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SPACE POWER TESTING IN THE FAST FLUX TEST FACILITY

D.W. Wootan[1], B.J. Makenas[2]

[1]902 Battelle Boulevard/PO Box 999, Richland, WA, 99352, 509-372-6865, david.wootan@pnnl.gov
[2] Retired, Richland, WA, 509-943-0941, bmakenas@gmail.com

Westinghouse Hanford Company was deeply involved in the development of a 100-kilowatt electric reactor for space, called SP-100, funded jointly by the National Aeronautics and Space Administration, the Department of Energy, and the Department of Defense. The SP-100 program was initiated in 1983 for the development of a compact nuclear reactor capable of producing electrical power in the range of 10 to 1000 kilowatt electric. This was a national program with contributions by the Jet Propulsion Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, the General Electric Company, Westinghouse Hanford Company, and a number of industrial suppliers. The mission of the program was to develop technology to support construction of a flight prototype in the mid-1990's. The tests of SP-100 fuel in the FFTF were the FSP series of tests. Irradiation testing results from the FSP-1 and FSP-1R tests showed that the selection of a sound fuel and material system for further development for space reactors had every expectation of success.

I. SP-100 Program

Westinghouse Hanford Company (WHC) was deeply involved in the development of a 100-kilowatt electric reactor for space, called SP-100, funded jointly by the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), and the Department of Defense (DOD), specifically the Strategic Defense Initiative Office. The SP-100 program was initiated in 1983 for the development of a compact nuclear reactor capable of producing electrical power in the range of 10 to 1000 kilowatt electric. This was a national program with contributions by the Jet Propulsion Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, the General Electric Company, Westinghouse Hanford Company, and a number of industrial suppliers. The mission of the program was to develop technology to support construction of a flight prototype in the mid-1990's.

The SP-100 program used a fuel pin type design, with a lithium liquid metal coolant to remove the heat from the core and transport it to an out-of-core energy conversion system. The SP-100 requirements for a seven year lifetime and low weight meant the fuel system would have to operate at significantly higher temperatures than is common in terrestrial reactors (1100 to 1400 K vs 900 K). The SP-100 reactor core required a peak fuel burnup of up to 5 atom%, a fast neutron fluence of up to 3 x 10^{22} n/cm^2, and coolant temperatures up to 1500 K. This necessitated the use of high temperature refractory alloys and introduced a complex thermodynamic system within the fuel pin. The performance of fuel elements under these conditions had to be evaluated by irradiation tests where the neutron damage, and thermal and chemical environment were accurately simulated.

II. Early Testing

An extensive irradiation program was conducted in the 1950's and 1960's to develop fuel pins for space nuclear reactors. That program emphasized refractory metal clad uranium nitride (UN) uranium carbide (UC), uranium oxide (UO_2) and metal matrix fuels (U-C-Zr and BeO-UO_2). Weaver and Scott[1], Gluyas and Watson[2] and Mayer[3] provided summaries and experiment descriptions of the irradiation experience with UN, UC, and metal matrix fuels. The UO_2 fuel irradiation data can be found in Chubb, Storhok and Keller[4] and Kangilaski[5]. Based on this earlier work, UN and UO_2 fuels in conjunction with refractory metal cladding showed a high potential for meeting space reactor requirements[6,7,8]. These early tests suffered from the non-prototypic feature of having been irradiated in thermal rather than fast neutron reactors. Thus, the effects of fast neutrons on cladding properties were not simulated, and the fission rate distribution across the fuel diameter had a marked depression in the center of the fuel. Moreover, the length of the fuel column was quite small in many of the experiments. This resulted in highly uncertain predicted temperatures and powers due to complicated heat transfer paths and magnified the effects of power peaking at the ends of the fuel columns in thermal reactors.

These early tests indicated that, because of weight and neutronics considerations, Ta alloys were most practical with a system design using UN. Based on compatibility and strength considerations, Mo alloys were expected to meet SP-100 performance requirements with either UO_2 or UN fuel. Nb alloys have the lowest creep strength but require a W diffusion barrier if used with UN. The extensive fabrication experience with Nb alloys tended to favor them as cladding materials, particularly for first generation systems. Previous irradiation testing provided guidance for the selection of fuel and cladding candidates. However, each of the fuel/cladding combinations had one or more feasibility issues with it, such as high temperature UN swelling, fuel/cladding compatibility, and fast neutron damage to cladding materials. These three feasibility issues were addressed by tests SP-1, SP-2, SP-3, SP-3R, and SP-3RR designed and constructed by Hanford Engineering Development Laboratory (HEDL) and irradiated in EBR-II.

III. FSP Tests in FFTF

The FSP-1 and FSP-1R tests were specifically designed to provide irradiation data on UN fuel pins with refractory cladding for the SP-100 space reactor program. Figure 1 shows a cross section of a FSP fuel pin, while Figure 2 shows the entire assembly. Fuel pins with bonded rhenium liners were included in the tests. Thirty eight fuel pins were irradiated in the sodium cooled Fast Flux Test Facility (FFTF) in each of the FSP-1 and FSP-1R test assemblies. The FSP-1 and FSP-1R test hardware consisted of 19 fuel assemblies, each containing two capsules. Each capsule consisted of an outer stainless steel tube separated by a gas-filled gap from an inner capsule made of TZM (a molybdenum alloy with titanium and zirconium additions). Each TZM capsule was partially filled with lithium (enriched in ^{7}Li) to simulate the space reactor coolant environment, and contained one test fuel pin. A helium cover gas was used over the lithium. During operation, the lithium expanded to cover the top, or plenum region of each pin. The temperature of each fuel pin during irradiation was set by using a specific mixture of helium and argon in the gap between the TZM capsule and the stainless steel capsule to control the conductivity of the gap. The 19 fuel assemblies were inserted in a standard FFTF duct with a removable top handling socket.

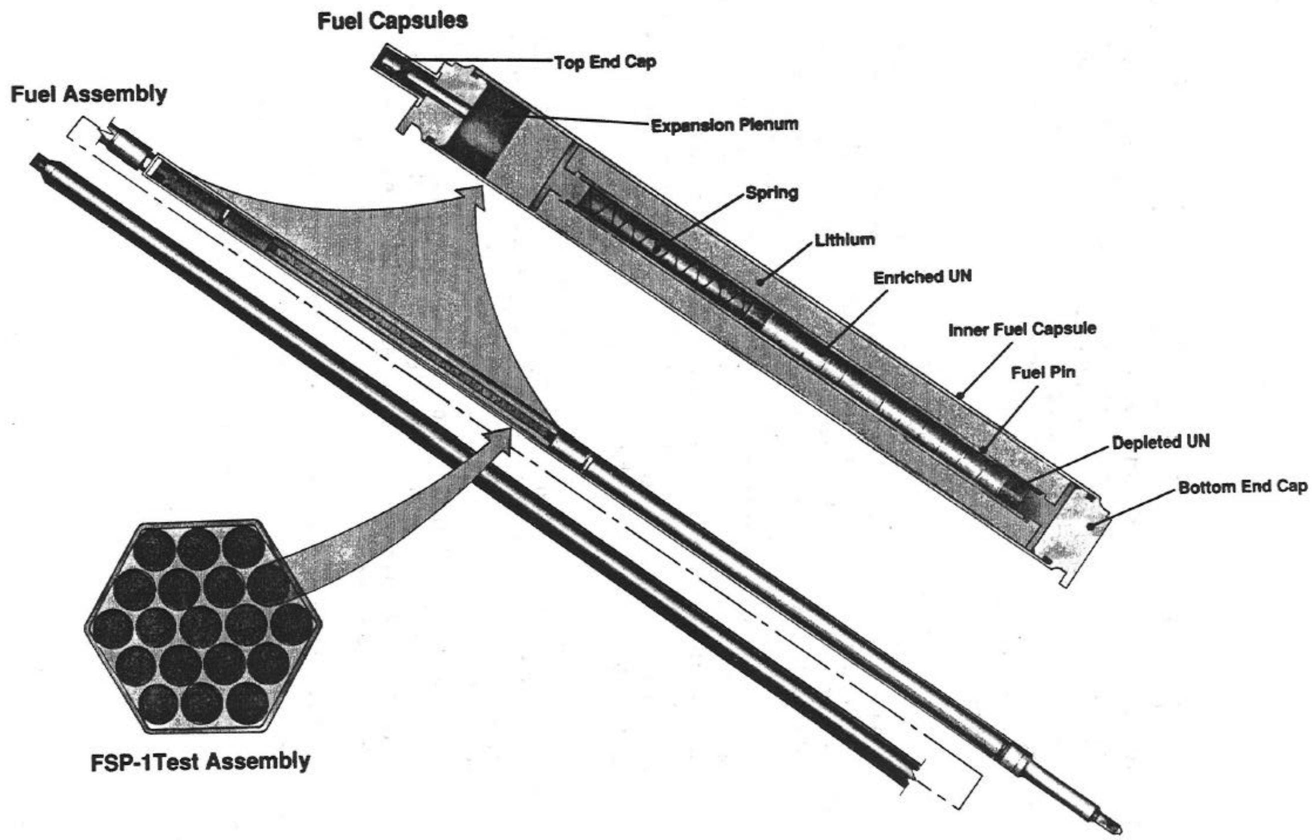

Fig. 1. FSP Fuel Pin[9]

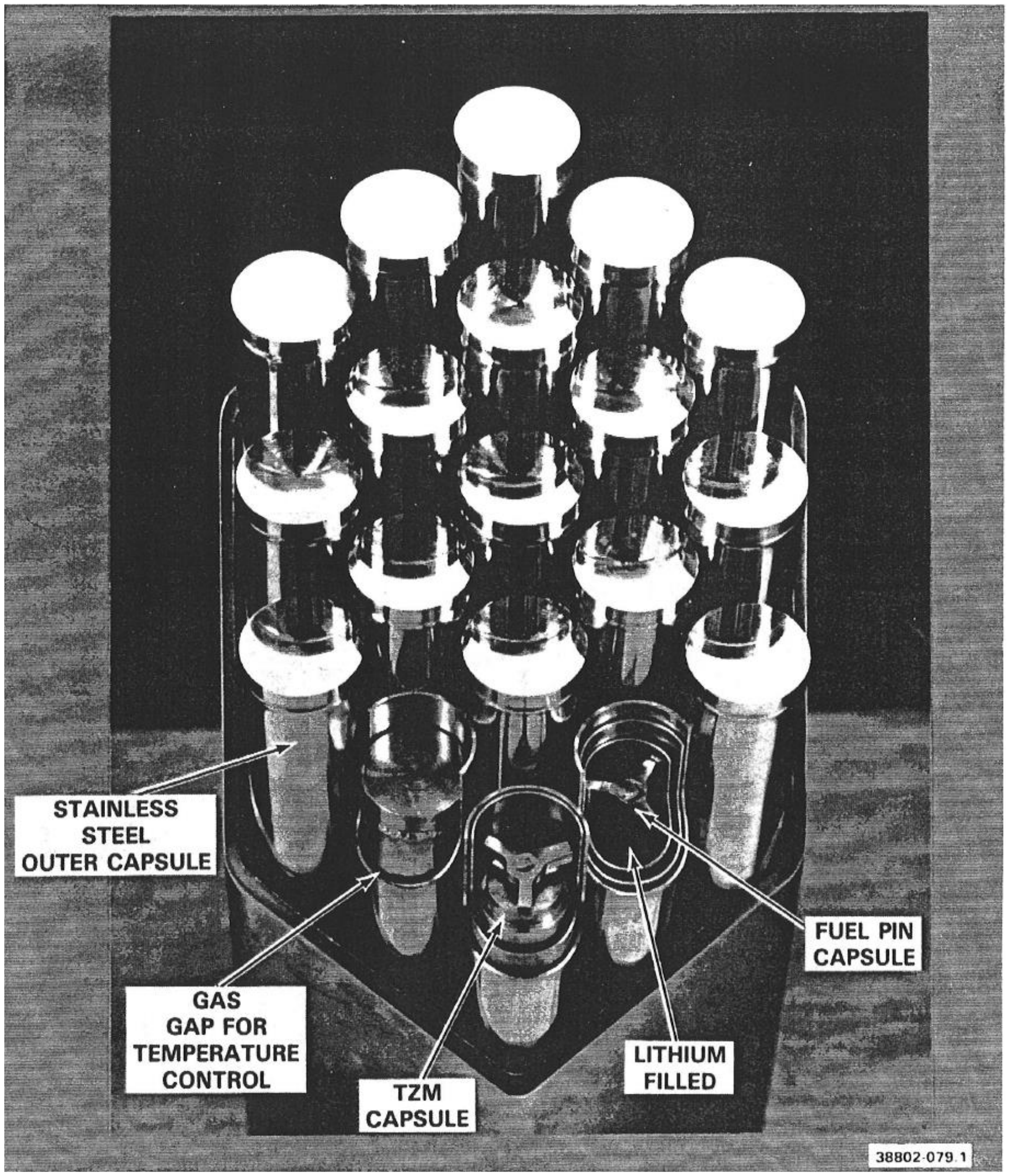

Fig. 2. FSP Test Assembly[10]

The FSP-1 test consisted of 38 fuel pins that were irradiated in FFTF for 269 full power days. All of the fuel pins contained UN fuel. Fuel pellets were included that had various densities, geometries, and enrichments. All pins had Nb-1Zr cladding with vapor deposited CVD (cold vacuum drying) tungsten or CVD rhenium liners. Two different cladding outer diameters, 5.84 mm and 7.62 mm (0.230 and 0.300 inches) were used. Pins were more than twice as long as the six inches typical of pins irradiated in EBR-II. The majority of fuel pins in this test achieved 2.3 atom% burnup, with some very low enrichment fuel pins achieving only 0.5 % burnup.

FSP-1R was a continuation of the FSP-1 test in FFTF. In FSP-1R, all but two of the 38 fuel pins utilized Nb-1Zr cladding and the fuel for all of the pins was high density (95% to 96% TD) UN fabricated at LANL. For most pins tungsten or rhenium CVD liners were used as a barrier between fuel and cladding. Two pins utilized unlined rhenium cladding. Pins were irradiated at 1300 K, 1400 K or 1500 K peak cladding design temperature. Post-irradiation examinations of FSP-1R fuel pins were conducted from mid-1992 through late-1994. Twenty two fuel pins were in both the FSP-1 and FSP-1R tests. Those 16 pins which were irradiated only in the FSP-1R test had 401 EFPD of reactor exposure. The lead fuel pin (irradiated in both FSP-1 and FSP-1R) reached 5.6 atom% burnup in 670 EFPD. Only nondestructive evaluations were performed on the pins from the FSP-1R test.

IV. Other Un-irradiated Tests

FSP-1RR was partially constructed but not irradiated. It was designed to add 4 fresh pins to a 38 pin continuation of the FFTF series. Two pins in this test contained the usual fuel columns of high density UN but also had a small stack of BeO pellets to act as an integral reflector. A third pin contained internal and external passive temperature monitoring devices. A fourth pin contained a small fuel/liner gap to study the interaction strains occurring during irradiation. Burnups of 9-10 atom% were predicted for some pins.

Other more advanced fuel tests were also proposed to more correctly simulate the SP-100 environment. Considerable design effort was devoted to a flowing lithium loop experiment intended for FFTF, but this test did not reach the fabrication stage.

V. CONCLUSIONS

Irradiation testing results from the FSP-1 and FSP-1R tests showed that the selection of a sound fuel and material system for further development for space reactors had every expectation of success. The in-reactor fuel tests yielded more than just information on one material system, such as the behavior of fuel pellets with various densities, with various geometries, and with various compositions and stoichiometries. Pins with several cladding alloys and liner configurations provided valuable insight on high temperature compatibility and stability issues. The work performed as part of this irradiation program benefits not only those projects which utilize a SP-100 style reactor, but also other design efforts which go beyond the SP-100 capabilities.

ACKNOWLEDGMENTS

SP-100 irradiation tests were fabricated and performed by Westinghouse Hanford Company under contract with the Department of Energy. Fuel pins for these tests were made at Los Alamos National Laboratory. Post-irradiation examinations were performed at Pacific Northwest Laboratory's hot cells in Richland, Washington, and at the Hot Fuels Examination Facility in Idaho Falls, Idaho. Significant contributions were made by many people including designers, fabricators, and hot cell personnel. Prominent among these were Rick Mason and Bruce Mathews at LANL and Dale Dutt, Janell Hales, and Richard Karnesky at Hanford.

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