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Fast Flux Test Facility - A History of Safety and Operational Excellence

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Fluor Hanford
P.O. Box 1000
Richland, Washington

Contractor for the U.S. Department of Energy
Richland Operations Office under Contract DE-AC06-96RL13200

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FAST FLUX TEST FACILITY – A HISTORY OF SAFETY AND OPERATIONAL EXCELLENCE

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Deborah L. Nielsen (BS, chemical engineering, University of Washington, 1985) is employed by Fluor Hanford. She is currently a senior engineer and has worked at FFTF for more than 18 years on projects ranging from systems and project engineering to reactor and environmental safety and regulatory analyses for new missions and closure.

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ABSTRACT

The Fast Flux Test Facility (FFTF) is a 400-megawatt (thermal) sodium-cooled, high temperature, fast neutron flux, loop-type test reactor. The facility was constructed to support development and testing of fuels, materials and equipment for the Liquid Metal Fast Breeder Reactor program. FFTF began operation in 1980 and over the next 10 years demonstrated its versatility to perform experiments and missions far beyond the original intent of its designers. The reactor had several distinctive features including its size, flux, core design, extensive instrumentation, and test features that enabled it to simultaneously carry out a significant array of missions while demonstrating its features that contributed to a high level of plant safety and availability. FFTF is currently being deactivated for final closure.

I. INTRODUCTION

FFTF is owned by the United States Department of Energy (DOE) and is located at the Hanford Site in southeastern Washington State, near the City of Richland (Figure 1). The reactor was designed and built in the 1970's and brought on line in 1982 during a period when world interest in development of a liquid metal breeder reactor was high. For approximately 10 years, FFTF operated successfully as a national research facility testing advanced nuclear fuels, materials, components, active and passive reactor safety technologies, and gaining operating experience for the next generation of nuclear reactors. As a frame of reference, the FFTF contains over 40 miles of piping, over one million feet of wiring and over 20,000 instruments and sensors. Tests were performed on articles ranging from miniature materials specimens at highly controlled, elevated temperatures to full-size reactor components under prototypic and abnormal conditions. FFTF also produced a wide variety of high purity medical isotopes, made tritium for the U.S. and Japanese fusion research programs, provided international testing support, and successfully tested high temperature lithium encapsulated fuel for a space fission reactor.

The reactor was last operated in 1992 and over the next decade numerous studies were completed in an effort to identify possible uses for this unique facility. Roles that were considered and found feasible included: tritium production; isotope production for medical, research, and industrial uses; plutonium-238 production for use in advanced radioactive isotope power systems for future National Aeronautics and Space Administration (NASA) space exploration missions; nuclear waste transmutation and actinide burn testing; low temperature irradiation testing; and support to the Nation's civilian nuclear energy research and development needs such as Generation IV advanced reactors. The FFTF was originally designed to operate 20 years to the year 2002. Conceptual studies were completed to extend the reactor lifetime to 30 years or more.

DOE reached a final decision in December 2001 to permanently deactivate the facility following completion of a programmatic environmental impact statement in December 2000 which cited a lack of clear commitments from likely users for a single large mission (DOE/EIS-0310). DOE expects physical completion of final decommissioning activities by no later than September 30, 2012.

II. TESTING CAPABILITIES

FFTF has demonstrated its ability to simultaneously support multiple research activities, provide irradiation services to national and international researchers, and produce a wide variety of high-purity isotopes. The size, power output, and extensive instrumentation and characterization of the reactor and heat transport system made the facility an attractive choice for multiple research needs. Figure 2 depicts the core map from Operating Cycle 11, showing the multiple testing underway at that time.

FFTF was designed to provide a fully instrumented test reactor with on-line, real-time test control and performance monitoring of all components and tests installed in the reactor. Three large instrumentation trees, each covering one-third of the FFTF core, provide proximity instrumentation (coolant temperature and flow) for each of the core components (Figure 3). Eight special test positions were engineered into the FFTF core that provide for contact instrumentation (Figure 4). In addition to measuring parameters such as flow, temperature, and pressure, other options, such as gas and electrical connections, are available to monitor and provide unique experiment and instrumentation capabilities.

FFTF's in-core environment is prototypic of sodium-cooled, mixed oxide-fueled fast reactors (Figure 5). The peak flux in the reactor core is 7×10^{15} neutrons per square centimeter per second with 60-65 percent of the neutrons having energies in excess of 0.1 MeV. The reactor core is 0.91 meters in height and 1.21 meters in diameter, thus providing a large volume of high flux for irradiation testing. The neutron spectrum can also be locally tailored, using a high temperature hydride moderator to meet the specialized needs of individual experimenters. This proven capability can provide optimum neutron energy for production of very high specific activity isotopes.

Space is provided for installing up to four 2.3-megawatt independently cooled "closed loop" irradiation testing systems. The basic equipment for one complete primary and secondary closed loop independent cooling system (Figure 6) is installed but was not started up. Since each closed loop system would have its own coolant systems, the purity, flow and temperature of the sodium coolant in each loop could be controlled independent of the FFTF Main Heat Transport System. A Closed Loop System consists of a Closed Loop In-Reactor Assembly (CLIRA) that contains the irradiation test specimen, a primary cooling system and a secondary cooling system. All loops have provisions to detect fuel failures in the primary coolant. In the CLIRA, the test section outside diameter can be as large as 6.99 centimeters. Twenty-six instrument channels are provided for monitoring test section variables such as pressure, temperature, flux, and strain. The CLIRA experiments could be re-instrumented following internal examinations.

Although the Closed Loop Systems were initially designed to use sodium as a coolant, other liquid metal coolants, such as lithium or lead-bismuth alloy, could be used in one or more of these systems with some modifications. This would provide unparalleled testing capability for development of advanced reactor fuels and materials for civilian and space fission reactor applications.

The strengths of the FFTF for testing were well recognized in the international community. Tests were conducted in the reactor for Canada, Japan, France, Germany, the United

Kingdom, and Switzerland, in addition to the testing conducted for United States programs. Researchers were attracted by the ability to test multiple target and fuel designs simultaneously as specimens, partial assemblies or full size components with a tailored neutron environment. The FFTF irradiation services were also desired because of the well-understood core performance, the large amount of in-core instrumentation, the capability for pin or container failure detection, and the versatile hot cell and support facilities for post-irradiation examination and handling needs.

Two of the important Open Test Assemblies (OTAs) used to support test programs were the Materials Open Test Assemblies (MOTAs) (Figure 7) and the Fuel Open Test Assemblies (FOTAs). The MOTA provided multiple containers capable of irradiating multiple material specimens. Each container was individually temperature controlled by the on-line mixing of argon and helium gases in the container annulus. This provided varying heat transfer from the container to the reactor sodium coolant. The support system for this test vehicle included multiple gas lines, temperature control loops, and an on-line control and monitoring system. A large number (thousands) of individual material samples and sample forms, as well as materials for the fusion program, were irradiated in MOTAs. During reactor operation, the FOTAs provided direct measurement of temperatures and pressures of individual fuel pins, allowing monitoring of fuel assembly performance during the entire irradiation phase – from steady state through transient conditions. These test vehicles could be adapted to support closed loop testing.

The Interim Examination and Maintenance (IEM) Cell (Figure 8), located below the operating floor within the FFTF containment structure, is a shielded hot-cell complex that provides a reliable means of conducting nondestructive examinations of test assemblies and core components under controlled argon atmosphere conditions. Four levels of operating galleries provide visual access for remotely operating the in-cell equipment. This highly shielded hot cell has a significant number of remote tools and equipment for diverse examination and disassembly needs. It contains two cranes and two very large electromechanical manipulators, as well as multiple pairs of smaller master-slave type manipulators for component and equipment handling. A sodium cleaning station is available to wash irradiated components of all external sodium residues after removal from the reactor. Cell ceiling valves and an access plug are provided over the cell for transfer of all core components and maintenance and examination equipment in and out of the cell. The main section of the IEM Cell is approximately 16.76-meters deep, making it one of the tallest hot cells in the world.

III. FFTF SAFETY FEATURES AND ACCOMPLISHMENTS

FFTF was built to modern reactor standards and has many features which contribute to a high level of plant safety. Prior to the shutdown of FFTF, DOE was performing a Probabilistic Risk Assessment (PRA) for operation. Preliminary results (based on 50 percent completion) indicated the probability of occurrence of a severe accident at FFTF was approximately 100 times less than at a typical commercial light water reactor, due to FFTF's unique design and safety features. It is the only DOE reactor built in accordance with the standards established by the American National Standards Institute and American Society of Mechanical Engineers. FFTF made significant contributions to the development of new standards and codes for special applications of fast reactor technology. Prior to initial operation, the Nuclear Regulatory Commission (NRC) and the Advisory Committee on Reactor Safeguards (ACRS) performed an extensive review of the plant design and Final Safety Analysis Report, the same review process used for commercial reactors.

Liquid-metal-cooled reactors, and FFTF in particular, have a number of important safety characteristics inherent in their designs. The sodium coolant used in FFTF has a very high thermal conductivity (approximately 100 times higher than water). During normal operation, and even under most accident conditions, the fuel cladding operated only a few degrees above the coolant temperature. A major concern for water-cooled reactors is the loss-of-coolant accident (LOCA). Sodium has a very high boiling point (>880 degrees centigrade) and thus the reactor and associated cooling systems operate at essentially atmospheric pressure. As a result, for almost all accident scenarios, there was no concern about boiling away the coolant, and thus overheating the fuel. When combined with the incorporation of guard vessels around each major component of the primary heat transport system and the use of elevated piping outside of the guard vessels, multiple independent and highly unlikely failures would be required to lose the coolant from the core. Operating at essentially atmospheric pressure reduces the probability of leakage and significantly reduces the leak rate in the unlikely event that a leak develops.

The plant was designed with special mitigative features to ensure safety, even if a leak were to occur (e.g., inerting of cells), including:

(1) A Reactor Shutdown System that was extremely reliable and met modern commercial reactor design standards. Both redundancy and diversity were incorporated into the

system to ensure an automatic reactor shutdown (scram) when any of the key operating parameters exceeded established values.

(2) A reactor core designed to ensure that the overall power coefficient was negative throughout the operating range. This means that any perturbation to the reactivity of the core tended to be self-correcting and self-limiting. Heating of the core reduced the reactivity, thus driving it to a lower power level.

(3) Emergency core cooling by natural circulation of the sodium coolant. No active equipment, such as pumps, was required. Natural circulation tests confirmed that the operating characteristics of properly-designed liquid metal systems, coupled with the excellent heat transfer properties of sodium, provided for inherently safe, reliable, and self-regulating heat removal under emergency conditions.

FFTF proved extremely robust and flexible, allowing its use for a variety of purposes beyond its original mission. The extensive instrumentation and characterization of the reactor and heat transport system supported a wide variety of tests performed to demonstrate the safety characteristics of Liquid Metal Reactors (LMRs). Instrumentation measured the coolant flow and temperature at the exit of each core subassembly, and specially instrumented assemblies were installed within the core region to provide detailed core operating data. For example, Fueled Open Test Assemblies (FOTAs) placed thermocouples within the core region during verification of the natural circulation decay heat removal process. These capabilities were also used during later testing performed to provide additional detailed information on the reactivity feedback characteristics of the reactor and during demonstration testing of devices designed to further enhance the inherent safety of LMRs. These devices, called Gas Expansion Modules (GEMs), used natural forces to introduce negative reactivity in case of a loss of flow accident (Figure 9) by increasing neutron leakage from the core.

FFTF produced many results that went beyond original expectations, setting new world records and receiving many awards. Variations in fuel, cladding alloys, fuel spacers and fuel assembly ducting were developed and demonstrated. Figure 10 shows the effect of temperature and fluence gradients on the lengths of fuel pins of 316 stainless steel versus D9 alloy clad pins. FFTF demonstrated that thin-walled stainless steel clad fuel pins have an extremely low failure rate in a high temperature sodium environment. Proof testing of core components showed that their lifetimes could be increased by factors of 300 to 500 hundred percent.

The reference driver fuel system performance was outstanding to goal burnups of 100,000 megawatt days/metric tons heavy metal (Mwd/MTM) (over 40,000 mixed oxide fuel pins were irradiated with only a single failure). A three-year driver fuel system (Core Demonstration Experiment) exceeded 238,000 Mwd/MTM burnup. Figure 11 presents FFTF's fuel burnup accomplishments. The achievement and reliability of such results is due in part to the large core volume of FFTF, which allowed partial core loading and irradiation of a group of experimental core components in correct relation to each other under prototypic conditions.

FFTF used a technique for locating a failed fuel (or absorber) assembly based on the use of unique mixtures of xenon and krypton gas in fuel and absorber pins. These tag gas mixtures were loaded into the pins at the time of fabrication. All individual pins of a given fuel assembly contained the same unique isotopic mixture, consisting of one std cc of xenon and one std cc of krypton. Over 106 unique mixtures were used. Each time a fuel or absorber pin failure was detected, cover gas samples were obtained with a tag gas sampling trap. The failed assembly was identified by matching the results of a mass spectrometer analysis with previously determined analyses of all tag gas mixtures in the reactor, correcting for burnup and background. Operational experience demonstrated the reliability of the FFTF tag gas system to successfully locate failed fuel pins.

In addition to irradiation testing of advanced fuels and materials for terrestrial applications, FFTF was also instrumental in developing and testing fuels and materials for the SP100 space fission reactor, and testing to support Thermionic Fuel Element and Plutonium-238 programs. Numerous experimental fuel pins with various fuel, liner and refractory alloy cladding were tested in FFTF. This provided valuable high burnup data on lithium encapsulated high density Uranium Nitride (UN) fuel. Significant design effort was also expended on development of a flowing lithium loop experiment (natural or forced convection) for space fission reactor fuel before cessation of this program.

A number of irradiation tests and studies were also conducted to support producing a wide variety of radioisotopes at FFTF. For example, by using the neutron energy spectrum tailoring technique to enhance nuclear reaction rates, an FFTF test resulted in the highest specific activity gadolinium-153 ever produced. Using this same technique, another test irradiated more than 30 target isotopes to verify production physics predictions. Several of the resulting isotopes were delivered to university and medical researchers. Significant work was also done to evaluate the feasibility of producing short-lived medical isotopes. Preliminary conceptual work and analysis were completed for a Rapid Radioisotope Retrieval system which would insert and remove isotope targets during reactor operation to meet the demand for short-lived radioisotopes. The availability of eight vertical spoolpieces on the reactor head, with direct access to the reactor core, would provide ideal access for such a system at FFTF.

FFTF provided important operational data on the performance of liquid sodium as a heat transport medium and demonstrated the reliability and efficiency of pumps, valves and other vital liquid metal reactor components. The large sodium loops and components have provided reliable service for more than 20 years.

The reactor achieved an operational efficiency factor exceeding 90 percent (100 percent was achieved for two of the years) during its 10 years of operation (Figure 12). Operation efficiency is the fraction of time that the reactor achieved its annual irradiation plan.

IV. CURRENT STATUS

At the present time, FFTF is being shutdown and deactivated, and FFTF personnel are making significant progress on this work. Key activities include fuel offload, sodium drain and auxiliary systems shutdown. Spent nuclear fuel is being washed and offloaded to interim dry storage casks and will be stored aboveground at Hanford until the final repository is available. The secondary sodium systems were drained in 2003 to a sodium storage facility constructed in 1996 to house the 980,000 liters (260,000 gallons) of FFTF sodium. Planning is in progress for draining the reactor vessel and primary system. Draining the reactor vessel presents unique challenges, as approximately 60,600 liters (16,000 gallons) of sodium will remain in the vessel below the inlet nozzles. An access hole will be drilled through the core basket and the wall of the low pressure plenum (part of the core support structure) to permit a pump assembly (approximately 18.3 meters long) to be inserted directly from the top through the reactor vessel head.

The pump discharge will be connected to the primary drain header and the sodium will be pumped to the storage tank. Current plans call for the sodium to be transferred to the Argonne National Laboratory-West, in Idaho, where it will be converted to sodium hydroxide at an existing Sodium Processing Facility before being transferred back to the Hanford Site for use by the high level Waste Treatment Plant.

The final end state for FFTF has not been determined. A National Environmental Policy Act environmental impact statement will be prepared to assess the potential environmental impacts of a range of reasonable decontamination, decommissioning and environmental restoration alternatives, as well as to provide a means for public input into the decision-making process. DOE's preferred final end state alternative is entombment.

Under this alternative, the FFTF complex (other than the Reactor Containment Building) and other designated support buildings would be decontaminated, demolished to three feet below grade, and backfilled with appropriate fill material to grade level. The Reactor Containment Building dome, above grade level, would be dismantled and removed, and the Reactor Containment Building, below grade level, would be filled with grout or other suitable fill material to immobilize remaining radiological or chemical hazards and prevent subsidence concerns. The reactor vessel, with irradiated steel internals would remain in place, as would asbestos, depleted uranium shielding and lead shielding. An environmentally acceptable engineered barrier would be used to cover the containment area. This barrier, with the lower containment superstructure, internal structures, and fill materials, would form the entombment. Appropriate monitoring of the remediated site would be established.

From a technical viewpoint, entombment has merit, because of the multiple existing boundaries to contain radioactive and contaminated material. If this end state is selected, FFTF could be at the cutting edge of demonstrating the acceptability of entombment for other DOE facilities (e.g., the Experimental Breeder Reactor-II [EBR-II]) as well as application to Nuclear Regulatory Commission (NRC)-regulated power reactor facilities.

ACKNOWLEDGMENTS

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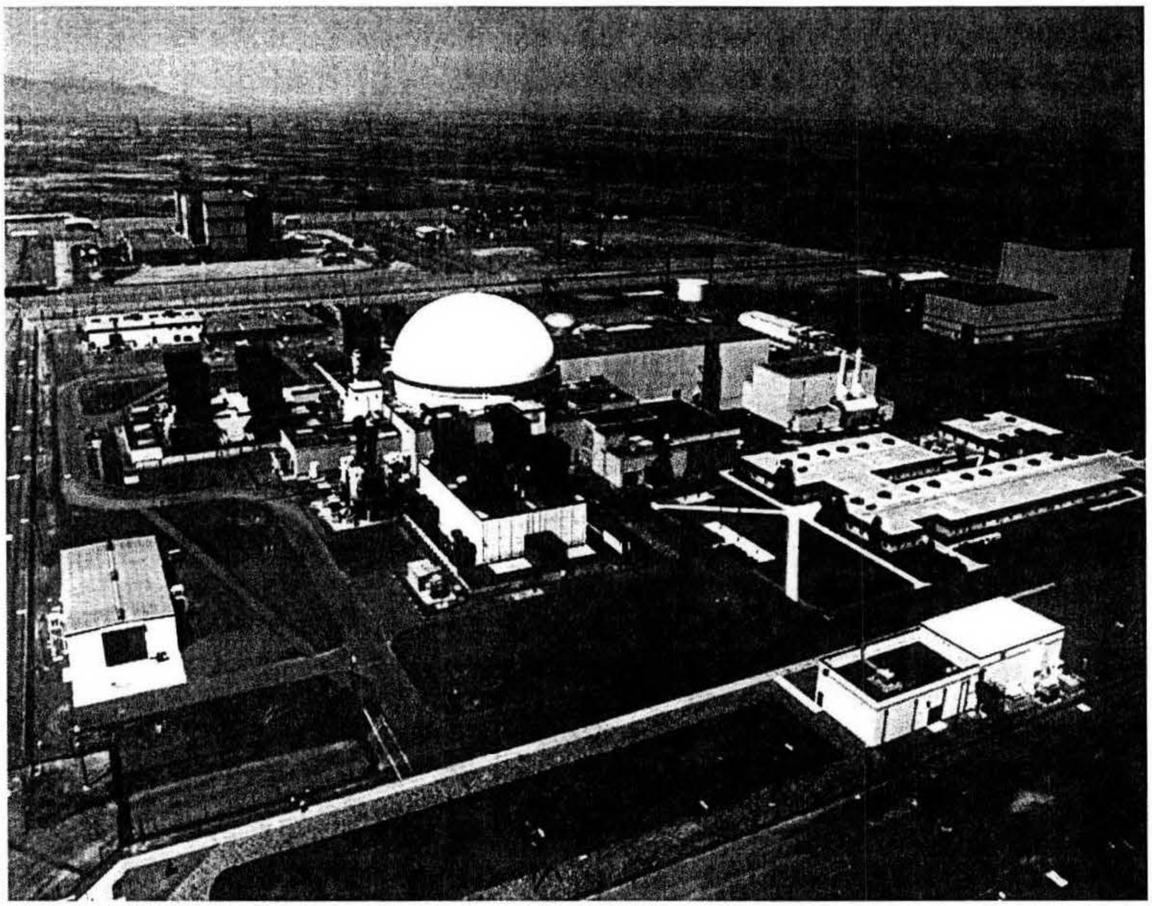


Figure 1. Fast Flux Test Facility

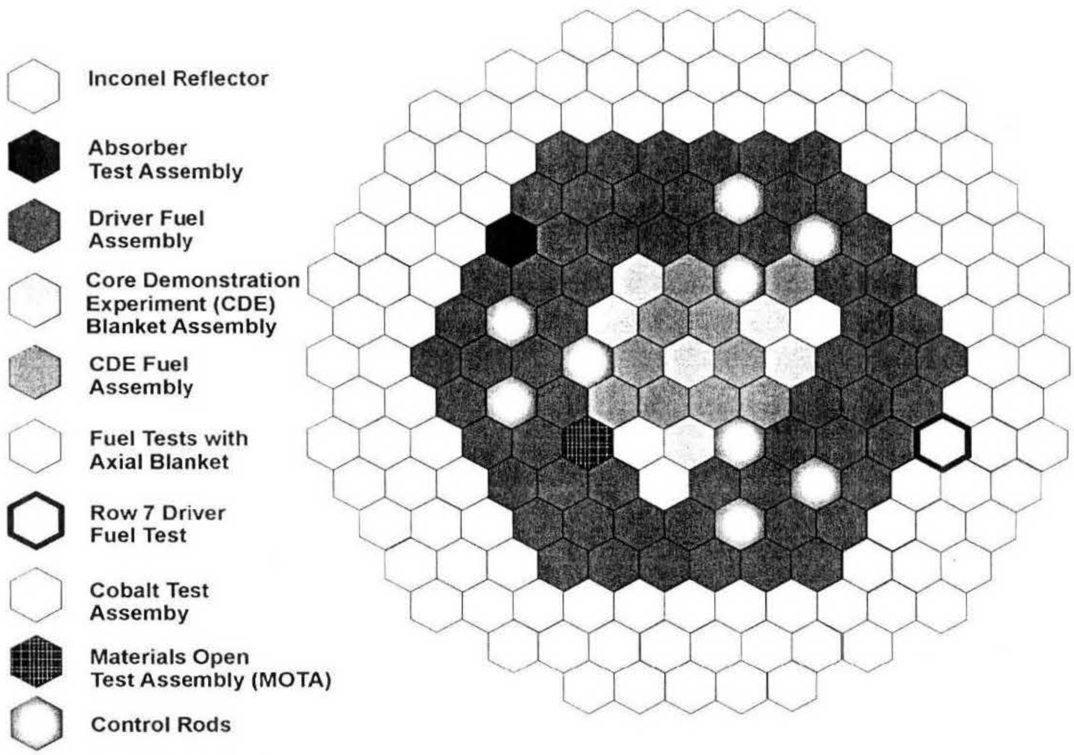


Figure 2. FFTF Cycle 11 Multi-Test Core

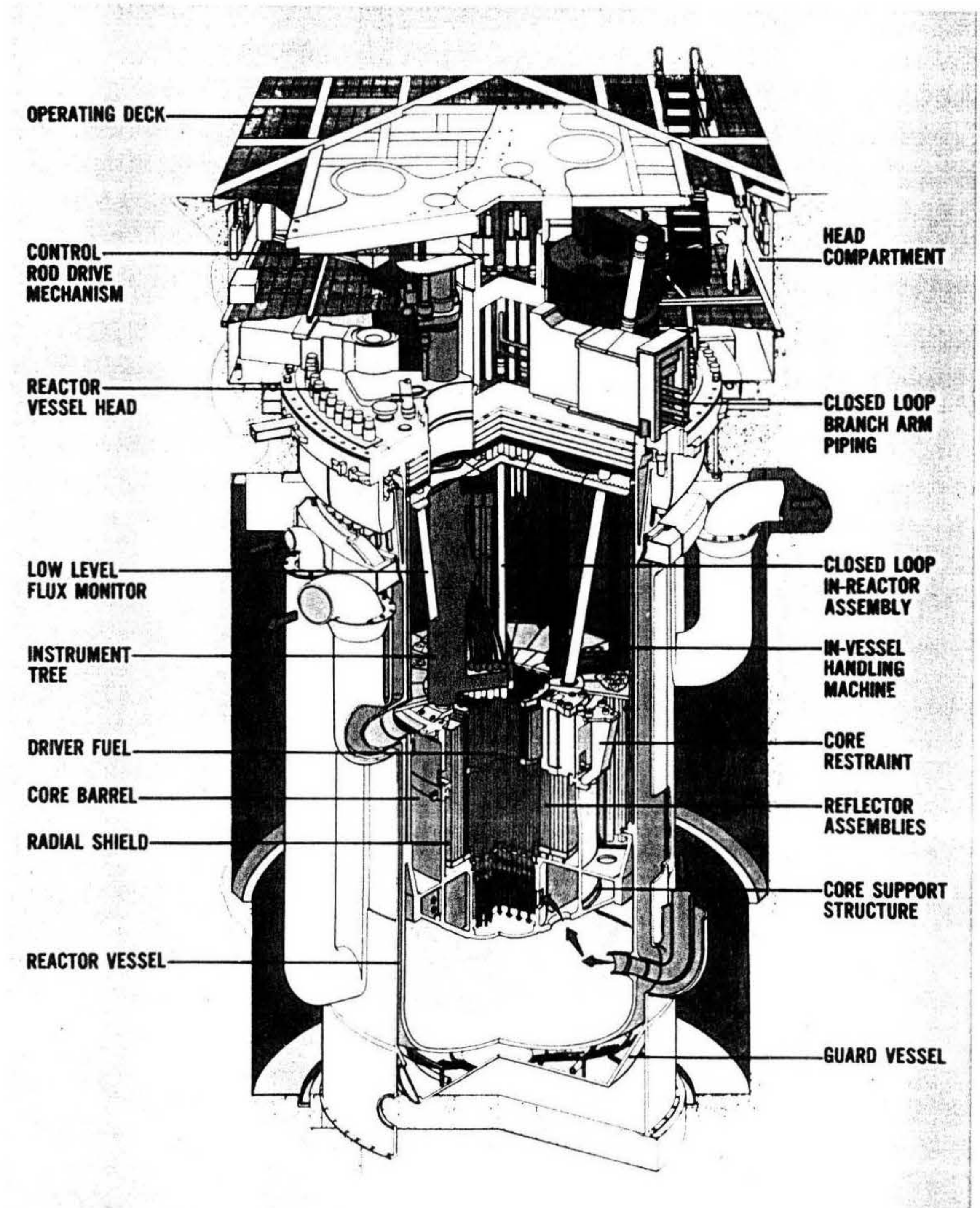


Figure 3. FFTF Reactor Vessel

TEST ARTICLES INSTALLED IN THE FFTF

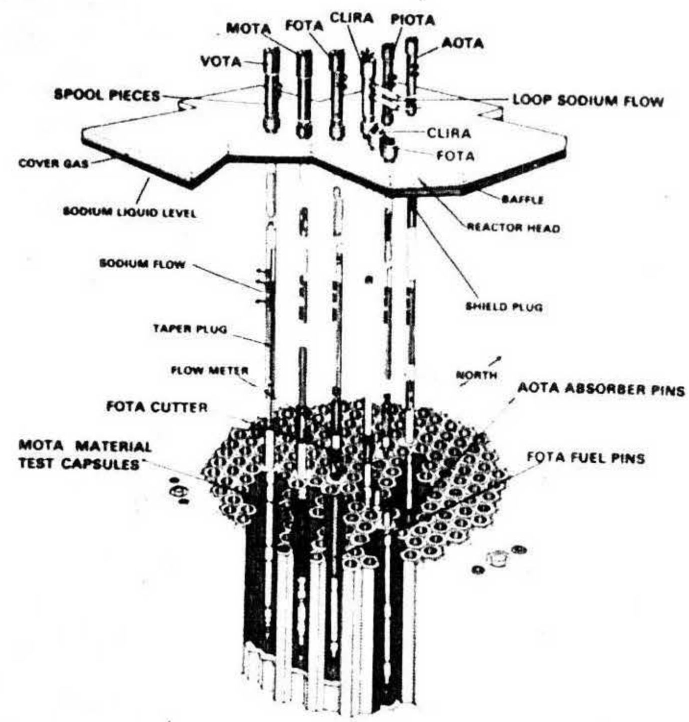


Figure 4. Test Articles Installed in the FFTF

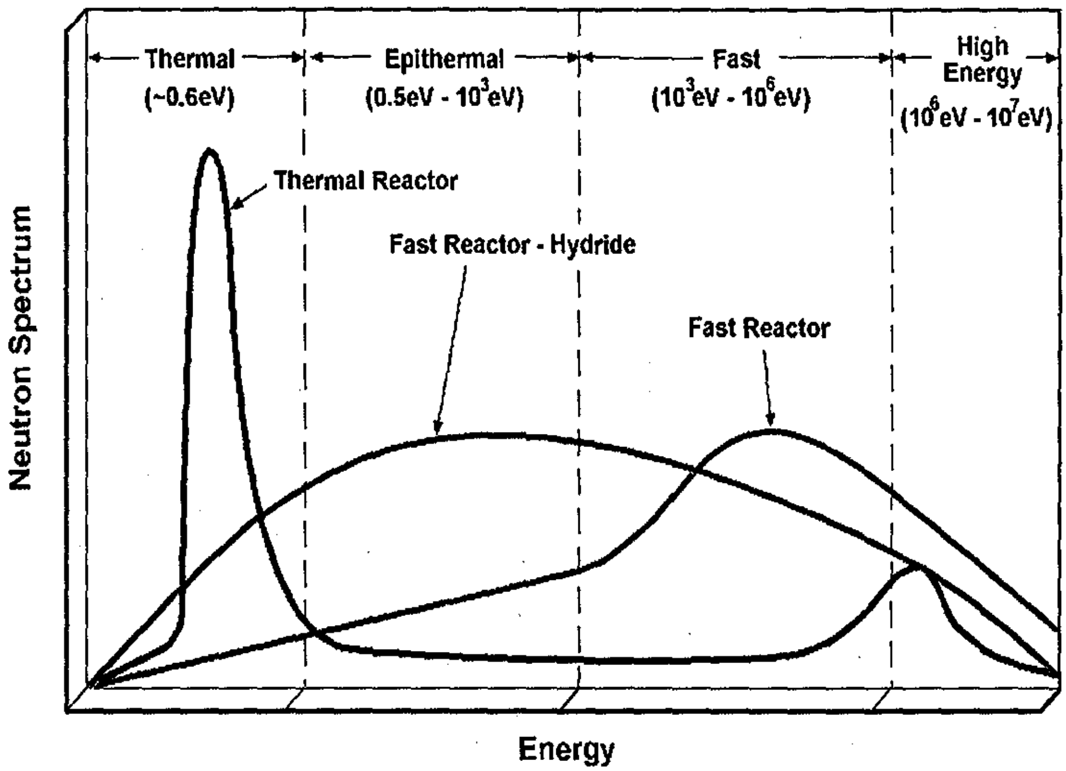


Figure 5. FFTF's Neutron Spectrum

Figure 6. FFTF Closed Loop System

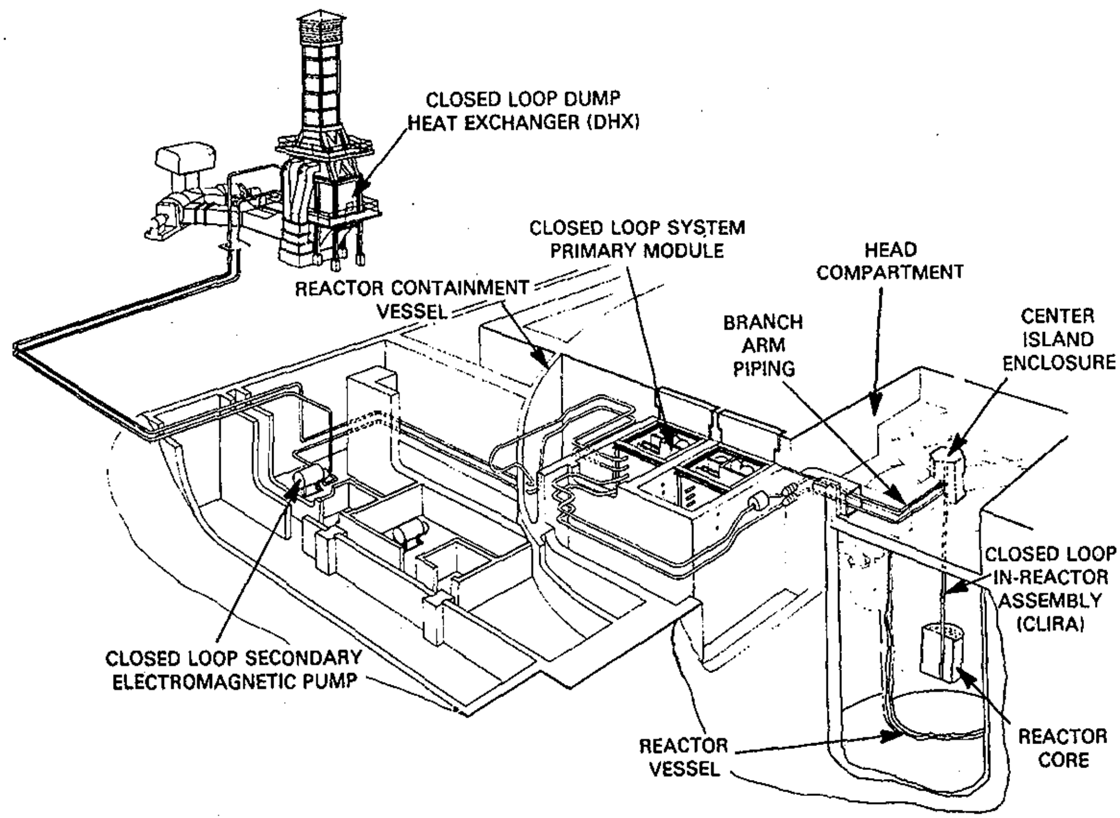


Figure 7. MOTA

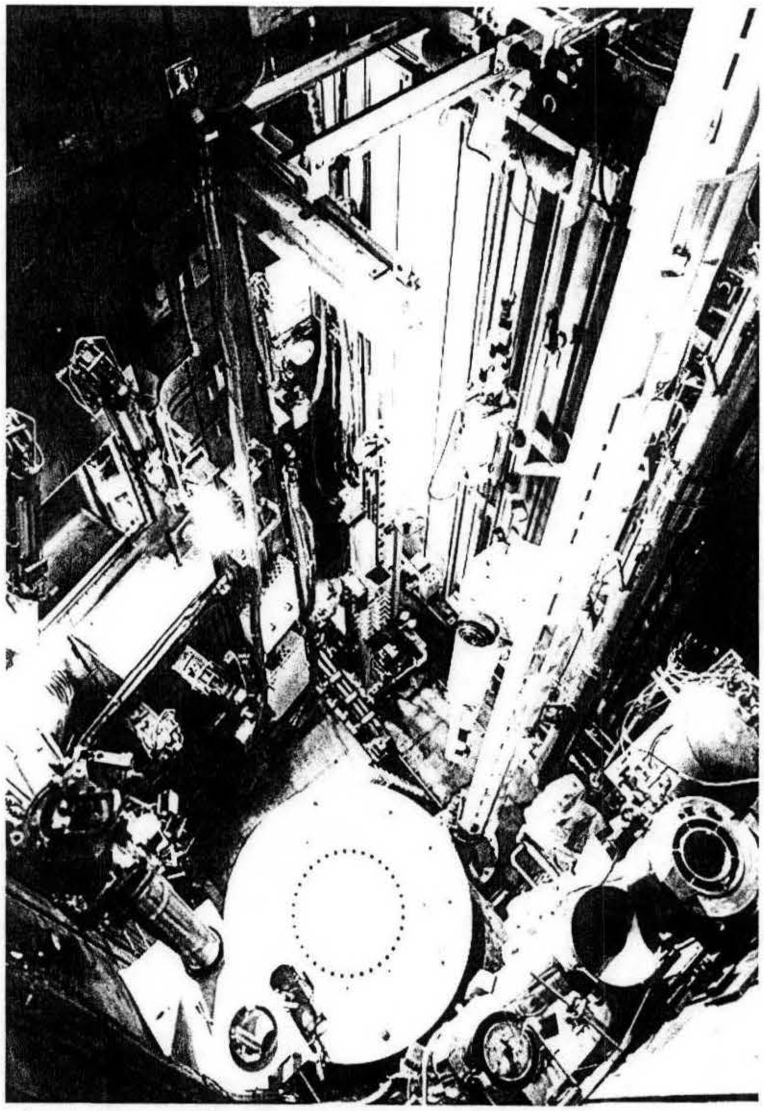


Figure 8. IEM Cell

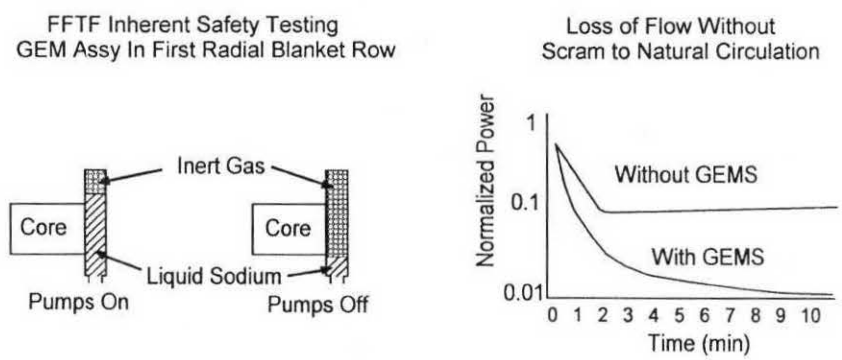
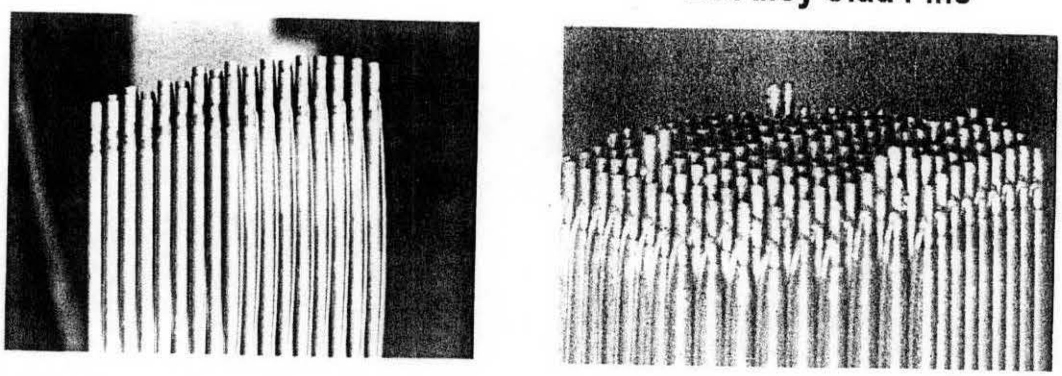


Figure 9. Gas Expansion Modules in FFTF

316 SS Clad Pins | **D9 Alloy Clad Pins**



Effects of temperature and fluence gradients | Varying lengths due to differing alloy heats

Figure 10. Irradiation Effects on Pin Performance

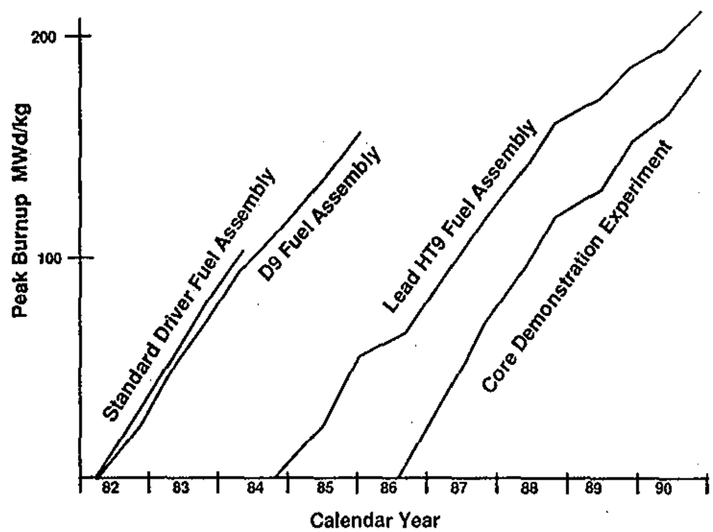


Figure 11. Fuel Burnup Accomplishments in FFTF

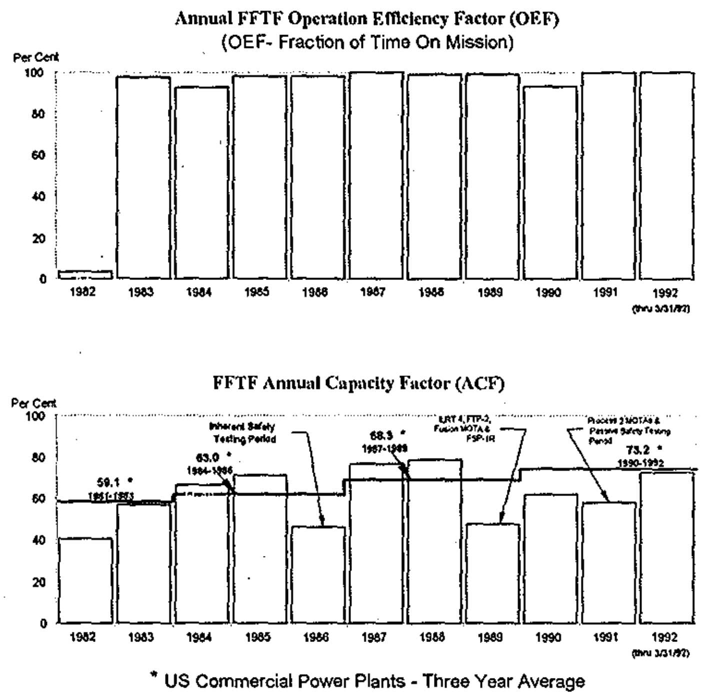


Figure 12. FFTF Operational Efficiency