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A Decade of Radiological and Shielding Experience at the Fast Flux Test Facility

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A DECADE OF RADIOLOGICAL AND SHIELDING EXPERIENCE AT THE FAST FLUX TEST FACILITY

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ABSTRACT

The Fast Flux Test Facility (FFTF) has operated for almost a decade after first going critical during February 1980. Based on about 2,000 effective full-power days of operation, it is concluded that radiological safety can be achieved in large liquid metal-cooled fast reactors. The collective dose equivalents received by operating personnel are significantly lower than those received at commercial light water reactors. No major contamination problems have been encountered in operating and maintaining the plant, and release of radioactive materials to the environment has been well below acceptable limits. All shields have performed satisfactorily and in agreement with design calculations. The experience derived from the design, construction, and operation of the FFTF should be of inestimable value in supporting future development of liquid metal reactors.

1. INTRODUCTION

The Fast Flux Test Facility (FFTF), located on the Hanford Site near Richland, Washington is owned by the U.S. Department of Energy and is operated by the Westinghouse Hanford Company. The key component of the facility is a three loop, 400-MW (thermal) sodium-cooled, mixed-oxide-fueled reactor that was designed for irradiation testing of fuels and materials in support of the commercial development of liquid metal fast reactors.[1] A secondary objective was to gain experience in the design, construction, and operation of a relatively large liquid metal reactor. The mission was subsequently expanded to include safety testing, irradiation of fusion and space reactor materials, and special isotope production.

In addition to the reactor, the containment building also houses the three primary sodium pumps and intermediate heat exchangers, an interim storage facility for both new and irradiated core components, and a multistory hot cell for maintenance and examination of radioactive components. Surrounding the containment building are sodium sampling cells, cover gas processing equipment, and a long-term irradiated fuel storage facility. This compact arrangement facilitates contamination control and radiological protection.

2. DESIGN ACTIVITIES

The FFTF has been a national effort since its inception. The Advanced Reactors Division of the Westinghouse Electric Corporation designed the reactor and reactor shields with technical support provided by both the Argonne National Laboratory (ANL) and the Oak Ridge National Laboratory (ORNL). Plant design was by the Bechtel Corporation, who also provided construction management. A nuclear mockup of the reactor in the Zero Power Plutonium Reactor Facility provided experimental data to confirm the core design and near-reactor shield characteristics. A major shield experimental program was carried out by the ORNL using the Tower Shield Facility (TSF).

The initial experiment at the TSF was to determine the neutron attenuation characteristics of sodium.[2] The measurements remain as a keystone to the design of sodium-cooled reactor shields. Another set of measurements studied is the attenuation of neutrons in steel.[3,4] A third set involved the routing of sodium piping from the reactor cell to the heat exchanger cell.[5,6]

In parallel with the experimental program, an extensive analytical effort was carried on at ORNL. By comparing experimental and analytical results, improvements were effected in both nuclear data and methods. The analytical effort was primary in the development and application of ANISN and DOT for the design of fast reactor systems.[7,8] These codes found widespread use by the shielding community through the 1970's and early 1980's. A relatively complete review of ORNL support to the FFTF can be found in Reference 9.

The design of plant shields by Bechtel personnel employed point kernel codes. The key aspect of the plant design was definition of radiation sources, particularly the primary sodium. Sodium activation measurements in an ANL mockup of the FFTF was used with two-dimensional diffusion theory calculations to predict sodium activity.[10] Conservative assumptions were made to include fission product releases.

3. SHIELD MEASUREMENTS

3.1 Plant Testing

A relatively extensive shield measurements program was completed during early power operation of the facility.[11] These measurements were made to ensure that no major defects had been introduced by construction, to establish radiation zones, to compare the results with the design calculations, and to establish the radiation environment associated with reactor structural components. Except for the hot cell walls, all of these measurements were made using the in-place sources generated by operation of the reactor. In the case of the hot cell, a 0.1 MCi cobalt source was employed to survey all surfaces of the cell before the installation of equipment. A number of interface shield problems were revealed by this survey and appropriate modifications effected in a timely manner.[12]

About 7.5 ft of high-density concrete was employed around the cells containing primary sodium to reduce the radiation level to background levels. Surveys of these cells revealed no measurable imperfections in the bulk walls. Small-size, low-intensity beams were found at some interfaces that required the placement of local shields.

3.2 Reactor Shield Measurements

Radiation levels within the reactor vessel and reactor cavity could only be made at a limited number of locations. These were made in conjunction with the reactor characterization program to accurately define the test environment to support the facility mission. Passive sensors were irradiated in special assemblies that were irradiated in the core, reflector, and in-vessel storage modules; within a dry thimble through the core; and within a thimble in the reactor cavity. Results of the measurements were in reasonably good agreement with calculations.[11] The measurements and calculations make it possible to define damage rates (displacement per atom) of structural components and thereby track lifetime and replacement requirements.

Neutron measurements were also made in the head compartment above the reactor using Bonner balls. design calculations indicated that the neutron field in the head compartment would be dependent on the number of stored fuel assemblies in the sodium pool between the reactor shield and the vessel. In fact, extensive design modifications

had been made to accommodate the presence of stored fuel. The measurements substantiated the concern, but also demonstrated that the modifications had been adequate. The major source of radiation in the head compartment is associated with depleted uranium gamma-ray shielding installed in the head compartment.

4. OPERATING EXPERIENCE

4.1 Personnel Radiation Exposure

Radiation doses to plant personnel have been very low, as shown in Table 1. These radiation doses are for about 200 radiation workers. In addition to operation and refueling of the reactor, these doses include operation of the hot cell and also a decontamination and maintenance facility located in an adjacent building. Replacement of an electromagnetic pump during the fourth quarter of 1984 caused the largest collective dose to date.[13] This work involved the cleanup of a few hundred pounds of primary sodium that leaked from the failed pump. Collective doses from this single event were about 4 person-rems 0.04 person-Sv), with the highest individual dose being 250 mrems. It should be noted that radiation workers at FFTF receive more dose from the natural background than from work. The average annual background local dose rate is about 100 mrem, including doses from radon. These low operating doses at FFTF are consistent with experience at other sodium cooled fast reactors. French experience at Phoenix was about 5 man-rems per year, with a high of 17 man-rems in the year an intermediate heat exchanger was replaced. By comparison, personnel doses at existing commercial pressurized water reactors was 390 person-rems in 1986[14] and 651 person-rems from boiling water reactors. The low personnel doses received at sodium cooled reactors is associated primarily with pressure and chemical difference between sodium and water systems that strongly influence the design. Radiation levels in areas that are normally entered to operate and maintain the plant are at background levels. Thus, almost all doses are associated with nonroutine maintenance and recovery operations. Such operations are governed by As Low As Reasonably Achievable principles with appropriate preplanning and training.

Radiation levels near piping and equipment containing the reactor cover gas increased significantly as a result of breached cladding on experimental fuel pins. Radioactive cesium resulting from the fission process is able to enter the sodium when the cladding loses its integrity. Cesium is chemically similar to sodium, but has a much lower boiling point. Thus, the cesium preferentially enters the cover gas and subsequently plates out throughout the system.

Table 1. Personnel Exposure Summary.

	Year							
	1982	1983	1984	1985	1986	1987	1988	1989
Average Dose Per Person (mrem)	36	11	37	4	10	5	7	6
Highest Individual Dose (mrem)	200	200	250	110	290	110	200	50
Collective Dose (person-rem)	10	5	13	1	2	1.1	1.5	1.2

Radiation levels at a distance of 1 ft from various pipes and components in the cover gas system range from background as much as 10 rem/h as a result of cesium plateout. By design, the reactor cover gas system is contained in shielded, controlled access cells that are only infrequently entered by operating personnel; therefore, plant doses have not increased significantly as a result of the cesium. To minimize further contamination of the cover gas system, a cesium trap was installed to remove it from the sodium before significant future releases from fuel could enter the cover gas. Operation of the cesium trap has removed essentially all of the cesium contamination from the primary sodium.

4.2 Nonroutine Radiological Events

As discussed above, replacement of an electromagnetic pump has been the major radiological event encountered in operating the plant. A second event was associated with a stainless steel structural pin from a test assembly that entered the cleaning water in the hot cell sodium cooling system. The pin subsequently lodged in a cooling tube and generated a dose rate of several rem/h at a distance of 1 ft. Preplanning and training limited the personnel dose to negligible levels in removing the pin from the system.

Another event involving radioactive material was the oxidation, swelling, and release of depleted uranium from a shield block located in the head compartment. Clad depleted uranium blocks were used in several locations in the head compartment because of space limitations. Apparently, the cladding on the particular block permitted air to interact with the uranium. Because of the low dose rates associated with depleted uranium, personnel doses were negligible in replacing the block and the greatest concern was that of contamination control.

Although other nonroutine events have occurred, careful preplanning and execution has kept personnel exposure to a minimum. These examples and the low integral personnel doses indicate the excellent performance of the facility from the standpoint of radiation protection.

4.3 Heat Transport Systems Cells

The dose rate within one of the FFTF primary heat transport system cells is being measured during extended outages to determine the buildup of radioactivity. There are three potential sources of radiation: activation of sodium and its impurities, fuel and fission products that might enter the sodium as a result of breached cladding, and the transport and deposition of radioactive corrosion products generated in reactor components.

As discussed, the predicted 11 mCi/gm concentration of ^{24}Na was generated in the sodium. The high-energy photons emitted in the decay of this isotope dictated the design of shields around the primary sodium system. Because of its 15-h half-life, the activity decays to negligible levels within a few weeks following reactor shutdown. The 2.6-yr half-life isotope ^{22}Na has reached a specific activity of about 0.8 µCi/gm of sodium and generates radiation fields of several hundred mrem/h within the heat transport system cells. This source could be removed from components by draining the sodium. The cladding breaches that have occurred to date have not released detectable amounts of fuel or fission products into the sodium other than cesium. The maximum cesium activity in the sodium to date was about 0.3 µCi/gm of sodium and created a calculated dose rate of about 100/mrem/h in the cells. As noted, the cesium trap has removed the cesium from the sodium and should eliminate any future releases from the sodium.

Plateout of corrosion products at one time produced a radiation field of about 600 mrem/h in the sodium cells from the plateout of ^{54}Mn. Predictions based on laboratory experiments indicated that ^{60}Co would plateout on hot surfaces of the sodium system and ^{54}Mn on cold surfaces. Gamma-ray spectrum measurements of the piping indicate only a very feeble presence of ^{60}Co on any of the sodium-wetted surfaces. However, as expected, the concentration of ^{54}Mn on cold surfaces is about an order of magnitude greater than on hot surfaces. Reduced fluxes and sodium temperatures associated with the current test program in FFTF have reduced the plateout of manganese so that dose rates are currently about 300 mrem/h in the heat exchanger cells.[15] It is believed that the data and analyses being obtained from the FFTF primary heat transport system cells will provide a basis for predicting the plateout of corrosion products in future designs.

4.4 Environmental Protection

The release of radioactive materials from FFTF to the environment has been extremely low. There are no radioactive liquid releases from FFTF. Those liquid radioactive wastes that exist are associated primarily with the sodium-cleaning process in the hot cell. These are collected,. transferred to a railroad tank car, transported to the Hanford Site storage facility, and placed in large double-walled tanks. Generation of solid wastes is also minimal. Here again, the waste is transported to the Hanford Site storage facility.

Total release of airborne radioactive materials through 1989 has been about 40 Ci of noble gases. These releases result in a calculated dose of less than 0.01 mrem to a maximally exposed offsite individual and are so low that they are not detectable. The first release was attributed to leaks in instrument tubing connections that were subsequently repaired. The second release was associated with a planned release of ^{41}Ar for test purposes. The later releases were associated with cladding breaches in test fuel. A comparison of releases from commercial light water plants[16] and FFTF is given in Table 2.

Releases of airborne radioactivity to the environment is minimized at FFTF by the two gas processing systems. The Radioactive Argon Processing System (RAPS) handles the reactor cover gas, whereas the Cell Atmosphere Processing System (CAPS) handles air, nitrogen, and argon from the hot cell and from inert cells that contain radioactive sodium. Both systems process the gas by holdup to permit radioactive decay. This is effective for all radioisotopes encountered except for ^{85}Kr, which has a half-life of 10.5 yr. Holdup is accomplished by a series of tanks and liquid-nitrogen-cooled charcoal beds. Although CAPS routinely handles about ten times the flow handled by RAPS, the argon cover gas contains more radioactivity. The CAPS also serves as a backup to RAPS. The successful operation of these systems is demonstrated by the tabulated results over the plant lifetime.

5. ANALYTICAL EXPERIENCE

5.1 MCNP Studies

Many of the day-to-day shielding calculations to estimate dose rates or design containers were made using point kernel codes. However, extensive use was made of the MCNP Monte Carlo code.[17] The use of Monte Carlo became more practical with time as the capability of computers grew during the decade. One MCNP study was made to compare the results with attenuation calculations made using both discrete ordinates and diffusion theory.[18,19] Using neutron flux and radiation damage rates as parameters, it was found that

Table 2. Radioactive Materials Released Per Light Water Reactor in 1987 and FFTF in 1984.

	(Activity in Curies*)			
Reactor Type	Airborne Fission & Activation Gases	Airborne Particulate	Liquid Tritium	Liquid Fission & Activation
Boiling Water Reactor (BWR)	2,500	0.2	6	1
Pressurized Water Reactor (PWR)	1,500	0.02	380	2
FFTF	20	0	0	0

*1 Ci = 3.7×10^{10} Bq. Values for BWR and PWR are averages; no power correlation has been established.

diffusion theory was reasonably accurate through the shield out to the reactor vessel wall. However, as expected for large distances from the core, the calculated flux at very high energies is low by an order of magnitude or more when diffusion theory is used. The study also concluded that for fast reactor shield applications, the precise self-shielding of the multigroup cross section is as important as the choice between using diffusion theory or transport theory.

The MCNP code was also used for a number of shielding studies involving compiled geometries and streaming paths.[20] These included streaming within the traverse tube housing the low-level flux monitor, the response of the ex-vessel flux monitors within graphite blocks located in the reactor cavity, streaming within an in-reactor assembly located near the center of the core, and streaming through ducts between plant cells. An additional series of calculations using MCNP concerned production of radioisotopes in the reflector region of the FFTF. Although these are not directly "shielding" calculations as such, they involved the attenuation and moderation of the neutron and gamma-ray spectrum as they leave the core. The first of these defined the production rate of ^{60}Co in a test assembly located just outside the core.[21] The measured ^{60}Co activity was only 4% less than the calculated value. A second study investigated methods of optimizing the production of ^{238}Pu in a moderated reflector position of the FFTF.[22] Biasing of the position and energy of the fission source neutrons with weight windows was shown to improve the efficiency of the calculations of high energy (n,2n) and (γ,n) reaction rates. This improvement was used to design a hydrogenous assembly to maximize the production of ^{238}Pu and minimize the production of ^{236}Pu via the high-energy (n,2n) and (γ,n) reactions. Subsequently, a 40-h CRAY XMP calculation supplemented by a 370-h SUN 4/260 was made to evaluate a multiple-isotope production assembly.[23]

5.2 Decay Heat Tracking

Before startup, it was recognized that a method was needed for keeping track of the decay heat and radioactive inventory associated with core components. Coefficients were generated for an exponential representation of the decay heat function[24]. Also included in that

study were coefficients for ^{239}U, ^{239}Np, and ^{242}Cm, those actinides that contribute significantly to decay heat in the time range of interest. A separate study defined the eight radioisotopes that would be generated in structural materials and contribute significantly to decay heat.[25] These parameters were included in a computer program to generate a database for each core component based on its unique operating history.[26] Output from the program is now provided to operations at the end of each operating cycle in a format for use with a desktop computer. The information is used routinely to ensure that facilities and equipment are operated within their safe heat removal limits.

6. SUMMARY

Radiological safety and satisfactory shield performance have been demonstrated at FFTF by 10 yr of experience following the load to criticality. The philosophy employed in the design of the plant layout and shields has ensured that operating personnel receive negligible doses during normal routine operation of the plant. The primary sodium system has operated efficiently and required very little maintenance to date. The electromagnetic pump failure that did occur was replaced with personnel receiving relatively small doses. Accepted practices and procedures are employed to control contamination and to ensure that doses are minimized when breakdown maintenance is required. Release of radioactive material to the environment has been minimal and below the level of detectability at the Hanford Site boundary. Although current light water reactor plants meet all established radiological safety requirements, the operating experience gained in almost 10 yr of operation of the FFTF indicates that even better radiological performance can be achieved using liquid metal reactors. The experience derived from the design, construction, and operation of FFTF should be of inestimable value in supporting future development of liquid metal reactors.

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