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MASTER

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NUCLEAR INSTRUMENTATION SYSTEM DESIGN IN FFTF AND CRBRP

R. P. Warrick

ABSTRACT

This paper describes the Nuclear Instrumentation System installed in the Fast Flux Test Facility (FFTF). The Nuclear Instrumentation System includes equipment for monitoring neutron flux levels from shutdown to full power. Detector location and mounting provisions are described. The design basis for equipment design is provided. Both in-vessel retractable detectors (fission detectors) and ex-vessel fixed detectors (compensated ion chambers and fission detectors) are used in the system. The in-vessel detectors are used for the Low Level Flux Monitoring System (LLFM) to monitor conditions during refueling and other shutdown activities. The ex-vessel flux monitoring systems are used to protect the reactor by providing signals to the Plant Protection System for use in deriving scram signals. The ex-vessel detectors are used with the primary and secondary flux monitoring system to control the plant from startup to full power operation.

Detailed discussion of startup testing in FFTF follows a brief discussion of pre-delivery development work and testing. With the exception of providing a high level neutron flux to the detectors, the system has been tested in its operational configuration to ensure capability to support all future plant operations. As a result of overlap between all ranges, proper detector operation for higher ranges can be confirmed before power is increased above the low range. While only minor problems were discovered in the electronics during this startup testing, several mechanically related problems were discovered in the detectors. These problems are described along with their solutions. The problems include deterioration of detector insulation resistance, handling difficulties of the detector installation assemblies and co-axial connector problems associated with the in-vessel retractable detectors.

Finally, a description of the Nuclear Instrumentation System planned for the Clinch River Breeder Reactor Plant is provided.

CONTENTS

FIGURES

NUCLEAR INSTRUMENTATION SYSTEM DESIGN IN FFTF AND CRBRP

The Nuclear Instrumentation System (NIS) of the Fast Flux Test Facility (FFTF) includes equipment for monitoring neutron flux levels from shutdown to full power. Both in-vessel retractable detectors (fission detectors) and ex-vessel fixed detectors (compensated ion chambers and fission detectors) are used in the system. The in-vessel detectors are used for the Low Level Flux Monitoring System (LLFM) to monitor conditions during refueling and other shutdown activities. The ex-vessel flux monitoring systems are part of the Plant Protection System and provide signals used to develop reactor trip functions, as well as to monitor reactor power level. The ranges covered by the various systems are shown in Figure 1.

Extensive startup testing of the NIS in FFTF was performed. With the exception of providing a high level neutron flux to the detectors, the system has been tested in its operational configuration to ensure capability to support all future plant operations. While only minor problems were discovered in the electronics during this startup testing, several mechanically-related problems were discovered in the detectors. These problems were resolved prior to startup and include deterioration of insulation resistance handling difficulties of the detector installation assemblies, co-axial connector problems associated with the in-vessel retractable detectors and adjusting the sensitivity of the ex-vessel detectors. The solutions are described.

The Nuclear Instrumentation System planned for the Clinch River Breeder Reactor Plant is a natural outgrowth of this work.

I. IN-VESSEL MONITORING

The in-vessel flux monitoring system consists of three channels that measure and record the reactor neutron flux from reactor shutdown to approximately 250 watts. The in-vessel system is used to monitor the flux during all phases of shutdown, refueling and startup operations. It is also used during power operation to assess reactor stability. These channels provide output to the local fuel handling console, the control console in the Control Room and the Digital Data Handling and Display System (DDH&DS). Each channel consists of a uranium fission counter, silica cable, a remote preamplifier, and a signal conditioner. A block diagram of this system is shown in Figure 2. Except for during power operation, the channels operate in a logarithmic count rate mode and measure neutron flux levels at the detector in the range of 2×10^0 to 2×10^6nv in the presence of gamma fluxes up to 1×10^6R/hr. The display is in counts per second on a six decade logarithmic scale from 10^0 to 10^6cps. Additionally, a rate display on a linear scale from -1 to 0 to +3 decades per minute (DPM) is provided. For periodic assessment of reactor stability during power operation, the system provides linear dc signals to the DDH&DS.

The three fission detectors are located at the core mid-plane position 120° apart circumferentially in the reactor shield at a radius 1.13 meters from the center of the core (Figure 6). The in-vessel position was selected to obtain maximum sensitivity. These in-vessel detectors and preamplifiers are installed in dry thimbles cooled to less than 149°C (300°F) by a closed circuit nitrogen cooling system. The design provides the capability to remotely retract the detectors axially approximately 1.5 meters (5 feet) into the reactor shield during full power operation. Hence, during shutdown, the detectors are inserted to be close to the core and then withdrawn during startup before the power level reaches approximately 0.1%. For the reactor stability measurements, the detectors remain withdrawn. The neutron flux at the retracted position is low enough (less than 5×10^{10}nv) that a reasonable detector lifetime can be achieved. The location of an in-vessel assembly in the reactor vessel is shown in Figure 3.

II. EX-VESSEL MONITORING

Two systems are provided which have detectors external to the reactor vessel. These systems measure neutron flux from 1×10^{-8}% to 150% of reactor full power (40mW to 600MW). The two systems are the primary wide-range system and the secondary power range system. Three redundant channels are provided in each of the systems. These systems provide outputs to the Plant Protection System, the Control System and the Digital Data Handling and Display System.

A. PRIMARY WIDE RANGE SYSTEM

Each primary wide-range channel utilizes a uranium fission chamber, a remotely located preamplifier, and signal conditioning electronics located in the Control Room. A block diagram of one channel of this system is shown in Figure 4. Each signal conditioner contains a counting subchannel (covering neutron flux level at the detector of 2×10^{0}nv to 2×10^{6}nv). A mean square voltage subchannel (covering neutron flux levels of 8×10^{3}nv to 2×10^{10}nv) and a 1% to 125% reactor power linear subchannel for accuracy and fast response in the power range (neutron flux of 2×10^{7}nv to 2×10^{10}nv). The counting subchannel instrumentation displays the reactor power on a logarithmic scale from 10^{-8}% to 10^{-2}% while the mean square voltage subchannel of the wide-range channel displays the reactor power on a logarithmic scale from 10^{-5}% to 150% power. The linear dc current subchannel of the wide-range channel displays reactor power on a linear scale from 0 to 125% power. For the counting and mean square voltage subchannels, reactor rate is also displayed on a linear scale from -1 to 0 to +3 dpm.

B. SECONDARY POWER RANGE SYSTEM

Each secondary power range channel consists of a compensated ion chamber and signal conditioning equipment in the Control Room that measures the detector current proportional to the flux level. A block diagram of one channel of this system is shown in Figure 5. The output is calibrated linearly in percent power from 0 to 125%. The expected neutron flux at the detector is 2×10^{7}nv to 2×10^{10}nv.

C. EX-VESSEL DETECTORS

The ex-vessel detectors are symmetrically positioned approximately 120° apart. The angular locations are such that two thimbles, one containing a primary wide-range detector and the other a secondary power range detector are located side-by-side midway between the in-vessel stored fuel locations. The detectors are installed in thimbles located in the reactor cavity between the reactor guard vessel and the steel-lined concrete wall of the reactor cavity. The detectors are positioned with their centers on the core mid-plane. The lower end of the thimbles are enclosed within nuclear grade graphite to enhance the thermal neutron spectrum and, thereby, improve detector sensitivity. The detector locations are shown in Figure 6.

III. USES OF THE FLUX MEASUREMENTS

Each of the two ex-vessel systems provides signals to the Plant Protection System from which flux-related reactor trip functions are developed. Figure 7 shows each of these trip functions. In addition, trips are developed by comparing the present flux signal with a delayed flux signal. These perform as conventional rate trips but have a better immunity to noise. Both increasing and decreasing rate trips are provided.

The ex-vessel systems are part of the Plant Protection System and, therefore, meet all performance reliability and separation requirements for such systems. Signals from the flux monitoring systems used for other than Plant Protection System purposes pass through a buffer designed and tested to prevent any credible fault on the output side of the buffer from perturbing the input side. In this way, the Plant Protection System is isolated from the effects of faults in the other equipment and separation requirements on the buffer output signals can be relaxed.

The signals from the secondary power range channels are also used by the Automatic Flux Control System to maintain a constant reactor flux. A block diagram of this system is shown in Figure 8. Displays of all channels are provided to the operator for plant control and system performance monitoring.

IV. PERFORMANCE MONITORING

Built-in test provisions have been provided to periodically monitor the performance of the equipment. These test provisions insert signals at the output of the detector in such a manner that the detector response will still be effective. In this way, channel performance can be tested without disconnecting the detector while maintaining the channels capability of providing effective protection for the plant. Test provisions which disable the functioning of the channel automatically trip comparators within the Plant Protection System. Thus, the reactor is continuously protected regardless of testing performed on the flux monitoring system.

The flux monitoring system is designed for easy calibration to indicate the correct level of thermal power. Periodic calorimetric determinations of reactor power using temperatures and flow rates of the sodium in the HTS secondary loops are used to adjust the nuclear range instruments.

The range overlap provides a method of monitoring the performance of the various channels during reactor startup. There will always be assurance that the next higher range channel is functioning before power is increased beyond the capability of the lower range channels. This overlap is necessary to permit the operator to bypass the low flux scram functions.

The outputs of two corresponding channels are continuously compared and if one channel deviates significantly from another, an alarm is given to the operator. This comparison provides an effective on-line monitoring capability and detects either up-scale or down-scale drifts of the instrument channels.

V. PRE-INSTALLATION TESTING

A. IN-VESSEL DETECTORS

Uranium fission chambers operating in the pulse mode were chosen for use in the FFTF in-vessel location due to their superior performance in a high gamma and temperature environment. To effectively reduce breakdown pulse noise (BPN) in sensors and cables operating at high temperatures and voltages, sensors of the integral cable, guarded input design are used and are cooled to less than 149°C (300°F).

The uranium detectors have been shown in testing at EBR-II to survive fluences greater than 10^{18}nvt and $8x10^{9}$R. On the basis of this testing, it is expected that a detector minimum lifetime of one year can be achieved. The successful completion of a greater than 1000-hour detector-cable test in the HEDL gamma pit [10^{6}R/hr at 149°C (300°F)] with a prototype Oak Ridge National Laboratory designed current sensitive preamplifier used for signal conditioning and readout established the assurance that the basic system design would meet the FFTF requirements. A fast collection time detector of the type ultimately used in FFTF was subsequently tested in the HEDL gamma pit. The collection time of this improved detector was 80 to 100 nsec obtained with 2 mm plate spacing versus approximately 120 nsec obtained with 3.2 mm plate spacing in the detector used in earlier testing.

B. PRIMARY WIDE-RANGE SYSTEM

The operating experience with the use of wide-range techniques has been obtained from the growing list of reactor plants that employ this commercially available system. The FFTF mean squared voltage system is an outgrowth of development work at Argonne National Laboratory in the EBR-II plant. The prototype FFTF mean squared voltage system has been successfully tested in EBR-II.

C. SECONDARY POWER RANGE SYSTEM

This system is a standard type with wide usage throughout the nuclear power industry.

D. VENDOR TESTING

RDT standards were utilized in the procurement of all systems to control the material, fabrication process, functional requirements and testing that demonstrated the integrity and reliability of the complete system. The testing, which included acceptance and qualification testing of the detectors and electronics, verified before shipment the systems capability to withstand the temperature, vibration (seismic), shock, pressure and radiation environments expected in the FFTF. Additionally, the system was operated in a test reactor under flux levels prototypic of those expected in FFTF.

VI. POST-INSTALLATION TESTING

After installation of the equipment in FFTF, an extensive testing program was used to ensure that the actual installation met all performance requirements. This testing program essentially duplicated all the vendor testing of the various instruments and included end-to-end checks of the channels by introducing simulated signals at the detector output. These tests confirmed the proper operation of the equipment. Very few electronic repairs were required during this testing.

The complete wide-range channels can be periodically checked for system continuity and calibration. The detector operability and the detector-to-preamplifier continuity can be verified by detecting the alpha disintegrations from the uranium coating. Also, when stored fuel is present, its substantial inherent neutron source strength is readily identifiable as a detector output. Built-in calibration provisions are available in all the systems for complete channel testing. These calibration facilities input a test signal close to the detector output which adds to the detector signal. In this way, the channel can be checked for operation without disabling its function.

VII. DETECTOR SYSTEMS

A. IN-VESSEL DETECTOR DETAILS

Figure 9 shows the mechanical layout of the mechanism used to raise and lower the in-vessel detectors and also the location of the preamplifier. Sealed feed-thru connectors are used to route the electrical cables through the cooling system pressure boundary.

The special connectors inside and outside the pressure boundary have been found to be very difficult to assemble properly. The coiled cables inside the assembly, necessary to permit movement of the detector, put a strain on the connectors. Several failures have occurred. These failures have been repaired and although the system is operating satisfactorily, the use of a potted-type feed-thru is being investigated. At the same time, the preamplifier may be removed from within the pressure boundary to decrease the number of signal leads which must penetrate the boundary. This change will permit more convenient maintenance on the preamplifier and a more reliable method of routing the signals from within the pressure boundary.

B. EX-VESSEL DETECTOR DETAILS

Figure 10 shows the installation details of ex-vessel detectors. It was found during the installation of these detectors that handling of the long detector support tube (6.1 meters, 20 feet) and the heavy shield plug (1.5 meters, 5 feet) was very difficult in the congested space within the head compartment. Two support conduits were broken off from the shield plug during handling. These were repaired and installation was successfully made with the present design. Serious consideration is being given to simplifying the method of installing these detectors.

During the test program, the insulation resistance of the ex-vessel detectors was periodically measured. These measurements showed an unexplained degradation of the insulation resistance and lower than expected thresholds for pulse breakdown noise in several of the detector leads. The detectors were removed and the cause of this degradation was determined to be ceramic insulators used within the cable-to-detector connectors. A sketch of this connector assembly is shown in Figure 11. The cause of the decrease in insulation resistance was shown to be contamination on the surface of the three removable ceramic insulators. This contamination was either due to improper cleaning during initial assembly or loss of hermaticity and subsequent contamination after assembly. As can be seen from the sketch, the sealing of the connector assembly depends on two copper and one aluminum washers. It was subsequently shown that this sealing arrangement was inadequate and leak tightness could not be maintained after mechnical handling and relatively minor temperature cycling. The ceramic insulators were replaced with polyimide parts and the metallic gaskets were replaced with organic "O" rings. This new installation was tested in a gamma field equivalent to 18,000 effective full power hours. The insulation resistance remained high and the gasket sealing remained intact.

While the insulation resistance problem was being investigated, it was also noted that the center pin of the connector did not engage reliably with the female pin on the detector. Review of the tolerance build-up of the various pieces showed that a very marginable penetration of the male contact into the female connector was being made. As a result, the amount of this penetration was increased during fabrication of the polyimide insulators. With these changes, the detectors were re-assembled and re-installed in the plant. They have performed reliably since this modification.

One of the uncertainties to be resolved during initial reactor operation was the flux levels at the ex-vessel detector locations. The detector installation design permits adjustment of detector sensitivity by varying the thickness of a boroplaster shield around the detector.

During the initial approach to criticality, the maximum thickness of boroplaster shielding was in place. It was calculated from in-vessel flux detector readings that criticality would be achieved before any significant signal was available from the ex-vessel detector. It appears that the source term at criticality was somewhat lower than expected and the flux levels at the detector locations was less than predicted.

The boroplaster shields were removed from two of the three fission chambers. When criticality was achieved on February 9, 1980, sufficient overlap of the in-vessel and the ex-vessel wide range system was confirmed. The measurements as compared with predictions are shown in Figure 12.

VIII. CRBRP NUCLEAR INSTRUMENTATION SYSTEM

The CRBRP flux monitoring system is a conventional ex-vessel three-range system based on FFTF design. Figure 13 shows the ranges of the various channels. The capability to use commercial flux monitoring systems operating at ambient temperature is one of the advantages of conventional pipe and vessel primary circuits. The detectors are located in three sets of three thimbles located within the reactor vault. The thimbles will be surrounded by graphite moderator. Neutron and gamma shielding is provided for the source range detector to reduce the neutron and gamma environments to levels consistent with the proportional counter design requirements. The thimbles are serviced from the Head Access Area where junction boxes and preamps are located. From these positions, cabling runs directly to the Central Control Room where the instrument racks are located and from where connections are made to the Plant Protection System, to the refueling control room in the Reactor Service Building and to the Data Handling System. The ranges covered by these instruments are very similar to the FFTF system.

A. SOURCE RANGE

The source range channels use high sensitivity (40 cps/nv), proportional counters to sense neutron flux over the range 4×10^{-1} to 10^4nv (equivalent to a power range of 130 milliwatts to 3.24 KW). It is anticipated that when the reactor is loaded with fresh fuel and fully shutdown, this counter will provide a count rate of greater than 3 counts per minute. Note that the detectors are located outside the reactor vessel rather than in the reactor vessel as in FFTF.

B. WIDE RANGE

The wide range channels use uranium fission chambers to sense neutron flux over 10 decades from 2 to 10^{10}nv. Each wide range channel will consist of a fission counter and electronics counting portion (for the lower six decades), a mean squared voltage portion (for the upper seven decades) and a 0-125% reactor power linear dc portion for accuracy and fast response in the power range. This latter portion will provide outputs to the Plant Protection System for initiating protective trips.

C. POWER RANGE

The power range uses three compensated ion chambers and signal conditioning electronics covering the 0-125% reactor power range. This channel drives fast responding linear dc amplifiers which provide output to the Plant Protection System. Buffered outputs are provided for the Plant Control System, indicators and the data logging system.

D. OVERALL DESIGN

The equipment was designed to RDT standards developed in the course of the FFTF Project. Those components of the Flux Monitoring System which form part of the Reactor Protection System have stringent reliability requirements placed on them. As a consequence, the linear power drawers for both wide range and power range are being designed for an unavailability rate of 20×10^{-6} per hour. In support of this program, twelve drawers will be purchased and tested for five years prior to reactor operation to demonstrate the designed reliability for this and other electrical and mechanical components of the protection system.

FFTF FLUX MONITORING SYSTEM RANGES

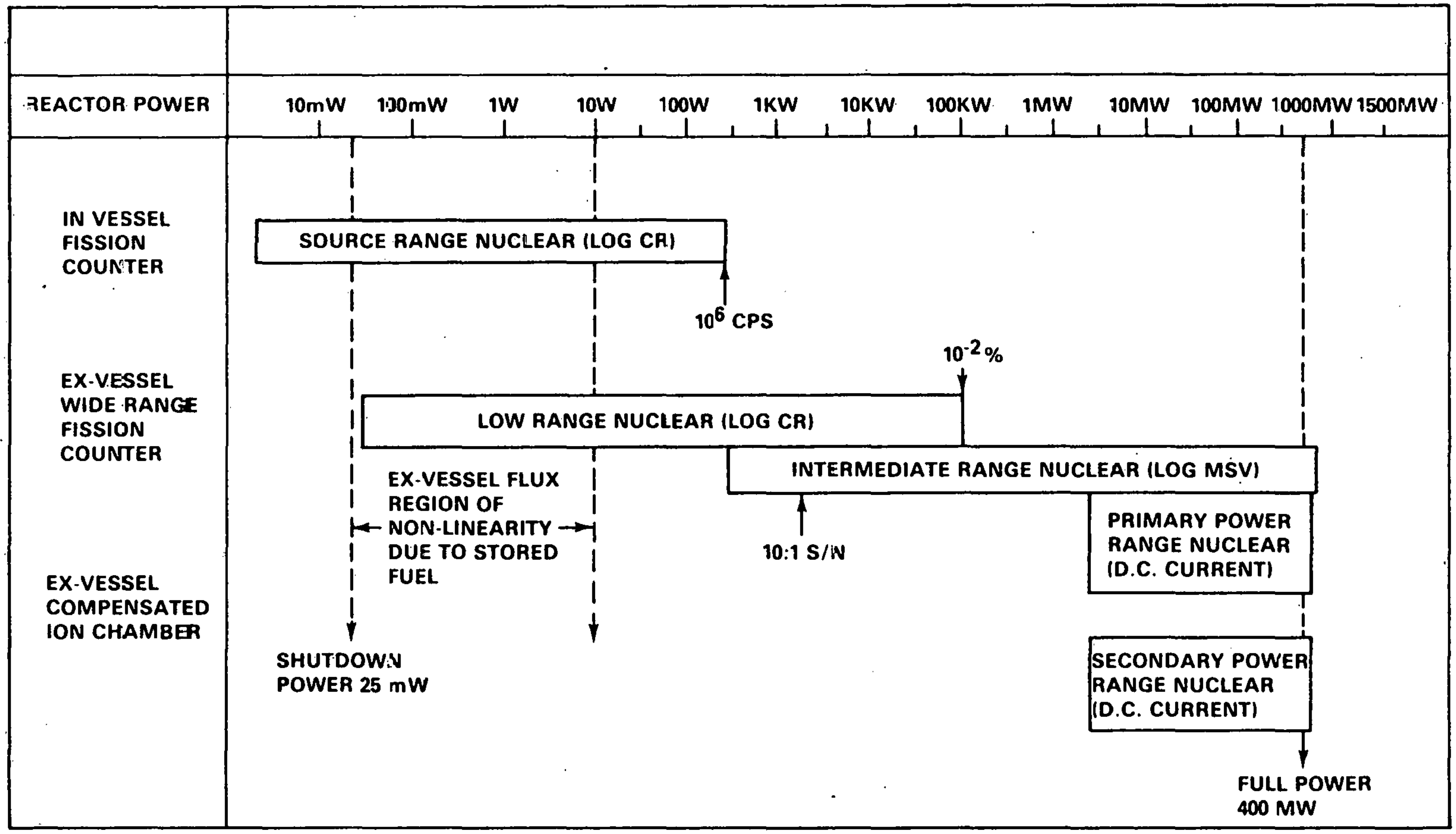
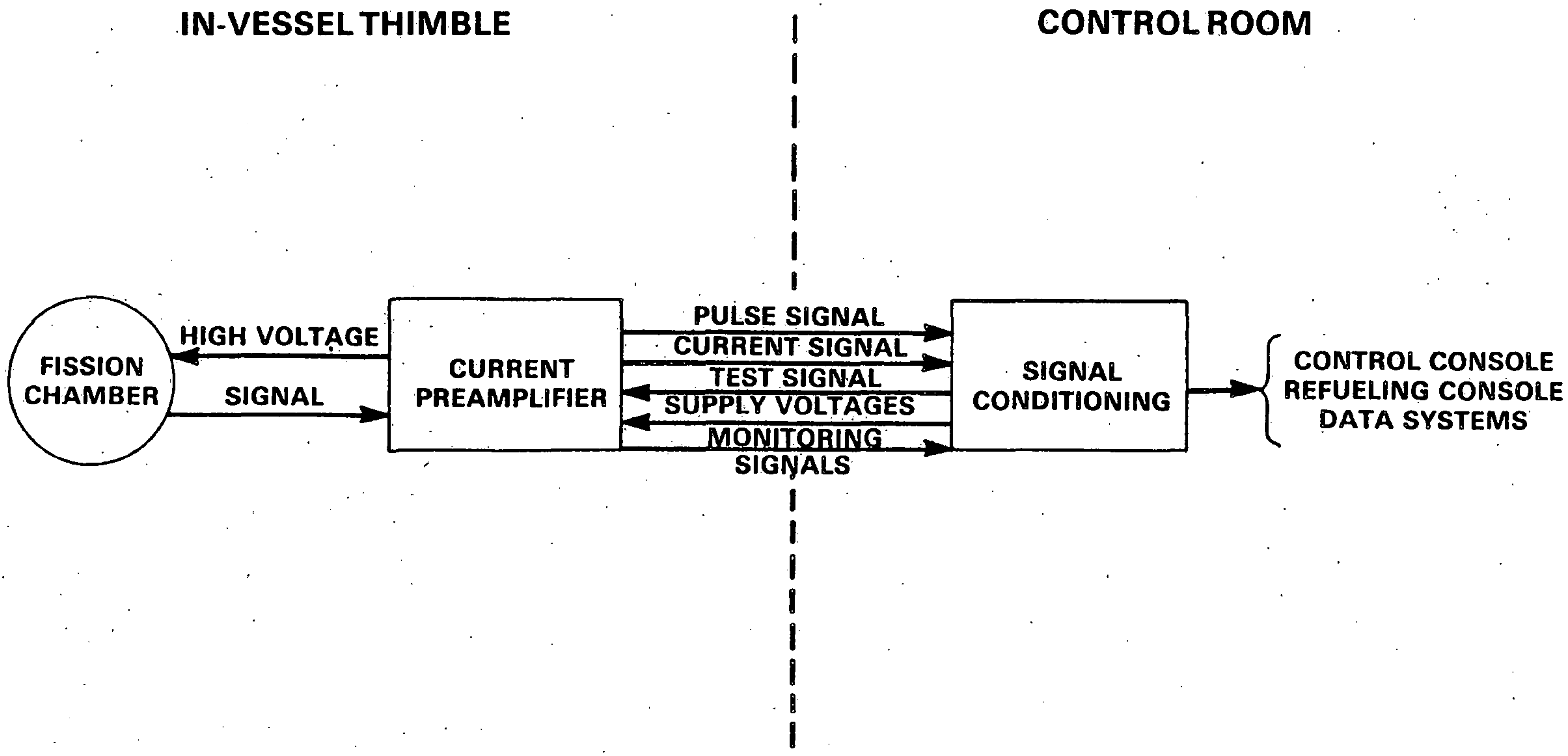


FIGURE 1

HEDL 8002-042.6

FFTF IN-VESSEL FLUX MONITORING SYSTEM



HEDL 8002-042.13

FIGURE 2

IN-VESSEL DETECTOR LOCATION

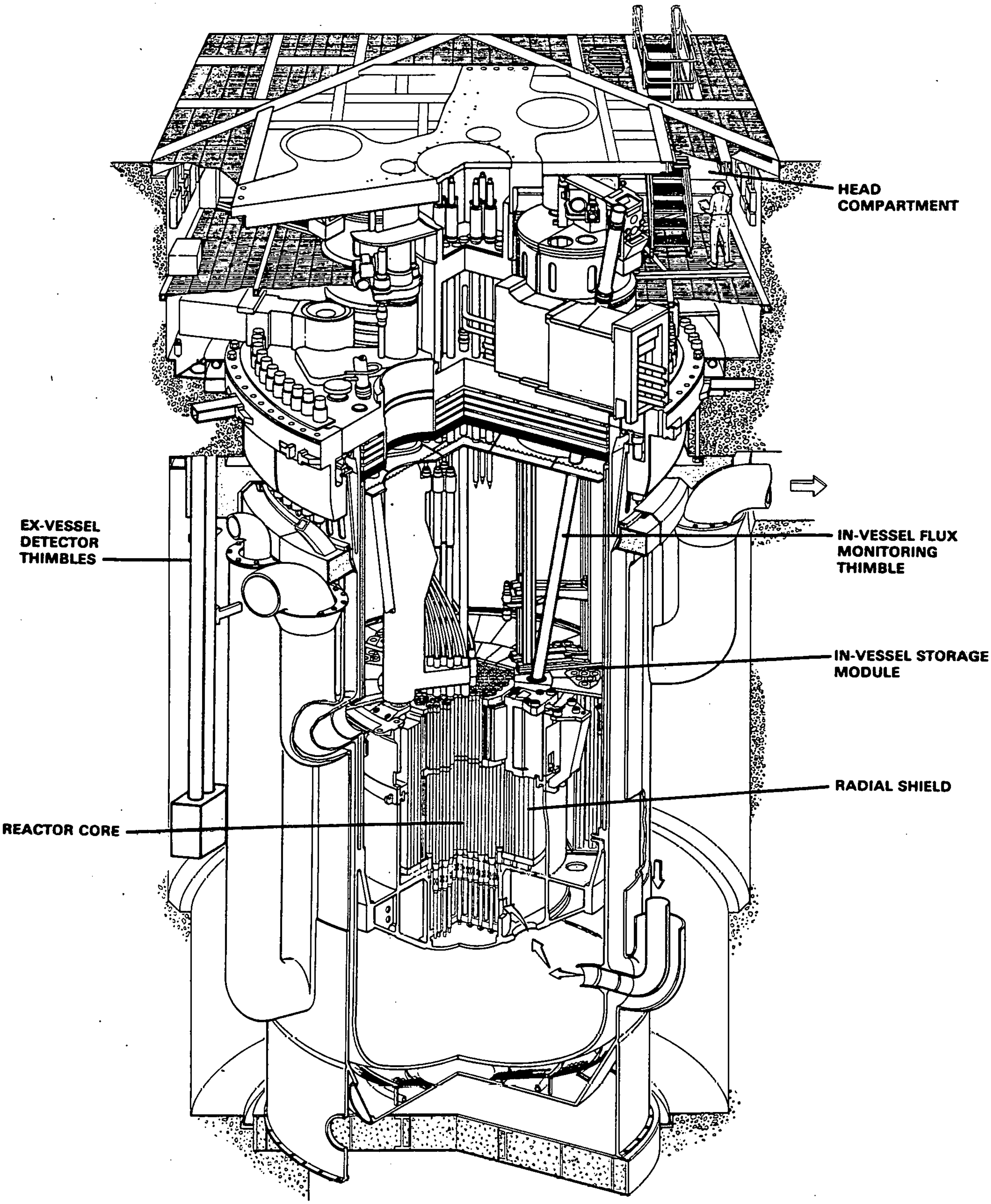
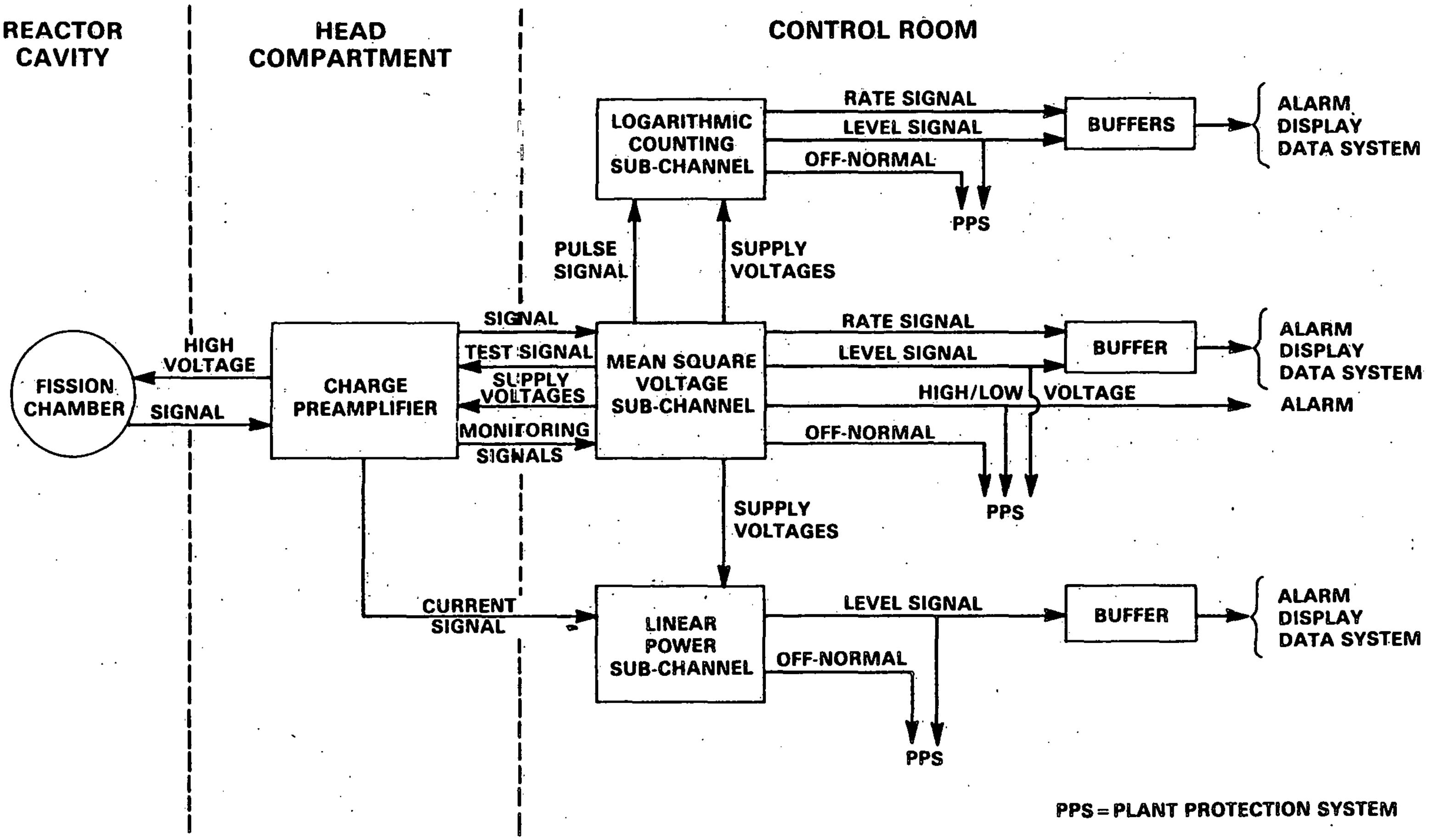


FIGURE 3

FFTF PRIMARY WIDE RANGE SYSTEM



HEDL 8002-042.12

FIGURE 4

FFTF SECONDARY POWER RANGE SYSTEM

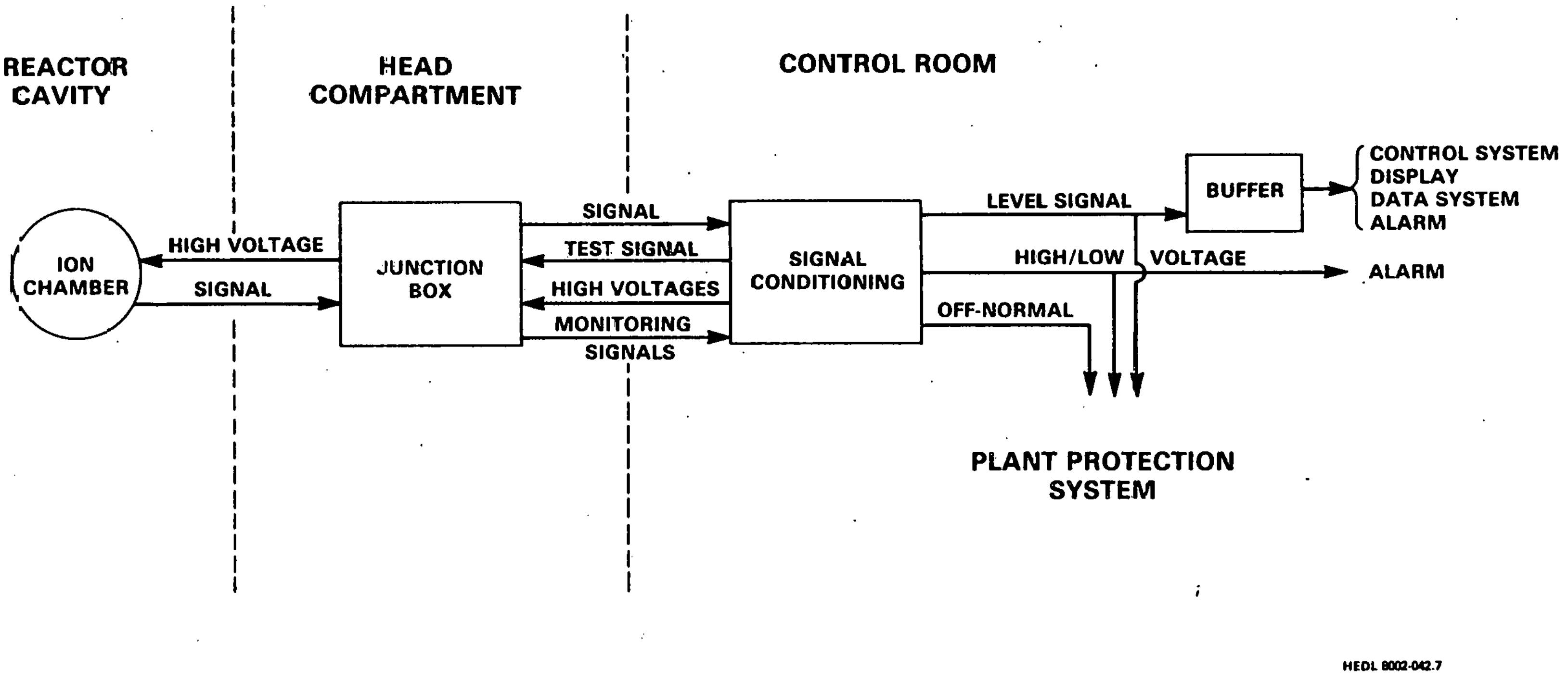


FIGURE 5

FFTF FLUX MONITORING SYSTEM DETECTOR LOCATIONS

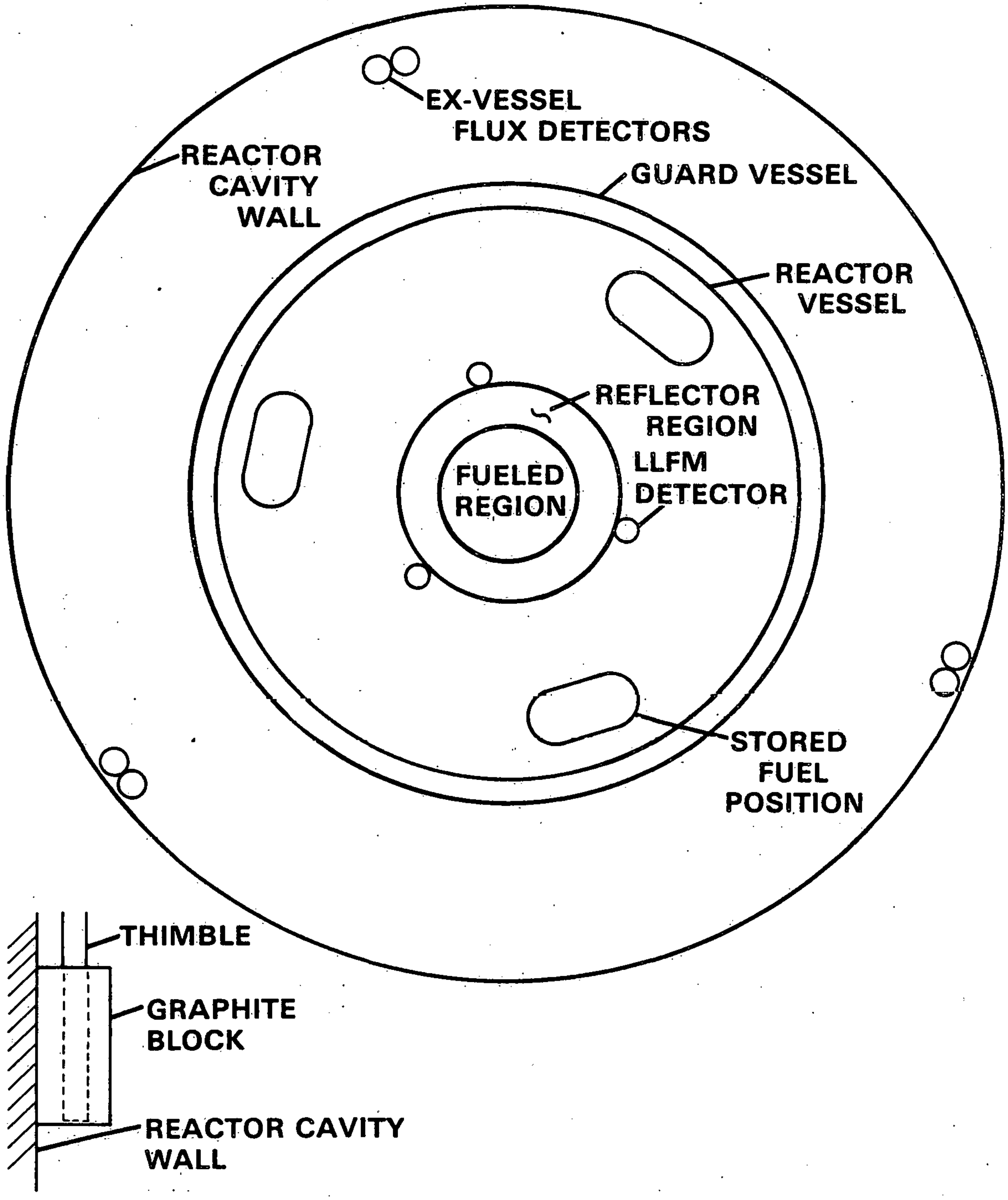


FIGURE 6

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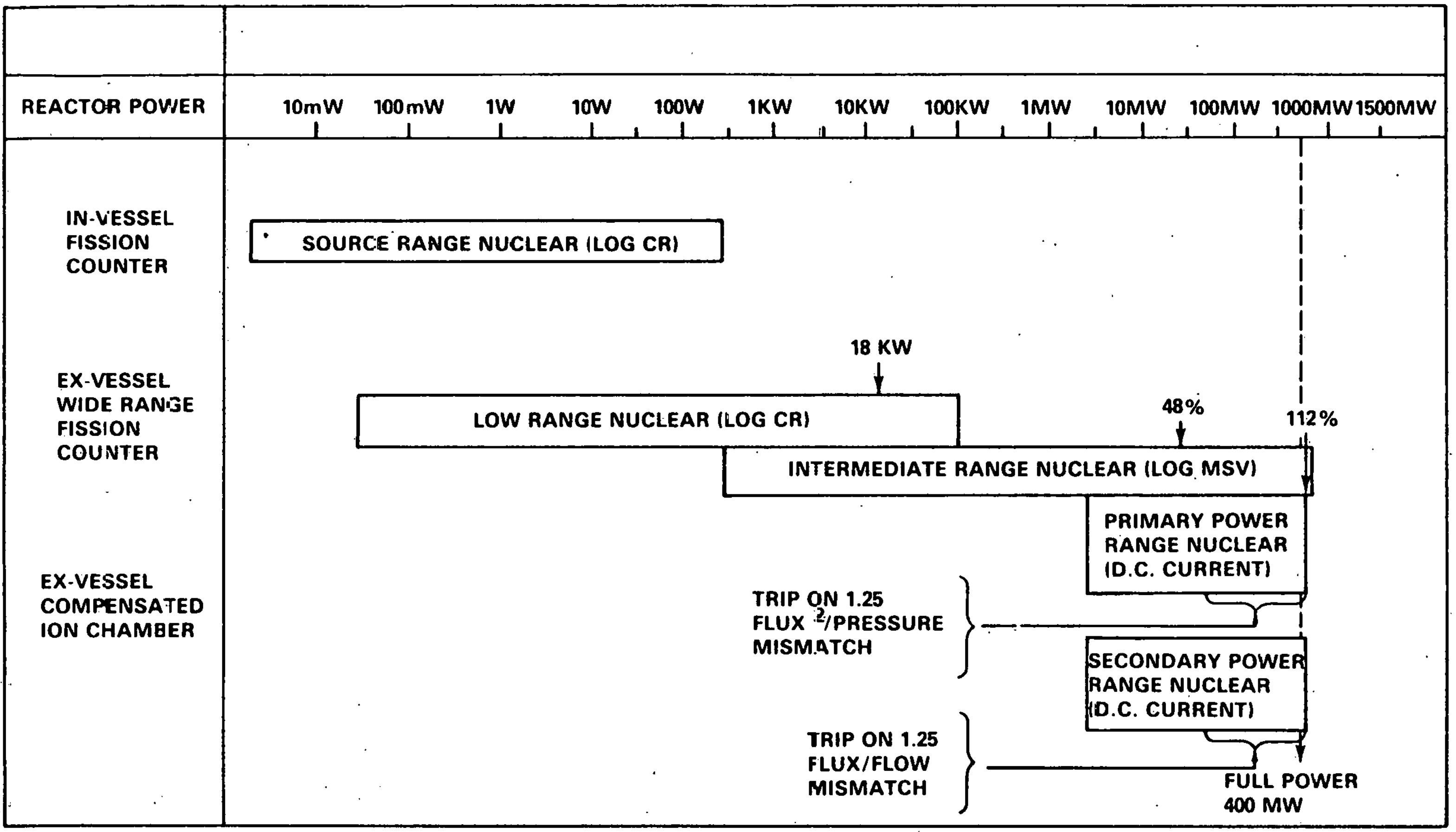
FFTF FLUX RELATED TRIP FUNCTIONS



HEDL 8002-042.11

FIGURE 7

FFTF FLUX CONTROL SYSTEM

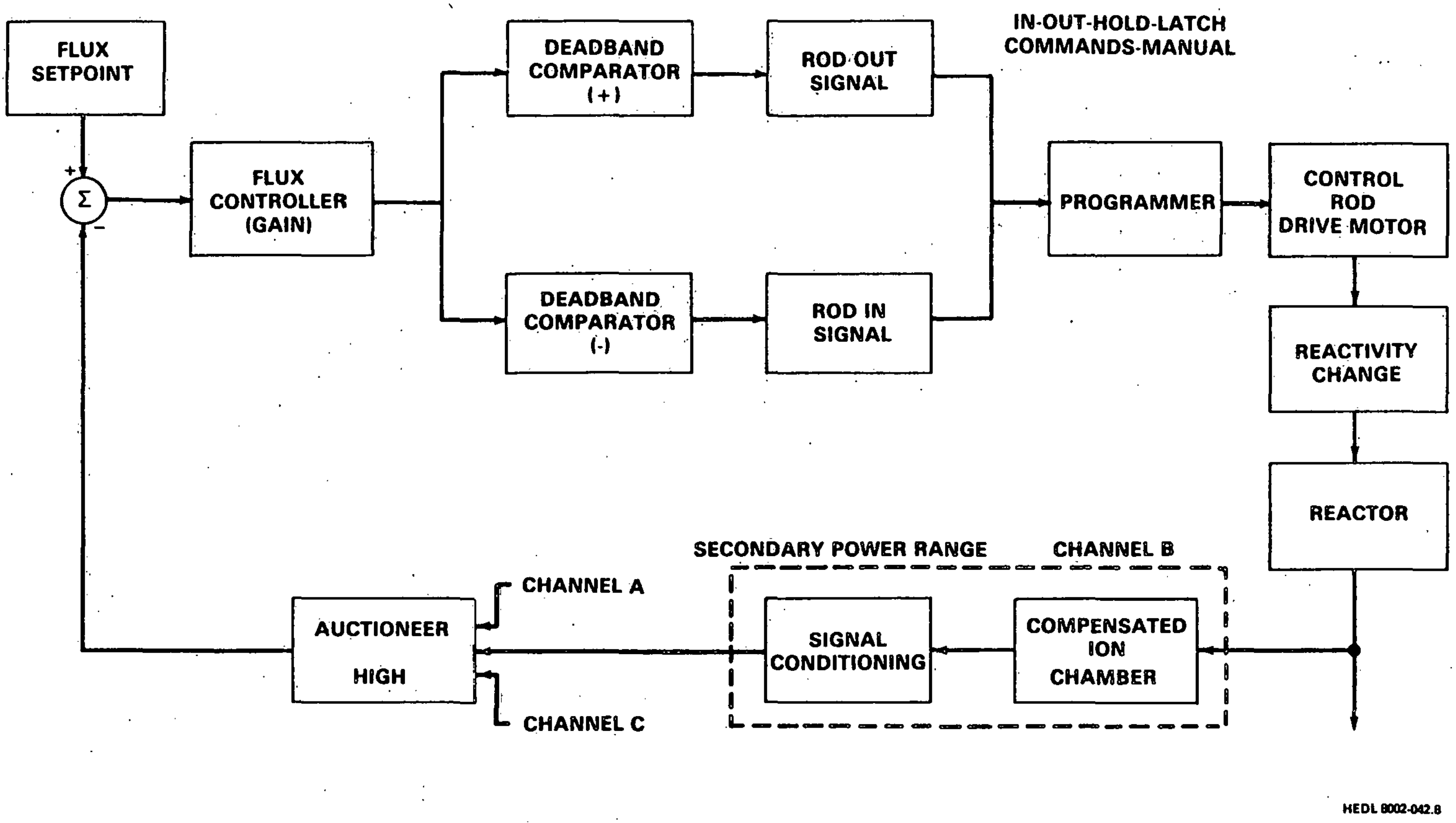


FIGURE 8

FFTF IN-VESSEL DETECTOR ASSEMBLY

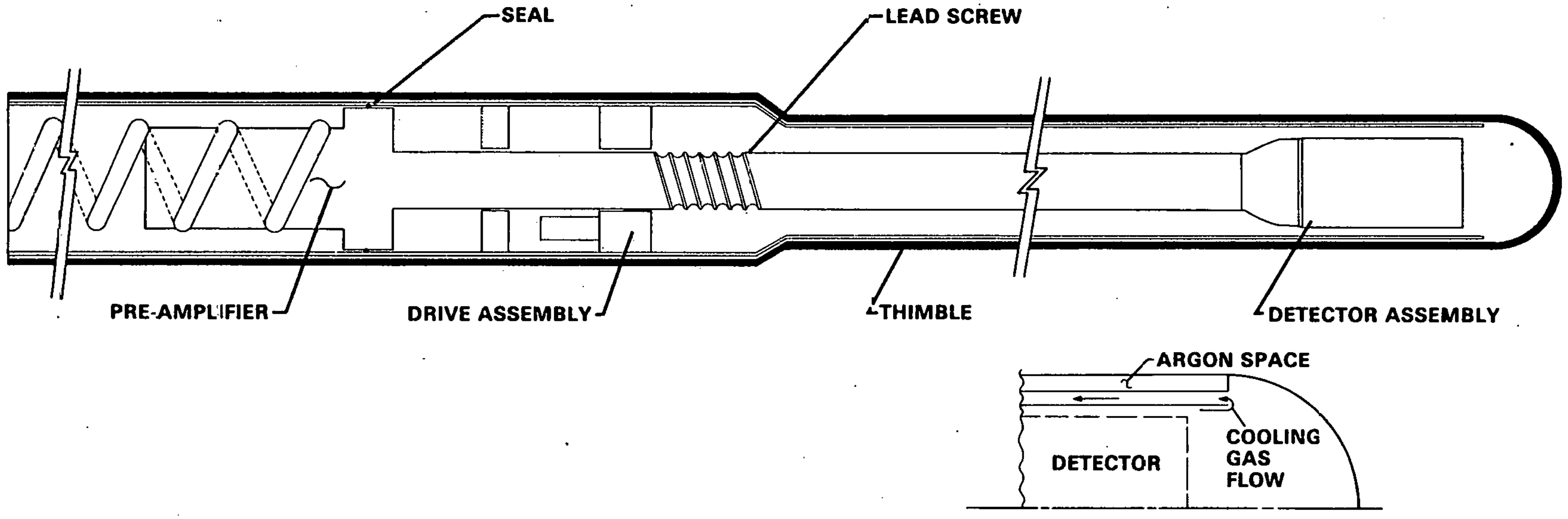


FIGURE 9

FFTF EX-VESSEL DETECTOR INSTALLATION DETAILS

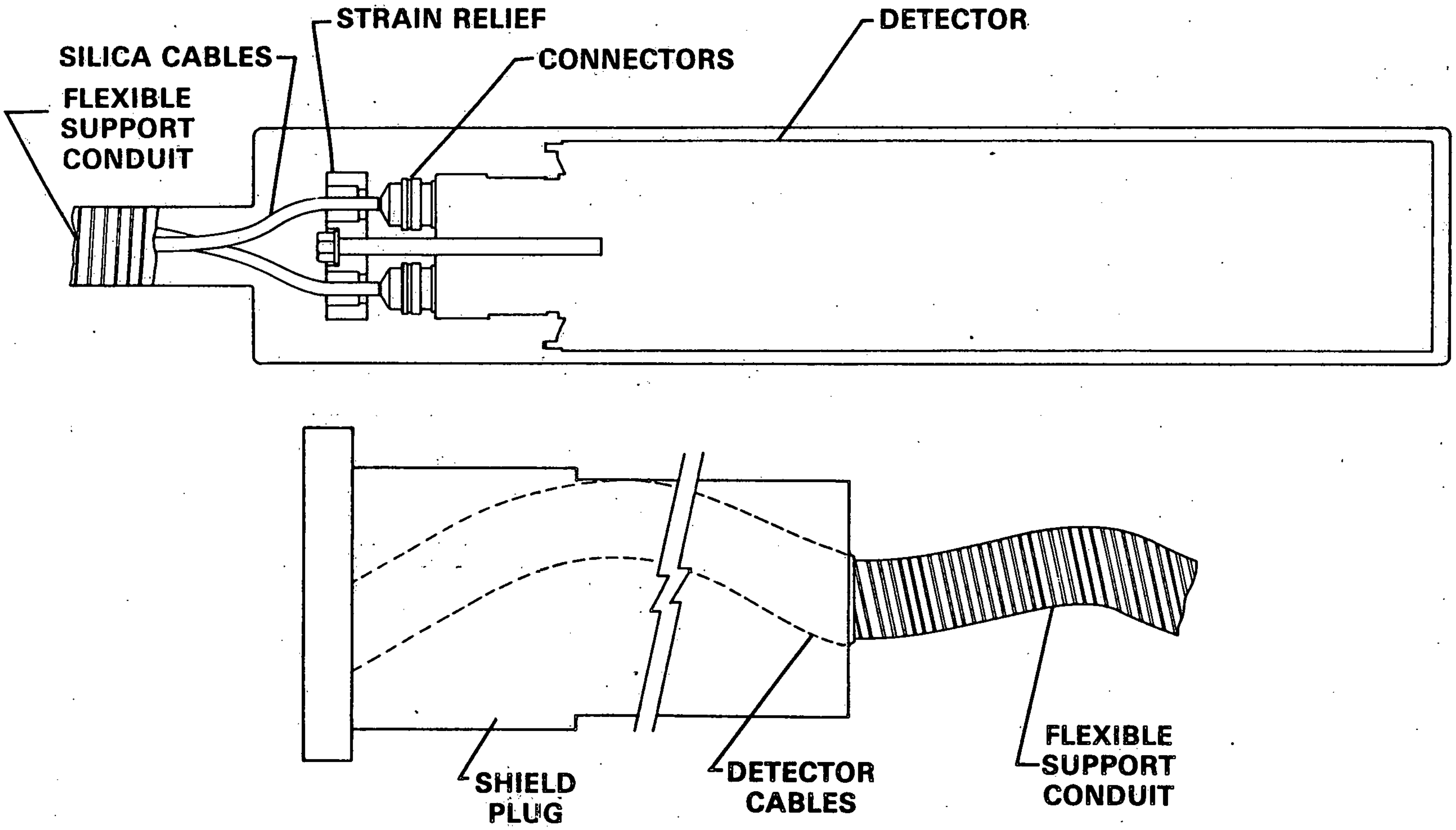


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FIGURE 10

EX-VESSEL DETECTOR CONNECTOR ASSEMBLY

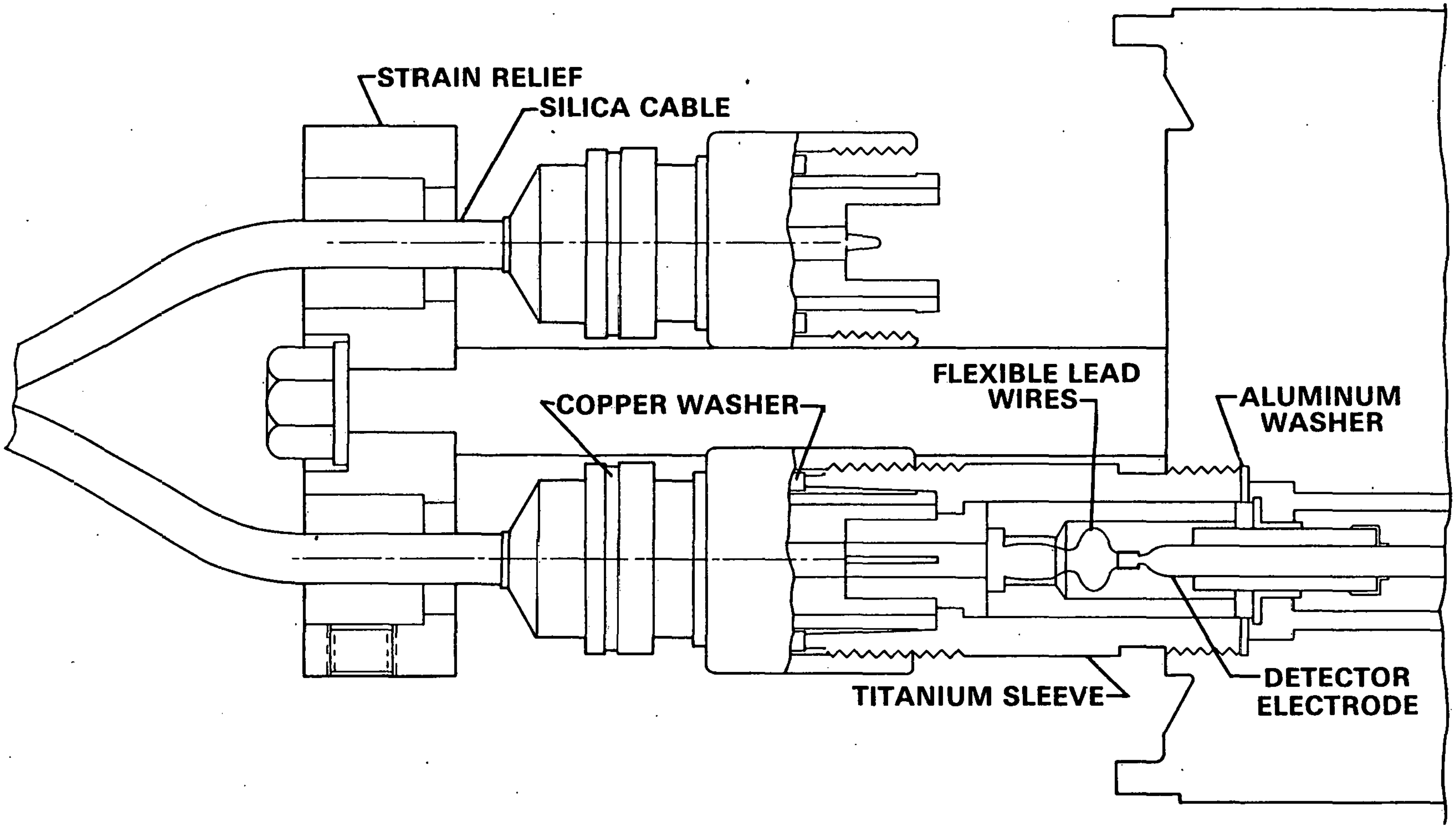

FIGURE 11

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FFTF MEASUREMENTS DURING INITIAL CRITICALITY

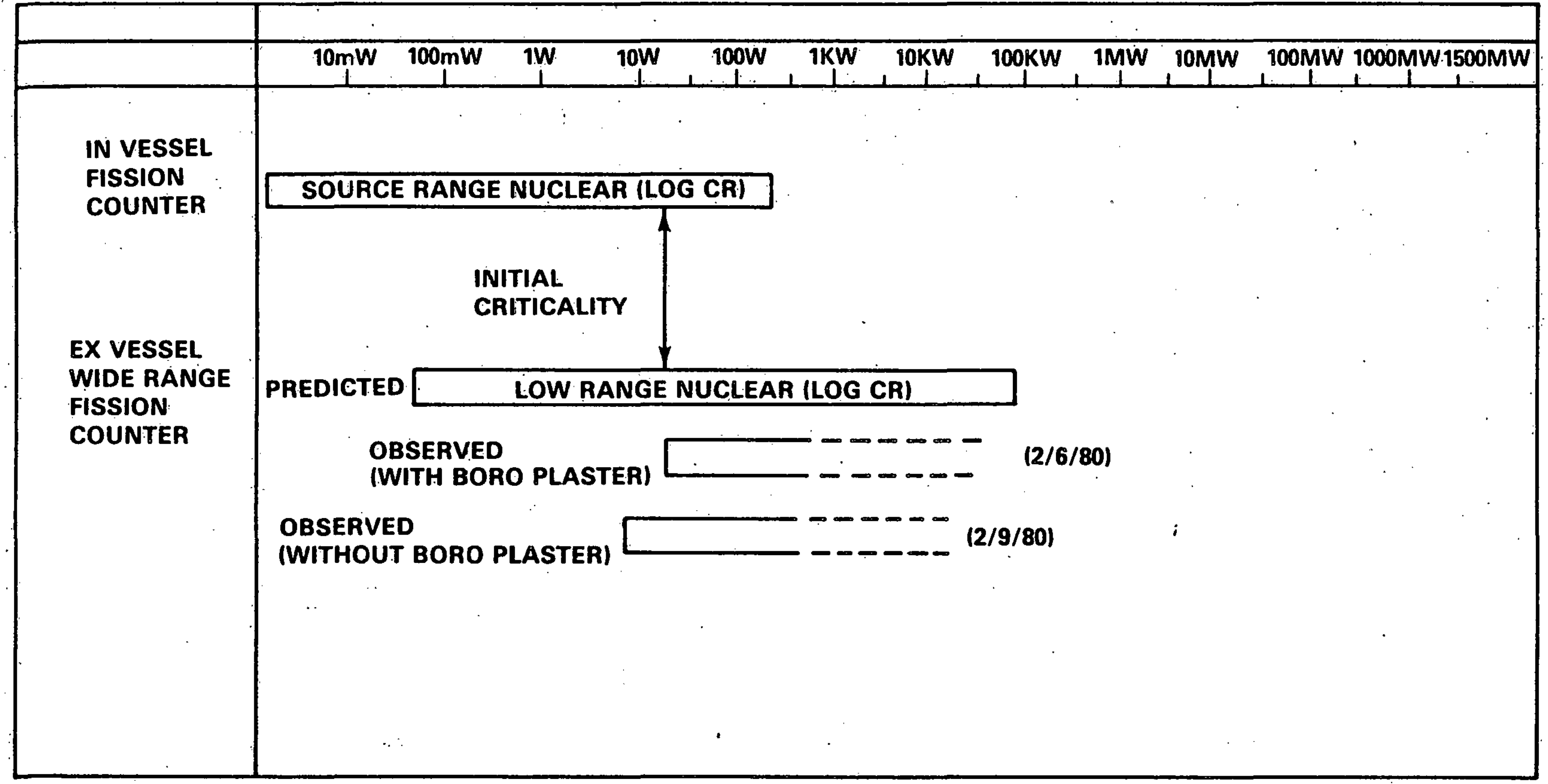

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FIGURE 12

CRBRP FLUX MONITORING SYSTEM INSTRUMENT RANGE COVERAGE

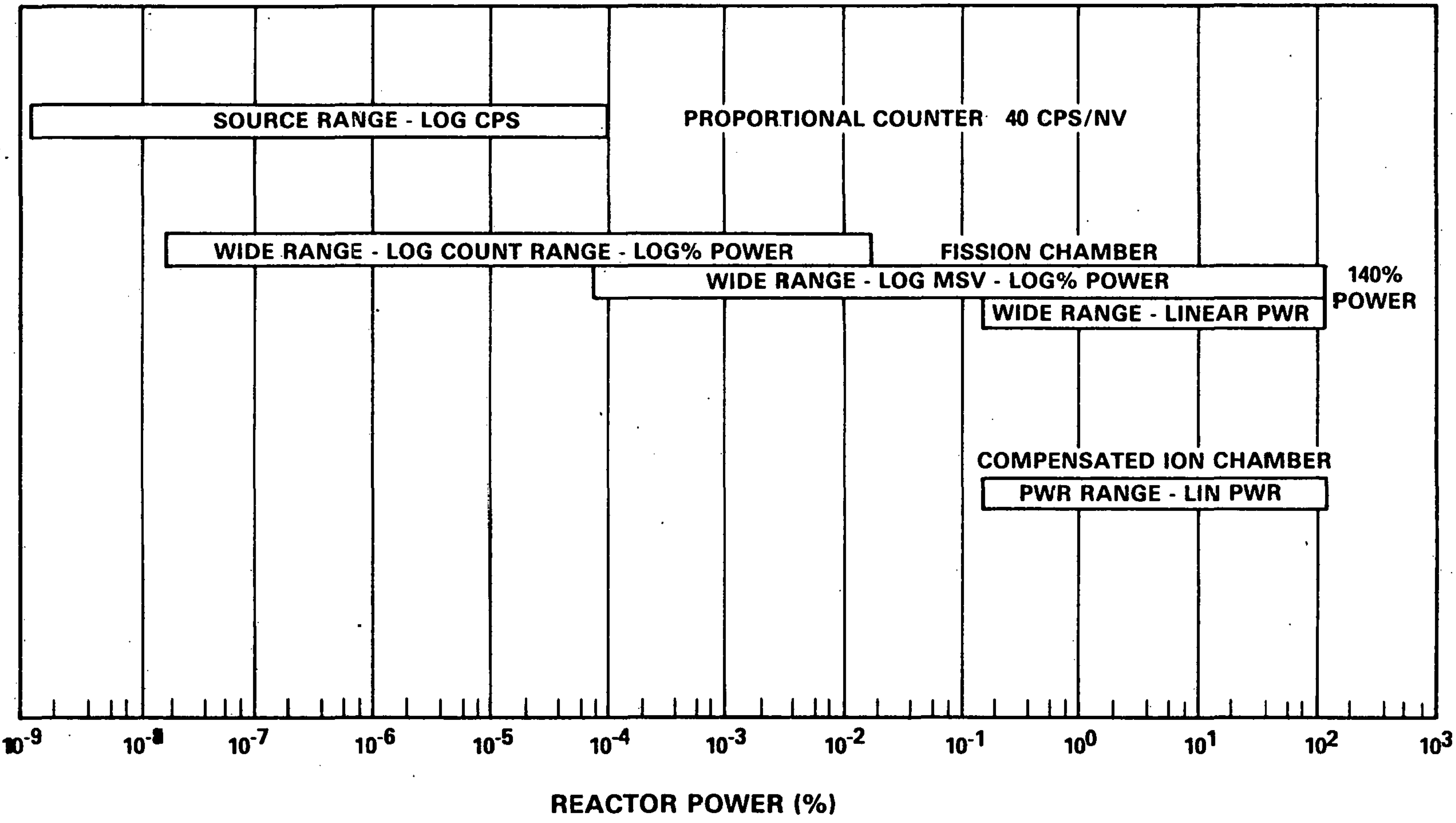

FIGURE 13

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