detectors are fission chambers and are located symmetrically in the side of the PCRV at the core midplane.

The basic differential worth measurement technique, called the double bump technique, is shown in Fig. 10. From a stable power condition, a small rod withdrawal (or insertion) is followed by an immediate

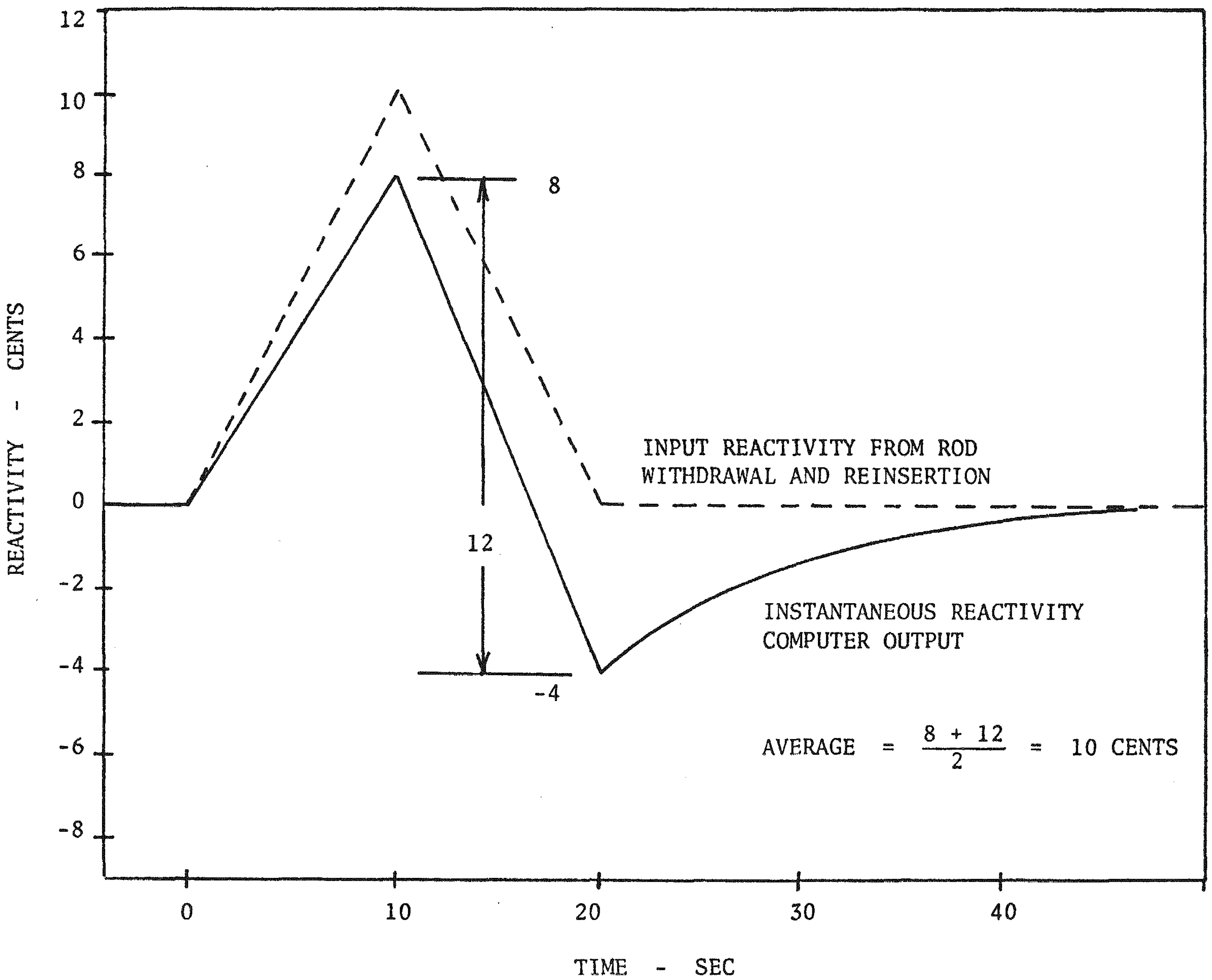

Fig. 10 Reactivity variation for addition and removal of 10 cents during power operation with temperature feedback

reinsertion (or withdrawal). The instantaneous reactivity at the start, at the turnaround and at the end of the rod motion is obtained from the reactivity computer. Transient analysis calculations have shown that the average worth per inch for this rod movement is, to a good approximation if the motion is small, the average of the worth per inch on the withdrawal (or insertion) stroke and the worth per inch on the reinsertion (or withdrawal) stroke. The effect of the temperature feedback on the double rod motion is thus effectively canceled out. In this technique, typically, rod motions of 3 to 6 inches are used. The effect on core power is minimal and the result is obtained in a very short time.

An extensive series of special measurements was carried out at near-zero power to compare reactivity results obtained instantaneously from the reactivity computer with those from asymptotic period measurements. One reason for performing these special tests was to evaluate spatial effects on the detector response to control rod motion in various parts of the core. A result of these measurements was that the reactivity computer results for the central control rod were within 5% of the period results and that for rods far from the center, the agreement was not as good. These comparison measurements required a special technique since period measurements can only be performed at zero power, being limited by source effects at very low power and by temperature feedback effects at higher power and since the reactivity computer output is affected by large statistical fluctuations at low power.

As a result of the good agreement obtained for the central control rod, a technique was developed, called the substitution method, in which any operating shim bank of rods can be calibrated against the central control rod. The central control rod is also the regulating rod and is normally maintained in a near half withdrawn condition where its worth per inch is greatest. In this substitution method, the double motion calibration technique is used to calibrate the central rod over a small distance and then the reactivity worth of a shim bank movement can be obtained from the central rod movement required to just compensate for the shim bank movement at constant power.

Use of these control rod calibration techniques at FSV have shown agreement between calculated and measured rod group worths to within 10% which is considered good confirmation of the calculational methods.

A summary of the significant features of the technique for control rod calibration is given in Table 4.

Table 4

Summary of Significant Features of Technique For Control Rod Calibration

- Analog reactivity computer.
- Wide range (10 decade) linear electronics provide input to reactivity computer.
- Average of three out-of-core detectors (fission chambers).
- Double bump technique to minimize temperature feedback effects.
- Use of instantaneous reactivity computer output readings at start and stop of rod motion.
- Comparisons of reactivity computer results with asymptotic period measurements at near zero power.
- Calibration of shim groups by substitution with central rod.
- Measurements can be made up to and including full power.
- Measurements can be made rapidly without significantly disturbing the plant operation.

6. TEMPERATURE COEFFICIENT OF REACTIVITY

A measurement of the core temperature coefficient of reactivity during startup testing is important since it provides confirmation of the calculated value that has been used in the core design and in the transient analyses.

For the HTGR, the temperature coefficient is obtained in the startup testing by performing the power rise in steps. Each power increase (and consequent temperature increase) is accomplished in a time short compared to changes in fission product concentration, particularly xenon-135. At each new power level, temperature equilibrium occurs within one hour and then, the reactivity change accompanying the power change is obtained from the change in the calibrated control rod bank position. A point on the rod calibration curve may also have been obtained at the new power level.

A small correction to the reactivity change is necessary, in general, to account for the change in xenon-135 absorption rate as a function of temperature. Also, if the power change occurred over a relatively long period of time a correction to the reactivity change will also be necessary to account for a change in the amount of xenon-135 present at the new temperature. This correction is obtained from a continuous calculation of xenon-135 (and other fission products) based on the actual time-history operation of the reactor. This calculation is performed on-line with the CDC-1700 data acquisition system computer.

7. XENON-135 REACTIVITY

Since xenon-135 is a relatively rapidly changing fission product and has a reactivity worth of about 0.03 Δk in the HTGR, a measurement of its reactivity worth is important in evaluating transient and load following operations.

In general, the xenon-135 reactivity changes can be obtained from the motion of calibrated control rod banks required to maintain constant power (constant temperature) following a power increase or decrease. A total time of up to two days is required at the new power to allow the xenon-135 to reach equilibrium so that in the HTGR startup testing program only several of the powers are held constant for the required time to obtain the xenon-135 data. In most cases the other data required at each power level can be obtained in much less than two days.

The stability of the core relative to xenon transients is to be demonstrated at full power. The technique to be used involves perturbing the flux in one region near the edge of the core by withdrawing the control rod in that region (maintaining constant power byinserting the central regulating rod) to affect about a 20% power density change in the region. After about 6 hours the control rod will be returned to its initial position. All of the power changes will be monitored by measuring the core helium outlet temperature from each of the 37 regions as a function of time for approximately 48 hours. Changes in the out of core nuclear instrumentation will also be recorded.