HEDL-SA-1729 FP

CONF-790933--3

NUCLEAR STARTUP, TESTING AND CORE MANAGEMENT OF THE FTR

R. B. Rothrock

August 1979

IAEA SYMPOSIUM ON PHYSIC
OF FAST REACTORS

Sept. 24-28, 1979   Aix-en-Provence, France

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of
Westinghouse Electric Corporation, under the Department of
Energy Contract No. DE-AC14-76FF02170

Nuclear Startup, Testing, and Core Management of the FTR

R. A. Bennett, J. W. Daughtry, R. A. Harris, D. H. Jones,
J. V. Nelson, J. A. Rawlins, R. B. Rothrock, R. A. Sevenich, B. D. Zimmerman

Introduction

The Fast Test Reactor (FTR) is a sodium-cooled, mixed-oxide-fueled, 400 MW(Th) fast reactor designed for irradiation testing of FBR fuels and materials. The reactor is located near Richland, Washington, and is operated by the Westinghouse Hanford Company for the U.S. Department of Energy. The FTR is presently undergoing nonnuclear startup tests, in preparation for the initial fuel loading. The reactor is provided with special irradiation facilities to enhance its experimental capabilities. These include eight in-core, contact-instrumentable test positions of approximately 12 cm. hexagonal cross section which permit continuous connection of experiment instrument leads during operation or refueling, and which may also be used for closed loop systems that provide specially tailored coolant conditions for test sections up to approximately 6 cm. in diameter. Special equipment is also provided for test handling, disassembly and examination, and for experimental data collection and recording.

The arrangement of the principal reactor internal components is shown in Figure 1, and a plan view of the core arrangement is in Figure 2. The eight special test positions are arranged in Rows 2, 4, and 6, approximately on core radii which divide the core into three trisectors. In order to permit instrument leads to remain attached to these eight experiments without interference during refueling, each trisector is served by its own in-vessel fuel handling machine and, during reactor operation, is covered by its own instrument tree which monitors the exit coolant conditions from those channels not provided with contact instrumentation. The three in-vessel handling machines and three instrument trees are mounted so as to rotate between their operating positions over the core, and 'parked' positions outside the core, without disturbing the overhead instrument connections to the eight test positions located on the trisector boundaries. In addition, due to the separation of the refueling machines, each trisector also has its own ex-vessel transfer port. This division of the core into three trisectors, each serviced by separate refueling equipment, results both in unique constraints and unique flexibilities for accomplishing the initial core loading, to be discussed in greater detail below.

The FTR core arrangement, shown in Figure 2, contains 91 active core positions in six hexagonal rows, surrounded by 108 radial reflector assemblies made of high-nickel alloy. The six-row active core includes three safety rods in Row 3 (normally fully withdrawn during operation) and six operational control rods in Row 5, which are withdrawn to approximately midcore at startup and reach approximately the full-out position at the end of each operating cycle. These nine control rods are operated by drive mechanisms mounted on the reactor head, through shafts which penetrate the instrument trees and which must be disconnected for fuel handling operations. The eight special test positions at startup will contain two instrumented fuel assemblies, in Rows 2 and 6; an in-reactor instrument thimble, in Row 2, for monitoring the initial fuel loading and for subsequent active neutron and gamma spectrometry measurements; a highly instrumented vibration test assembly; an instrumented absorber assembly; and standard fuel and structural components. Additional instrumented positions will be used for structural materials irradiations under controlled temperature conditions, and for closed loop tests, in future operating cycles. Besides the nine control rod and eight instrumented test positions, the remaining 74 of the 91 active core positions will ordinarily be occupied by either driver fuel assemblies or by experimental fuel assemblies of approximately equivalent power and reactivity. These seventy-four 'driver' core positions are all mechanically identical, and accept 3.65-meter (twelve-foot)-long core components, with separate outlet coolant instrumentation provided in the instrument trees for each position.

A further description of the reactor, and in particular its nuclear design, can be found in References 1 and 2. The results of the supporting critical experiment program are summarized in Reference 3, and key nuclear parameters are summarized in Table I, extracted from these sources. The balance of the present paper is concerned with reactor physics aspects of FTR startup, testing, and initial operation.

Reactor Physics of FTR Startup and Operation

• Initial Fuel Loading

A conventional symmetric procedure of loading the reactor from the center outware (in all three sectors) with control rod withdrawals at intervals to obtain rods-out count rates is relatively inefficient with the FTR, because:

(1) Fuel transfer equipment must be repeatedly moved from one ex-reactor transfer port to another in order to service all three trisectors; and

(2) For each rods-out data point desired, all three in-vessel handling machines and instrument trees must be rotated into the proper positions, and all nine control rod drivelines connected.

These disadvantages can be circumvented by loading fuel into one trisector completely; then parking its handling machine and rotating its instrument tree in place while the next trisector is completely loaded, and so on. This process has the additional advantage that the control rods can be connected and operated in those trisectors where fuel loading is complete and the instrument trees are in place. This allows relatively frequent withdrawals of three or six rods, when either one or two trisectors have been loaded, in addition to maintaining a cocked rod, if desired, during fuel movements. The control rods in the trisector being loaded remain disconnected and fully inserted, of course. This plan, termed 'trisector loading,' will be employed in the initial loading of the FTR. The sequence of partial core loadings now planned is illustrated in Figure 3. Each individual fuel loading step involves the removal of one of the simulated core assemblies, which were originally installed in the reactor during its construction to maintain core geometry and filter the coolant; and its replacement by a fuel assembly. All control absorbers and other nonfuel components required for the initial core loading have already been installed in the reactor.

The normal operational low-level flux monitors (LLFM) consist of fission chambers located in three thimbles which penetrate the radial shield region approximately as shown in Figure 3. These are intended for core monitoring during normal reactor startups and for shutdown and refueling operations. They will also be installed and operating during the initial fuel loading. However, the large changes in net detection efficiency (neutrons counted per core source neutron) for these detectors as the separate trisectors are loaded would make conventional plots of relative inverse count rates difficult to interpret.

Because of these potential problems, a series of experiments was performed in the FTR Engineering Mockup Critical Experiment ('EMC'), assembled in the ZPR-9 facility at Argonne National Laboratory, to simulate the fuel loading process. Neutron detectors were installed in shield regions in locations representing the LLFMs, as well as in several in-core locations, and count rates were measured for several symmetric and asymmetric partially-loaded core configurations representing both normal and 'trisector' loading schemes for the FTR. Because the sequence of experimental configurations constructed began with a fully loaded core and proceeded by removing various regions of fuel, this was termed the 'Reverse Approach to Critical' experiment. In addition to experimental count rate data from in-core and ex-core detectors, subcritical reactivity measurements were also made by calibrated autorod and by the rod drop (inverse kinetics) technique for several of the partially loaded configurations.

As fuel was removed from the ZPR-9 matrix locations representing the outer two rows of FTR fuel, experimental count rates from the detector near the core center showed a smooth and monotonic dependence on the amount of fuel remaining, for either symmetric or asymmetric loadings. The experimental count rates for the detectors in LLFM positions showed abrupt slope changes, as expected, as the amount of fuel present in each of the trisectors was varied. Selected results illustrating these effects are shown in Figure 4.

Results of this experiment were carefully analyzed to determine how the loading process may best be monitored with both in-core and ex-core detectors, and whether a symmetric loading procedure holds any substantial advantages over the operationally more efficient trisector loading scheme. Detailed analyses were made at both Oak Ridge National Laboratory(4) and the Hanford Engineering Development Laboratory(5) which showed the relative count rates from the ex-core detectors could be satisfactorily computed provided sufficient detail was included in the calculational models. This generally involved two-dimensional diffusion theory or S_N analyses, with spatially dependent axial bucklings used in non-fueled regions of the core; these were in turn obtained from three-dimensional calculations of selected reference cases. Special numerical convergence tests were also employed to ensure flux convergence in regions far from the fission source.(5) Relative count rates for in-core detectors were more readily computed by simple two-dimensional techniques, since they are surrounded by the core neutron source, and are relatively unaffected by uncertainties regarding the axial leakage from non-fueled regions. From the results of this experiment, it was concluded that (1) the core loading process can be monitored most readily with a detector located near the core center; and (2) if a central detector is available, then either a symmetric or asymmetric fuel loading sequence can be safely used. Consistent with these conclusions, the procedure now planned for monitoring the initial FTR fuel loading will rely chiefly on count rates from detectors within the in-reactor thimble located near the core center, for the purposes of predicting criticality and detecting anomalous conditions during the loading process. However, count rates will also be taken with the LLFM's as a further assurance that the loading is proceding as intended, and to provide data for analysis and checkout of calculational models. Due to the expected changes in detection efficiency for these remote detectors as the loading proceeds, calculated tables of expected relative count rates as a function of the amount of fuel loaded have been prepared for use as a guide in interpreting the results.

Count rates will be taken with one or more of the operating control rods withdrawn during the loading of the final trisector. When a core loading has been reached that is predicted to be critical with all rods out, based on extrapolated inverse count rate data, the in vessel handling machine and instrument tree serving the final trisector will be rotated into position and all nine rods will be withdrawn to achieve either a critical rod position or a slightly subcritical state with all rods out, from which the absolute core reactivity can be established through a rod drop measurement. This initial criticality is presently expected to occur after loading about 58 fuel assemblies, out of a total of 73 planned for the fully loaded initial core. Once the core loading at near-critical is determined and a reactivity calibration has been obtained, fuel loading will be continued in the final trisector until a fully loaded core of 73 fuel assemblies is reached. Core excess reactivity will be checked at that time to insure that it is in the proper range to continue with the acceptance tests, and if not, any necessary adjustments will be made.

Startup Physics Tests

An extensive series of physics related measurements will be made on FTR during the startup testing period to confirm key nuclear design and safety features, and to measure nuclear parameters needed for efficient operation as an irradiation facility. The following types of measurements are planned:

- Control rod worths and worth profiles, excess reactivity, and shutdown margin;
- Reactivity worth of selected core component substitutions;
- Temperature and power coefficients of reactivity;
- Dynamic analyses employing rod drop methods; and
- Extensive nuclear core characterization using active and passive sensors.

As several of these tests are of a more or less conventional nature, the following discussion will focus on cases involving methods or experiments that are somewhat unique to the FTR. This category includes the general means of making subcritical reactivity measurements; the dynamic measurements at power; and the core characterization program.

Absolute subcritical reactivities will be determined by inverse kinetic analysis of the neutron level transient following a control rod drop, to be performed by on-line computer. Of the variety of inverse kinetics algorithms available for this purpose, the Yang-Albrecht algorithm(6) will be used in the initial FFTF measurements. The inverse kinetics analysis will be supported by precalculated values of control rod worths to which the experimental results may be compared. This calculation also yields estimates of the changes in detection efficiency which occur due to flux shape perturbations when the control rod is dropped, allowing corrections to be made in the inverse kinetics calculations to refine the value of the inferred experimental rod worth. In addition to the difference in reactivity before and after the rod drop (the experimental rod worth), the absolute subcritical reactivity may also be obtained from this technique. In cases where a less precise but more rapid experiment is desired, or where reactivities must be measured in far subcritical configurations, the modified source multiplication ('MSM') method (7) will be used. This technique infers the difference in subcritical multiplication factor from LLFM counter readings taken at two different states, using precalculated 'configuration factors' to account for changes in detection efficiency or in neutron source between the two states. To establish the MSM reactivity values on an absolute scale, a rod drop absolute reactivity measurement is ordinarily made at a slightly subcritical state to provide a reference count rate calibration point. Many of the reactivity measurements required during the acceptance tests and for subsequent routine operation will be performed as subcritical reactivity difference measurements, and will utilize the MSM method with a rod drop calibration at a reference state. The use of MSM for subcritical reactivity measurements was verified and compared with other experimental methods during the FTR critical experiment program.(7)

Dynamic characteristics of the reactor at power will be measured with the rod drop technique,(8) which has also previously been employed at the EBR-II reactor.(9) This procedure involves a small, rapid negative reactivity excitation of a few cents in magnitude, in order to produce a reactor down-transient. This neutron level transient is recorded and analyzed in order to extract features of the reactor dynamic response. Since the FTR does not have a special low-worth transient rod for this purpose, an operational control rod will be used. The rod is first lowered to near the bottom of the core, and then scrammed for the last few inches of its stroke, to achieve the desired small, rapid negative reactivity insertion. Since this procedure entails a substantial misalignment of the control rods at power, precautionary measures are taken including a small power reduction prior to the experiment and a controlled power recovery afterwards, to prevent damage to core components or experiments.

The reactor characterization program is especially important in view of the experimental purpose of the reactor, and has been previously described in detail.(10) It includes measurements with active neutron and gamma instruments (calorimeters, spectrometers, and absolute fission chambers) located in an instrument thimble near the core center, as well as the irradiation of passive monitors (foils) at several locations throughout the core. The foil irradiations will be performed both at low power ($\sim$ 4MW) and at high power, and in each case will utilize eleven specially built characterizer assemblies. Six of these assemblies have been built to simulate driver fuel assemblies, and contain driver fuel pins with special features to facilitate remote disassembly and removal of selected pins in which the dosimeters are contained. Of the remaining five characrerizer assemblies, one simulates a structural assembly and four simulate FTR radial reflectors, all with special features for the irradiation and recovery of foil packages. Reaction rates to be measured include fission and capture rates of important actinides as well as standard fast reactor dosimetry reactions, and multiple foil packages to be used for neutron energy spectrum unfolding.

The dosimeter irradiations are planned to provide information about both the gross shape of important reaction rate distributions, and their local perturbations in the vicinity of heterogeneities such as absorbers or nonfuel experiments. This is accomplished by arranging the characterizers so that results from the two irradiations combined will span approximately a core diagonal (with some positions common between the two irradiations, for normalization of results), and locating additional characterizers next to sources of local perturbations. In the axial direction, the foil packages will extend from near the lower grid plate through the active core and axial reflector regions, and into the region normally occupied by the (upper) fission gas plena. Results of the dosimeter irradiations will help establish the basic 'unperturbed' FTR nuclear environment, and also test the ability to calculate the local perturbations within and near experiments, an important aspect of experimental irradiations in the FTR.

- Nuclear Core Management and Operational Physics Support

Following the acceptance tests, the FTR will be operated as a fast neutron irradiation facility on approximately 100 full-power-day irradiation cycles. Including the additional time required for refueling and maintenance, from two to three cycles of operation per year are expected. Based on current irradiation plans, from 30 to 40 experiments may be in the core at any one time, using many of the standard 'driver' core positions and the first reflector row, in addition to the eight special instrumented test positions. A wide variety of experiments are now being prepared for irradiation during the initial operating cycles, including mixed-oxide and carbide fuels; internal and external blanket assemblies containing uranium and thorium materials; boron carbide absorbers; instrumented fuel and structural experiments, and others. Each experiment is designed to be irradiated in a specific nuclear environment, and in many cases it may have a significant impact both on the overall core reactivity and power margin and on the local environment of its neighbors. It is therefore the objective of the continuing nuclear core management activities to coordinate the core locations and irradiation schedules of the experiments so as to maintain a stable environment from cycle to cycle, satisfy all design and safety related core constraints, and provide for each experiment a nuclear environment consistent with its irradiation objectives.

The initial planning of each reloaded core configuration will be done with the aid of two-dimensional calculations, which can represent all the essential operating and safety constraints with sufficient accuracy for this purpose. Core management options which can be exercised to adjust the core reactivity and power balance include replacement or shuffling of fuel; exchange of fuel assemblies for structural 'shim' assemblies, or of reflectors for absorbers; and if necessary, relocation or temporary removal of experiments. In addition to satisfying experimental requirements, refueling plans must ensure that all standard core components (driver fuels, control absorbers, reflectors) are replaced on a regular schedule consistent with their permissible irradiation lifetime. Once a core loading has been chosen that satisfies operational, safety and experimental objectives, detailed prerun calculations will be made to obtain predicted local neutronic environmental data for comparison with experiment requirements and previous irradiation histories. In order to account satisfactorily for partially inserted control rods and axially nonuniform experiments, an explicit three-dimensional, full core calculation is considered to be necessary. The '3DB' multigroup diffusion theory computer program(11) is presently used for this purpose. A variety of comparisons of two- and three-dimensional diffusion theory calculations with FTR critical experiments have shown(1,2) that key reaction rates are calculated with satisfactory accuracy in the vicinity of the core, when using the diffusion approximation. These calculations, along with auxiliary two dimensional analyses for control rod worths, will provide the basis for the standard prerun documentation to be prepared for each cycle, which will include predicted values of important operational and safety parameters as well as reaction rate distributions. A similar set of calculations will be performed, in somewhat greater detail, following each cycle and incorporating any list minute changes in operating plans that were not reflected in the prerun analysis such as different core loading, cycle length or power history, or control rod positions. Results of these postrun analyses will be maintained as a permanent record of the FTR irradiation history, for use by the FTR Project and to assist experimenters in the interpretation of their postirradiation data. Each irradiation cycle will generally begin with a mix of fresh and irradiated standard and experimental core components. For convenience, a computerized data storage system has been devised to maintain detailed records of the irradiation histories, isotopic compositions, and life fractions remaining for all partially irradiated components, with provisions for editing and updating data for each cycle. This data system is interfaced with the two- and three-dimensional diffusion theory computer programs through use of input generator codes which extract isotopic compositions for each component from the data base and prepare isotopic 'mix tables' in the proper format for a diffusion theory flux calculation.

The scope of the planned FTR irradiation program has broadened considerably since the initial core design was fixed and components ordered. One example of current importance is the irradiation of experimental inner blanket assemblies in inner core positions which would ordinarily be occupied by driver or experimental fuels. Such experiments were not anticipated in establishing reactivity allowances for the initial driver fuel inventory, which was purchased to specifications which predate the current interest in heterogeneous core designs. To cope with increased reactivity requirements to support these and other experimental programs, the first reload driver fuel supply has been ordered with increased enrichment, providing up to about 4% $\Delta k/k$ greater reactivity. Between the original and reload driver fuel purchases, and allowing for some fueled experiments provided from off-site independent fuel sources, a sufficient fuel inventory should be on hand at startup to operate for about fourteen irradiation cycles. A typical reload batch would contain about 20 fresh driver and experimental fuels, in addition to sufficient control absorbers, reflectors, or other components to replace all components that have reached the end of their irradiation lives. The fresh driver assemblies will be selected from both the original fuel inventory and the (higher enrichment) reload fuel purchase, with the fraction of fuel coming from the two sources adjusted according to current experimental reactivity requirements.

The selection of specific fuel assemblies to make up the replacement batch is complicated by the use of gas tags to aid in the in-reactor in-reactor identification of leaking fuel.(12) To each assembly is assigned a set of tag ratios of xenon and krypton isotopes, and all 217 pins within that assembly contain a small amount of tag gas mixture conforming to these specific isotopic ratios. Thus in the event of a fission gas leak from a fuel pin, some of the tag gas mixture will also escape into the reactor cover gas where it can be sampled and mas spectrometrically analyzed to determine the identity of the leaker. Eighty different sets of tag ratios have been provided, compared with a nominal equillibrium core loading of 76 fuel assemblies, so that it is possible to load the reactor without duplication of gas tags. The total fuel inventory at startup, counting both the original and followon fuel purchases, consists of four sets or 'cores' of from 77 to 80 fuel assemblies each, all with gas tags conforming to the same set of 80 different isotopic ratios. The fuel assemblies are also divided into three different combinations of enrichment/flow zones, each with an associated set of gas tag ratios. Consequently, careful planning of future reload batches will be needed to minimize in-reactor gas tag duplications and to maintain a proper balance within the spare fuel inventory with respect to gas tag ratios and enrichment/flow zones.

References:

1. W. W. Little and S. Ramchandran: "Nuclear Design Aspects of the Fast Test Reactor", Paper A42, International Symposium on Physics of Fast Reactors, Tokyo, Japan, October, 1973.
2. P. L. Hofmann: "FTR Neutronics: Status, Problems, and Development Programs", ANS National Topical Meeting on New Developments in Reactor Physics and Shielding, September, 1972 (Conf-720901, Book 2, page 839)
3. P. A. Ombrellaro, et al: "Biases for Current FFTF Calculational Methods", Proceedings of the ANS Topical Meeting on Advances in Reactor Physics, Gatlinburg, Tennessee, April, 1978 (CONF-78041, page 259).
4. D. L. Johnson: "Methods for Monitoring the Initial Load to Critical in the Fast Test Reactor", HEDL-TME 75-78, August, 1975.
5. J. T. Mihalczo, G. C. Tillett and D. L. Selby, "Evaluation of Initial Loading Counting Rate Data from Experiments with the Mock-Up Core for the Fast Flux Test Facility", Nuclear Technology, vol. 30, page 422 (September, 1976)
6. C. Y. Yang and R. W. Albrecht: "Inverse Kinetics Determination of Subcriticality", Nuclear Technology, vol. 22, page 323 (1974)
7. R. M. Fleischman: "Evaluation of the Modified Source Multiplication Technique for Subcritical Reactivity Assessments in the FTR", HEDL-TME 74-53 (October, 1974)
8. R. A. Harris and R. A. Sevenich: "Evaluation of Rod Drop Stability Tests in FFTF", HEDL-TME 77-105 (January, 1978)
9. H. A. Larson, "Kinetics Research and Testing at EBR-II", ANL-8086 (April, 1974)
10. J. W. Daughtry et al, in 2nd ASTM-Euratom Symposium on Reactor Dosimetry, Palo Alto, California, 1977.
11. R. W. Hardie and W. W. Little, Jr., "3DB, A Three-Dimensional Diffusion Theory Burnup Code", BNWL-1264, March, 1970.
12. J. A. Figg, et al, "Gas Tag Location Systems for FFTF and CRBRP Failed Assemblies", HEDL-TME 78-14, July, 1978.

TABLE I

FTR NEUTRONICS CHARACTERISTICS

Peak Flux	7×10^{15} n/cm^2-sec
Fraction Flux > .1 Mev	.65
Fissile Pu Mass	552 kg
Pu-240/Pu Total	12 w/o
Pu/(U+Pu) Zone 1	22.4 w/o
Pu/(U+Pu) Zone 2	27.4 w/o
Axial P/A Power	1.21
Radial P/A Power	1.40
Average Discharge Burnup	49 Mwd/kg
Peak Discharge Burnup	80 Mwd/kg
Breeding Ratio	0.45
Delayed Neutron Fraction	0.003
Doppler Coefficient	-.005 (T dk/dT)
Central Na Worth	-9×10^{-5} δk/kg
Doppler Power Coefficient	-.24 ¢/Mw
Na Power Coefficient	-.02 ¢/Mw
Radial Expansion Power Coefficient	-.20 ¢/Mw
Axial Expansion Power Coefficient	-.10 ¢/Mw

FFTF REACTOR

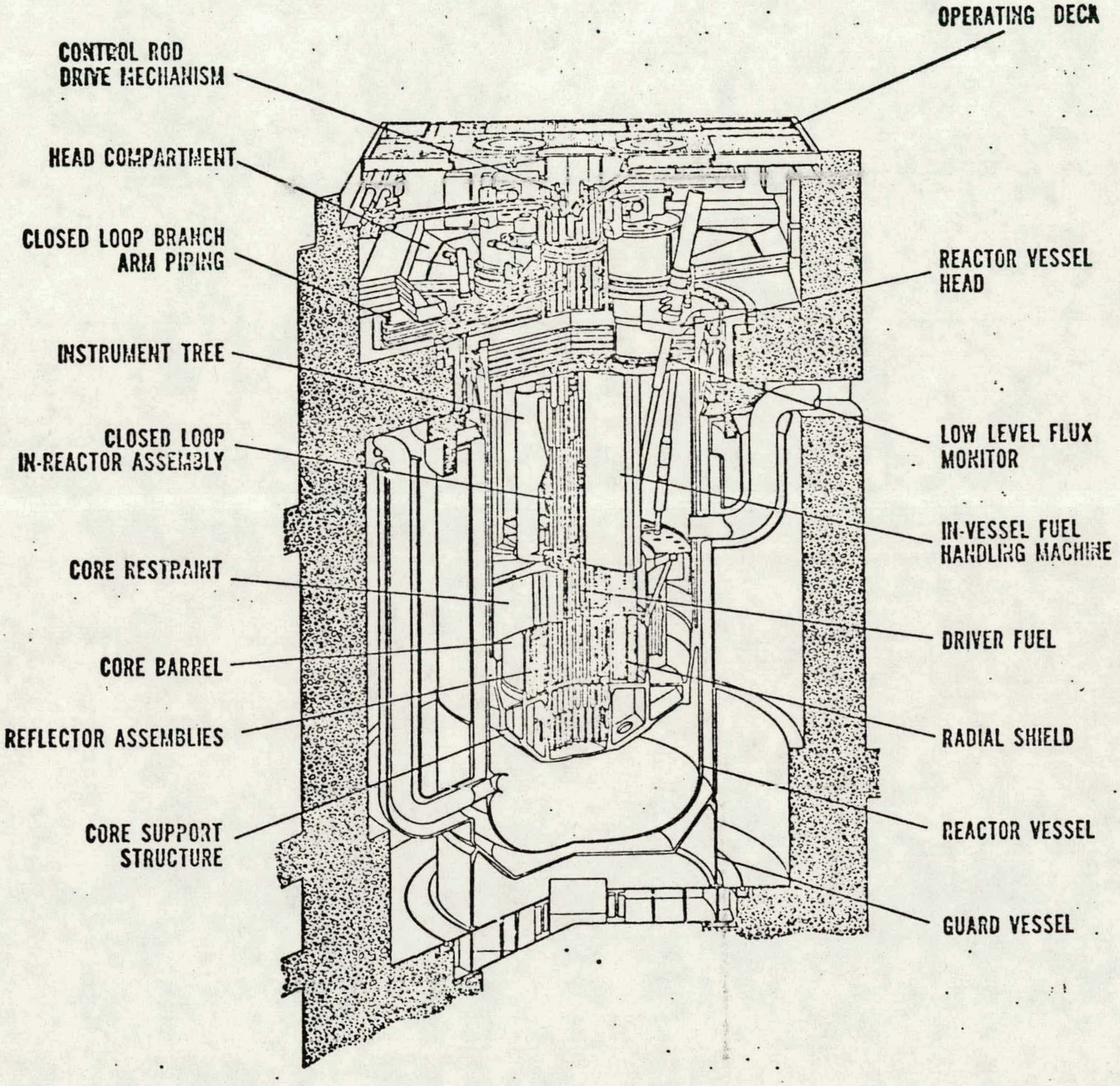
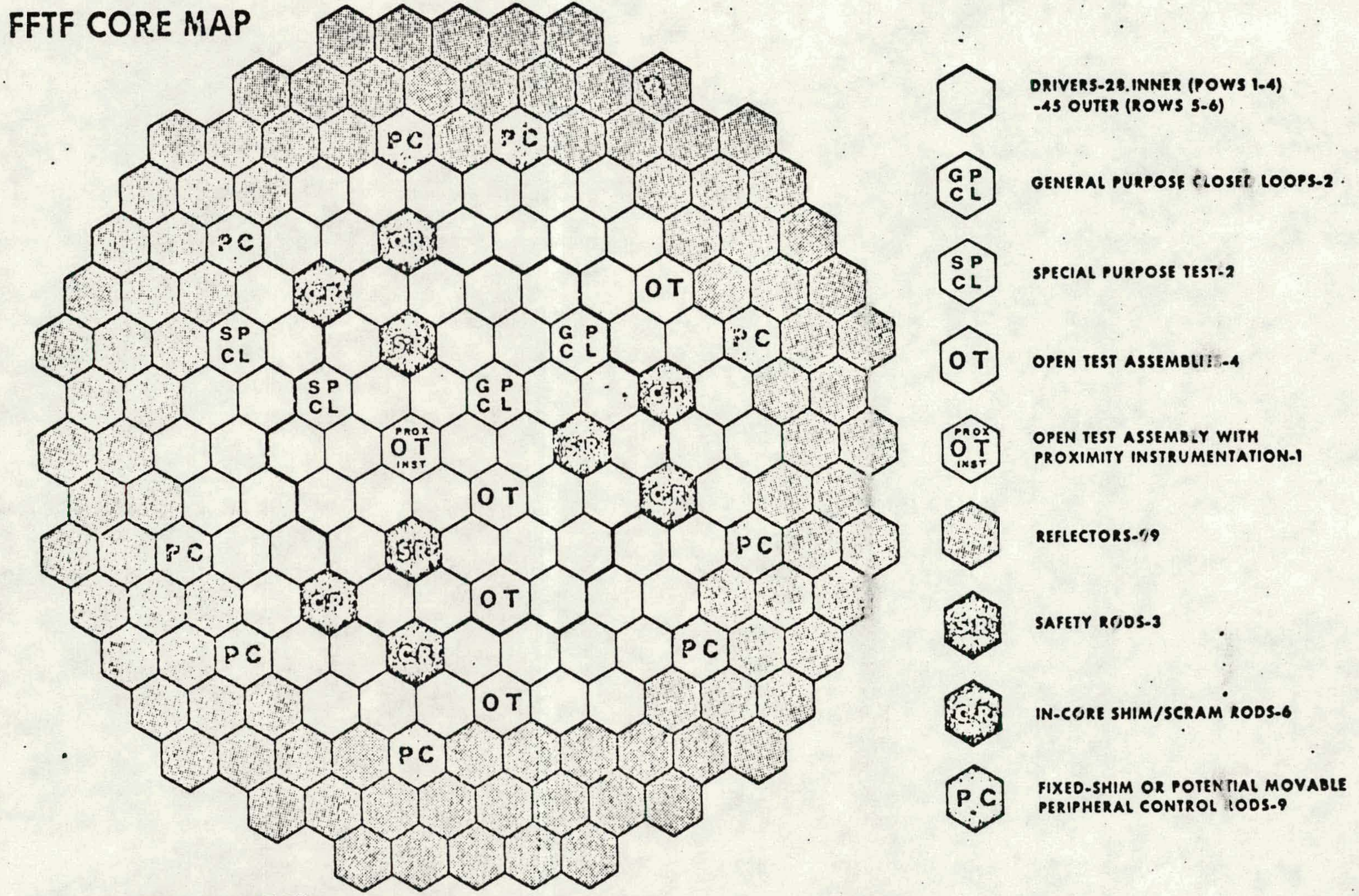


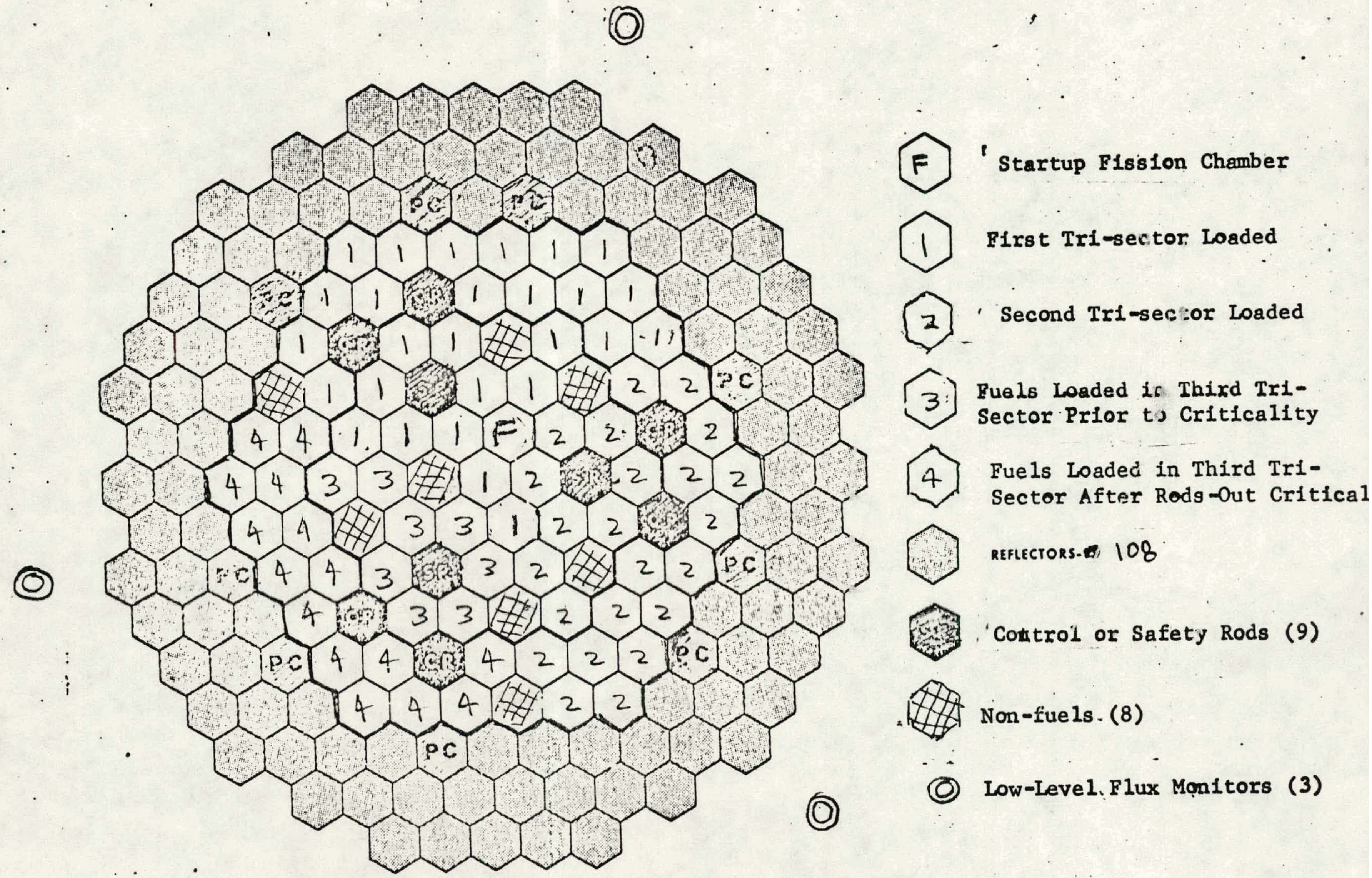
Figure 1. Reactor Elevation

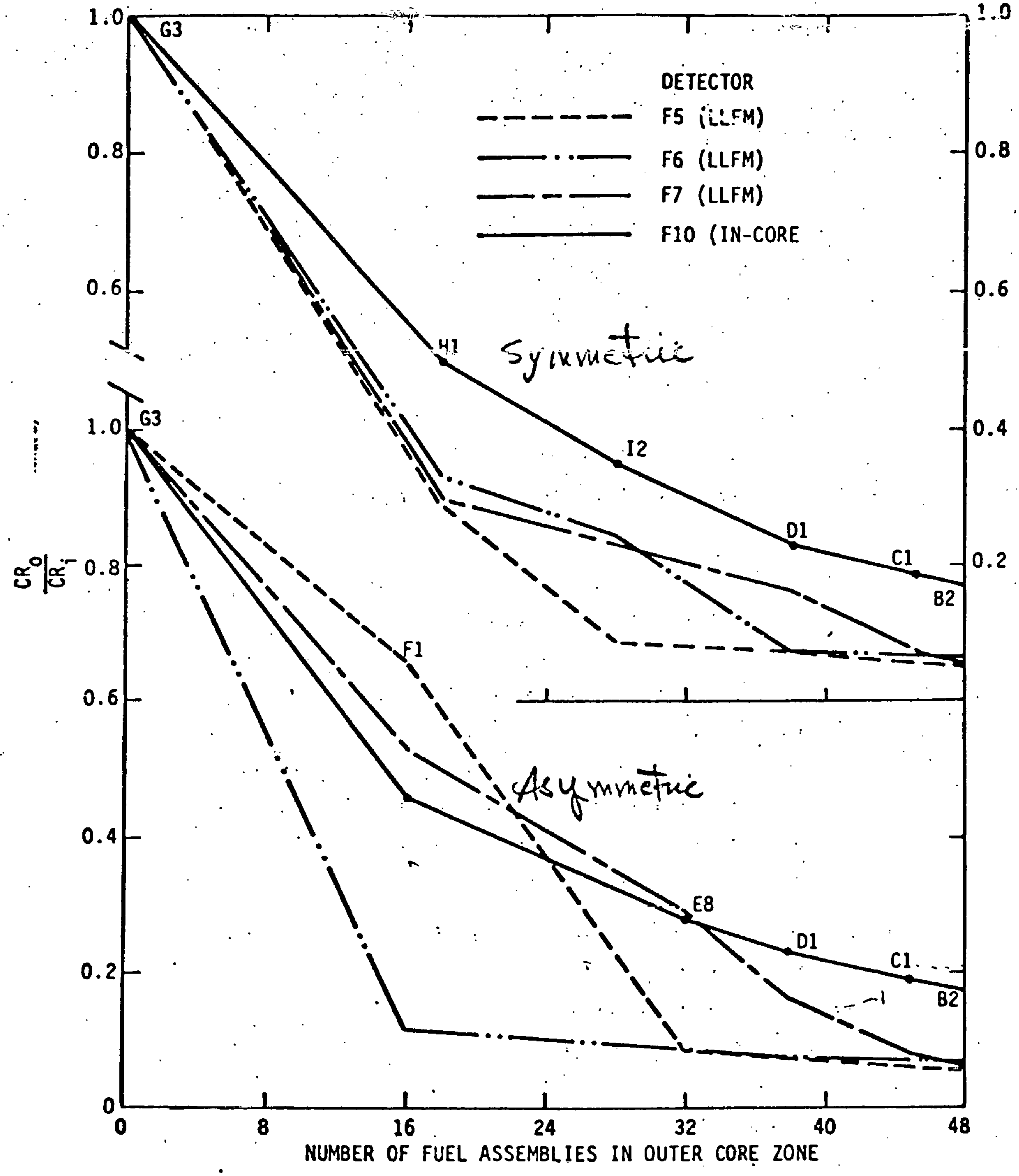


NOTE: REACTOR CAPABILITY=
6 CLOSED LOOPS

Figure 2. FTR Core Map

Figure 3. FFTF Core Loading Sequence





HEDL 7506-110.7

FIGURE 4. Plots of inverse count rates versus fuel elements loaded.