Journal of Nuclear Materials 204 (1993) 109–118
North-Holland

journal of nuclear materials

Status of fuel, blanket, and absorber testing in the fast flux test facility

R.B. Baker, F.E. Bard, R.D. Leggett and A.L. Pitner
Westinghouse Hanford Company, P.O. Box 1970, Richland, WA 99352, USA

Over 67000 fuel, blanket and absorber pins have been irradiated in the Fast Flux Test Facility (FFTF) during its first 12 years of operation. Tests are run in highly controlled and monitored environments with core components similar in size to those in commercial liquid metal reactor (LMR) designs. While primary emphasis was placed on mixed oxide fuels, significant development programs have included metallic fuels, UO_2 blankets, B_4C absorbers, and other fuels and materials of interest. Irradiation programs for mixed oxides have included progressively lower swelling cladding and duct alloys (e.g., 316 SS, D9 SS, and the ferritic HT9), which also have application to other core components. In many instances the current exposure levels of the advanced FFTF tests are the highest attained and reported in the literature. This paper summarizes the status of irradiation experience at the facility, presents some general conclusions, and reviews the potential for obtaining additional significant data.

1. Introduction

Summarized in this paper is the status of the first 12 years of operation of the Fast Flux Test Facility (FFTF) with respect to United States (US) Department of Energy (DOE)-sponsored development of fuel, blanket, and absorber assemblies for commercialization of liquid metal reactors (LMR) (i.e., excludes international testing). On December 2, 1980, the FFTF reached its full design power of 400 MWt for the first time. The facility had two primary missions related to LMR fuels and materials: (1) provide modern irradiation testing capability to push technology beyond the current state-of-the-art, and (2) provide designers of core components a bridge for the gap between initial development (i.e., in limited small test reactors) and application in full-sized commercial plants. The latter was accomplished by demonstrating components under conditions very near those of full-sized LMRs while providing a highly monitored and characterized environment.

More than 63500 mixed oxide (UO_2–PuO_2 or MOX) driver and test fueled pins [1], 1000 metal-fueled (U–Pu–Zr and U–Zr) pins [2], and 100 carbide-fueled (UC–PuC) pins, have been irradiated in the FFTF since December 1980. In addition 35 nitride-fueled (UN) pins have been irradiated in support of the U.S. space reactor program. The U.S. LMR testing programs also included over 600 blanket pins using UO_2, and over 2370 control rod and absorber test pins using B_4C [3]. Many of these tests have been reported in the literature, but a number of endeavors are incomplete (i.e., not reported, partially examined, or only irradiated) because of changing program emphasis. Recent redirection of U.S. LMR programs resulted in the FFTF being placed in hot standby pending the U.S. DOE evaluating the plant's use for isotope production or other applications not related to commercial LMR development.

The general configurations of FFTF fuel assemblies and fuel pins are illustrated by the mixed oxide driver shown in figs. 1 and 2 [1]. Blanket assemblies are similar but typically use fewer and larger diameter pins [4]. Absorber assemblies are composed of duct and nozzle units similar to those shown in fig. 1, with movable internal pin bundles connected to the plant control rod drives [3]. All active positions in the FFTF core are monitored by proximity instrumentation for coolant outlet temperature and flow rate. In addition, there are special test assemblies to provide contact instrumentation for pin bundles. Other test rigs also are available, including one that allows rapid interim examinations [2].

The typical peak power of a FFTF driver fuel pin is about 430 W/cm with peak cladding temperatures of about 600°C. Approximately 76 fuel assemblies are

0022-3115/93/$06.00

used with peak powers up to about 7.5 MW per assembly. The peak fast neutron flux ($E > 0.1$ MeV) is about 4.5×10^{15} n/cm^2.

General design features of the various tests and irradiation exposure reached to date are summarized in table 1, and figs. 3 and 4. Table 2 provides a summary of all the pin breaches experienced in the FFTF programs and includes the apparent general breach modes. The specific test categories are discussed in the following sections.

2. Reference fuel tests

The first test program conducted included 28 assemblies to confirm designs related to the "Reference" driver fuel for the FFTF. Addressed in this program were mixed oxide for fuel and 20% cold-worked (CW) AISI 316 stainless steel (SS) for cladding, wire wrap, and ducts. The primary goal was to demonstrate satisfactory performance to design peak burnups of 80 MWd/kgM and beyond, with a corresponding fast fluence of about 12×10^{22} n/cm^2. Verified during this program was that fuel performance was predicable and robust throughout life based on examination of 11 test assemblies irradiated to incremental burnup levels; fuel bundle thermal-hydraulics were predictable through measurements from multiple thermocouples located throughout the pin bundles of two special assemblies; fuel pin limits (e.g., power-to-melt, pin endurance with initial partial fuel melting, and high cladding temperature) were conservative through results from seven specialized tests; and pin endurance calculations were valid through irradiation of five run-to-cladding-breach (RTCB) tests [1].

This program also included development supporting commercialization by testing cladding fabricated by different commercial vendors and the effects of axial blankets. One test included lead pins for a potential FFTF driver fuel design using enriched UO_2 fuel. In addition, an alternate method of fuel fabrication (i.e., using fuel microspheres pressed into pellets) was tested

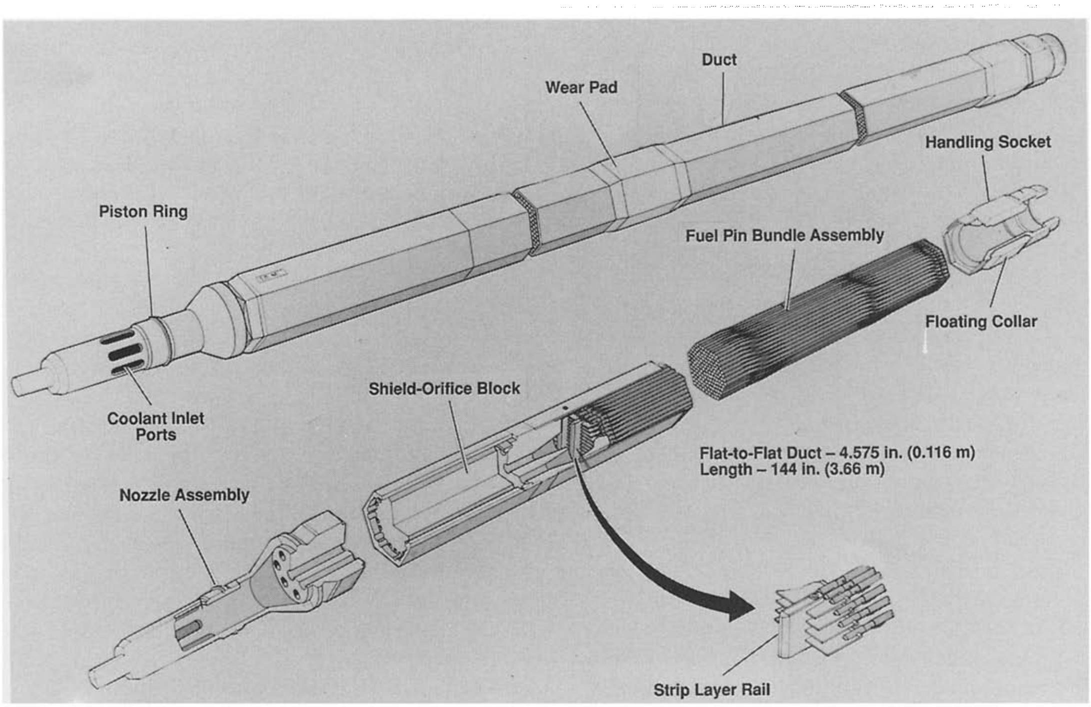

Fig. 1. Schematic of Fast Flux Test Facility series I driver fuel assembly.

in one assembly. This test closed the fuel cycle at FFTF by reprocessing and using fuel from previously completed FFTF Reference fuel test pins.

The Reference design tests were highly successful [1], meeting the desired goals. The five RTCB tests reached high burnups, over 110 MWd/kgM, without pin breach and were terminated because of duct deformation. This is often the life-limiting mechanism for this design because it ultimately results in core reload difficulties. Besides deformation due to creep strain, austenitic alloys used for the assembly hardware for the Reference fuel eventually deform due to irradiation induced swelling (dependent both on fast neutron fluence and temperature) leading to bow and dilation of the duct in the core region. In turn, this eventually leads to unacceptably high loads for pulling the component out of the core [1]. Besides the Reference test assemblies, the related commercially fabricated FFTF driver pins (over 47500) have performed exceptionally well, with only one pin breach incurred (table 2).

Postirradiation examination (PIE) of tests in this program is extensive and results are summarized in ref. [1]. This PIE further confirmed the robust performance of this design; however, a number of unique tests from this program remain undocumented. These include the following: (1) the high power (designated "DE-9") test that experienced initial partial fuel melting, then was irradiated to high burnup and finally pin breach [1] (table 2); (2) the alternate fuel fabrication test; and (3) the only driver that sustained a pin breach.

Reference fuel pins also were used in six tests at the Transient Reactor Test (TREAT) Facility [1] using sodium loops. These TREAT safety tests demonstrated the pins' ability to survive transient overpower levels significantly beyond the FFTF Plant Protection System (PPS) trip points. The primary trip point is set at a power level of 1.15 times the steady-state power level. The secondary trip point is set at 1.25. Fourteen Reference fuel pins with burnup ranging from 2 to 54 MWd/kgM were tested at overpower ramp rates of 5¢/s, 50¢/s, and 1$/s. It has been experimentally determined in past test programs that slower transients are actually the more challenging due to the mechanisms of failure [1]. At the fastest ramp rates, the FFTF pins survived power levels 7.7 times steady-state power. Two of the 5¢/s overpower ramp fuel pins breached at power levels 3.0 times the steady-state power levels they operated at in FFTF. Other pins did

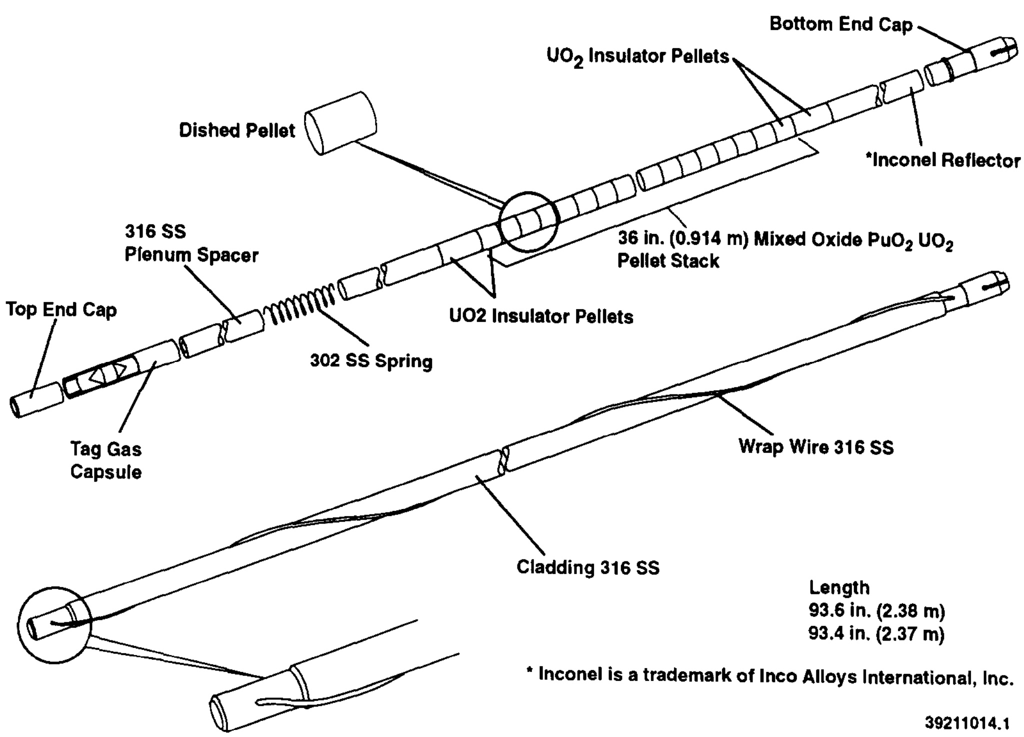

Fig. 2. Schematic of Fast Flux Test Facility series I and II driver fuel pin.

Table 1
Summary status of Fast Flux Test Facility tests since startup

Test category	Primary cladding duct materials	Fuel or absorber [a]	Pin size and wall [b] (mm)	Maximum test pin				Number of FFTF test assemblies				Pins TREAT tested
				Burnup (MWd/kgM)	Fast fluence ($\times 10^{22}$ n/cm^2)	Power (W/cm)	Cladding temp. (°C)	Irradiated (no. pins)	With pin breach	In-core	With PIE and doc [c]	
Reference fuel	316 SS [d]	UO_2–PuO_2	5.84/0.38	122	17	360 [531]	670	28 (6076)	3	0	15	14
Extended Lifetime	D9 SS [d], 316 SS [d]	UO_2–PuO_2	5.84/0.38, 6.99/0.38, 6.86/0.56	188	27	439	675	29 (D9: 2377, 316: 3413)	8	0	5	0
Long Lifetime	HT9	UO_2–PuO_2	6.86/0.56	238	39	442	661	17 (2996)	0	3	2	5
Metal fuel	D9 SS	U–Zr,	6.86/0.56									
	HT9	U–Pu–Zr		94	15	457	604	1 (169)	0	0	1	0
		U–Zr	6.86/0.56	143	20	548	643	7 (857)	0	5	0	0
Miscellaneous fuel	316 SS,	(U, Pu)O_2,	5.84/0.38									
	D9 SS	UO_2		113	15	469	615	8 (1357)	0	0	0	0
		(U, Pu)C	9.40/0.51	79	13	860	607	2 (128)	1	0	0	0
Blankets	316 SS	UO_2	12.85/0.38	14	13	220	556	2 (122)	0	0	0	0
	HT9	UO_2	9.91/0.51	42	23	390	612	6 (546)	0	0	0	0
Absorber	316 SS, D9 SS	B_4C	12.0 to 19.9	[330×10^{20} cap/cc]	20	200	440	6 (171)	0	0	2	0

[a] Fuel and absorber columns are 91.4 cm long, blankets are 124.5 cm long, pins are 244 cm long.
[b] 5.84-mm pins used in 217-pin assembly, 6.99- and 6.86-mm in 169-pin assembly, 9.9-mm in 91-pin assembly and 12.85-mm in 61-pin assembly.
[c] PIE and documentation complete.
[d] All 316 and D9 stainless steel is 20% cold worked.

Table 2
Summary of all breached pins at the Fast Flux Test Facility

Test designation	Pin			Peak exposure		Breach behavior				PIE (location) [a]
	Test category	Cladding	Fuel	Burnup (MWd/kgM)	Fast fluence ($\times 10^{22}$ n/cm^2)	Gas release		Delayed neutron signal	Days operation	
						Initial	Characteristic			
AB-1	reference fuel	316 SS	MOX	8	1	rapid (small)	bubbles	no	10	no
DFA-16392	reference fuel (driver)	316 SS	MOX	103	16	rapid	continuous	yes	2	no
DE-9 [b]	reference fuel	316 SS	MOX	101	14	rapid	bubbles	yes	2.5	yes (85.1)
MW-4	extended lifetime fuel	316 SS	MOX	102	16	rapid	continuous	no	16.5	no
RTCB-4	extended lifetime fuel	316 SS, Adv. UK SS	MOX	108	17	slow	bubbles	no	4	no
FO-1	extended lifetime fuel	D9 SS	MOX	73	11	rapid	bubbles	no	1	no
AAD-6	extended lifetime fuel	D9 SS	MOX	129	18	slow	bubbles	no	3.5	no
D9-2	extended lifetime fuel	D9 SS	MOX	155	25	slow	continuous	no	6.5	yes (50.8)
PO-2	extended lifetime fuel	D9 SS	MOX	95	16	slow	continuous	no	11	no
PO-4	extended lifetime fuel	D9 SS	MOX	108	17	slow	continuous	yes	1	no
PO-1	extended lifetime fuel	D9 SS	MOX	122	21	slow	continuous	no	12	yes (81.0)
ACN-1	miscellaneous fuel	316 SS, D9 SS	(U, Pu)C	75	13	rapid	bubbles	yes	7.5	no

[a] Location distance from bottom of 91.4-cm-long fuel column.
[b] Partial fuel melting at startup.

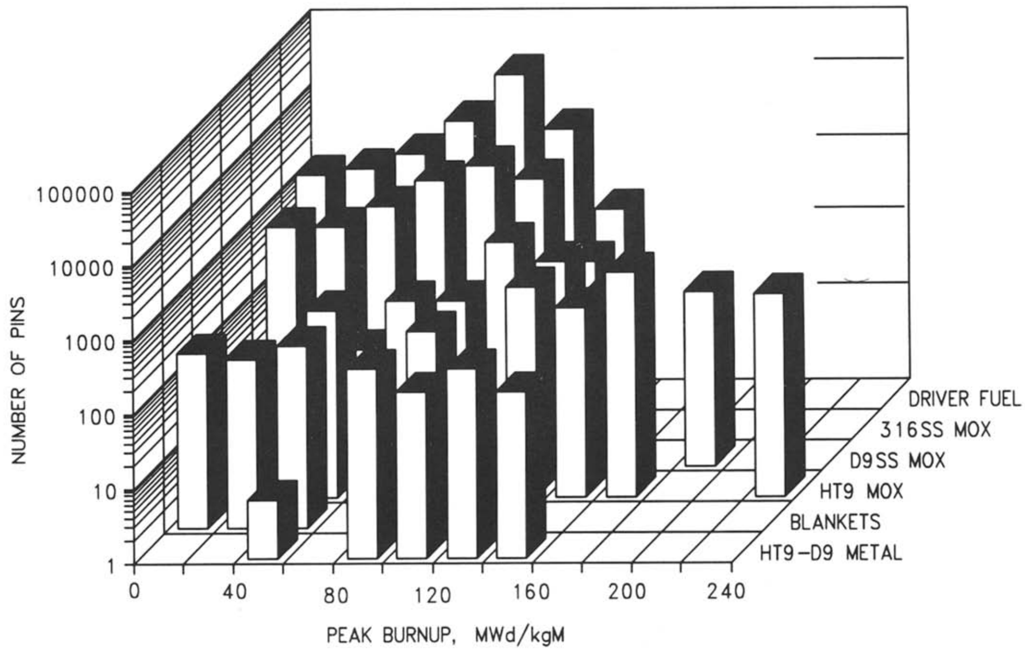

Fig. 3. Status of burnup in driver and test pins in Fast Flux Test Facility (original design goal for drivers was 80 MWd/kgM).

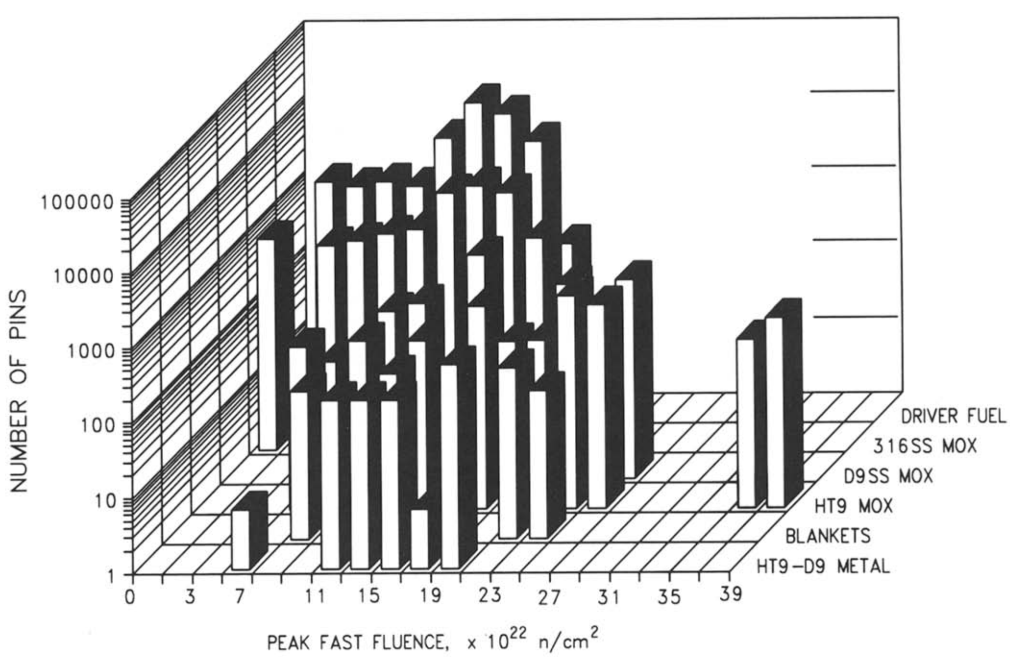

Fig. 4. Status of accumulated fast fluence on driver and test pins in Fast Flux Test Facility.

not fail at 1.8 times the steady-state power level. This confirmed a substantial margin to failure beyond the FFTF secondary PPS action.

3. Extended Lifetime fuel tests

The Extended Lifetime program goal addressed mixed oxide fuel systems capable of achieving higher peak burnups than the Reference fuel system (e.g., over 120 MWd/kgM) and greater exposure capability (peak fast fluences of over 16×10^{22} n/cm^2). The primary structural material used was the 20% CW titanium stabilized stainless steel designated "D9." This program also had tests of a high breeding ratio fuel pin design and several potential improvements to the pin spacing system of the Reference fuel.

The program included 29 assemblies: 4 assemblies with the FFTF Reference diameter pins (5.84 mm) and D9, 2 assemblies with relaxed fuel pin specifications using D9, 4 tests for the high breeding ratio fuel system using large-diameter (6.99 mm) thin-walled (0.37 mm) D9 cladding and high smeared density (86%) fuel (PO test series [1]), 5 assemblies using grid spaced pins, and 14 assemblies with candidate modifications to the Reference wire wrap pin spacer design (e.g., rather than uniform wire wrap, they employed distributed wireless pins, tight pin bundles, staggered start wire wrap, etc.). For these latter assemblies, two employed ducts made of a ferritic-martensitic material, designated "HT9," while the balance used either 316 or D9 SS for cladding and ducts.

Results have shown that use of D9 with mixed oxide fuel can meet or exceed the desired goal (i.e., 120 MWd/kgM). Duct and cladding swelling is delayed to higher fluence levels [5,7] with D9, resulting in much higher exposure capability. However, the functional limit of D9 is lower than extreme test conditions shown in table 1. It has been observed [6] that when swelling is large (e.g., greater than 10% diametral) in stainless steels like D9, they are prone to brittle failure at handling temperatures, apparently due to localized channel fracture at temperatures of less than 230°C. Indeed, this behavior was observed during PIE of the breached pin and a sibling from the D9–2 test (table 2) which had peak exposures of 25.2×10^{22} n/cm^2. These pins had experienced over 11% diametral swelling and suffered brittle fracture while being routinely handled in the hot cell. Examinations confirmed evidence of channel fracture. On this basis, application of D9 to production core components should impose exposure limits that result in less than 10% diametral swelling. A limit of 21×10^{22} n/cm^2 is used for designs with 5.84-mm-diameter cladding for the FFTF.

Pin breaches have occurred in a number of tests in this program (table 2) owing to the aggressive designs (e.g., thin cladding wall versus cladding diameter, high cladding temperatures, etc.) and the ability to obtain high exposures without being as limited by deformation of the assembly hardware due to irradiation swelling. In all cases, in-reactor behavior showed the pin breaches were nonpropagating, benign, and slow evolving. This is evidenced in part by the information in table 2 where there was only one case of measured delayed neutron signals related to the breaches and the long time periods (i.e., days) involved. Metallographic characterization of pin breaches has not been pursued, primarily because of this favorable in-reactor behavior and because either the cladding breaches were so small they could not be located without first washing the breached pin (causing the breach site to be significantly altered physically) or resources were limited.

Five of the Extended Lifetime tests have been examined and documented [7]. A number of tests remain unexamined at this time, including the highest exposure test using D9, all the alternate pin spacer tests, and all the modified wire wrap tests.

4. Long Lifetime fuel tests

The objective of this program was to develop mixed oxide fuel systems to reliably operate in LMRs for periods of 3 years or more. The primary objective was to qualify driver assemblies with large-diameter pins (e.g., 6.86 mm) to peak burnups greater than 150 MWd/kgM with fast fluences of over 22×10^{22} n/cm^2 and then proceed to a system with the capability of 200 MWd/kgM and fast fluences of over 30×10^{22} n/cm^2. The ferritic HT9 was used as the cladding, wire, and duct material. The test program includes four exploratory lead tests, a fuel pin variables test, and finally a qualification demonstration – the Core Demonstration Experiment (CDE) – using a partial core load of 10 fuel tests [4]. In addition, an ultra-long life core concept [1], which operates at low pin powers (e.g., 270 W/cm peak) for 5 to 10 years, has also been addressed with two tests [4].

This category of tests has shown excellent performance, reaching world record levels of burnup with mixed oxide fuel (table 1). The CDE was successfully completed, and a lead exposure test remains in-core for potential further irradiation. Because of material strength, the bulk of the tests have been run at cladding temperatures somewhat lower than the tests using austenitic steels [5]. The only dubious observation from pins examined was some HT9 cladding deformation (e.g., creep strain dilation) toward the top of the fuel column in the highest temperature, highest smeared density pins. This behavior, however, also has been observed in austenitic clad pins which operated at high temperatures to high burnups. In both cases, the deformation appears to be associated with (1) the migration and buildup of fission products (e.g., cesium compounds) in the upper fuel column resulting in significant stress between the fuel and cladding, combined with (2) the reduced creep strength of the cladding materials due to high temperatures. Peak cladding temperatures in these pins occurs at the top of the fuel column [1] as a consequence of the upward flow of the sodium coolant and the shape of the axial power profile in the fuel.

Three transient tests were run in TREAT on five pins from this test program. The pins had peak burnups of either about 65 or 120 MWd/kgM. They were subjected to 5¢/s transient powers of 4.5 times steady-state power or 100¢/s to 16.5 times steady-state power, establishing failure thresholds and performance data. The HT9 pins exhibited superior transient overpower capabilities with large margins to failure, typically greater than the pins built to the Reference FFTF driver design. These fuel pins also demonstrated a propensity for pre-failure axial fuel relocation (e.g., movement of molten fuel up into the pin gas plenum and out of the active core region), a highly desirable inherent safety characteristic that can serve to mitigate or even terminate transient overpower accident events [4].

5. Metal fuel tests

This set of tests addressed three objectives: (1) verifying performance of "long" fuel pins using the Integral Fast Reactor (IFR) design, (2) qualifying a proposed FFTF metal-fueled driver capable of burnups to 150 MWd/kgM, and (3) providing data for the U.S. DOE Advanced Liquid Metal Reactor (ALMR) [5], which uses U–Pu–Zr fuel and HT9. These tests are discussed in detail in ref. [2].

The first objective was addressed with the IFR-1 test irradiated for Argonne National Laboratory (ANL) using U–Zr or U–Pu–Zr metal fuel sodium bonded to D9 cladding. The second objective was addressed in a series of seven tests using U–Zr fuel sodium bonded to HT9 cladding, run by Westinghouse Hanford Company (WHC) in collaboration with ANL. Support for the ALMR was provided from all the tests. One FFTF test also provided a unique comparison of three fuel types (UO_2–PuO_2, UO_2, and U–Zr) under similar conditions, each using HT9 cladding. This test obtained burnups of up to 100 MWd/kgM and was specifically designed for comparing the fuels and validating performance code.

All the metal fuel tests have performed very well. Four assemblies remain in-core, with the peak burnup reached at 143 MWd/kgM. There have been no pin breaches even with highly aggressive test conditions. Only the IFR-1 test and six low burnup HT9 clad pins containing U–Zr are receiving PIE. The remaining tests (including the test for multiple fuel comparison), and those in the core, currently are not planned to have any PIE.

6. Miscellaneous fuel tests

Fuel tests for various other U.S. LMR objectives also have been irradiated in the FFTF. These include five tests supporting the Clinch River Breeder Reactor (CRBR), two assemblies to provide pins for subsequent safety testing (e.g., high enrichment fuel), a sodium chemistry test (i.e., modified Reference driver including a radionuclides trap), and two advanced carbide fuel tests. All 10 tests reached their goals except one of the carbide fuel tests. No tests in this category are scheduled for PIE. A related FFTF test not included in table 1 is the cooperative U.S. DOE/Swiss test containing carbide fueled pins that has recently received PIE [5].

7. Blanket assembly tests

This program included UO_2 blanket assemblies capable of reliable operation in (1) a "Reference" blanket system using 316 SS, and (2) a Long Lifetime (e.g., over 3 years) design using HT9. The Reference system tested both a radial and an inner blanket. The Long Lifetime concept tested six inner blankets as part of a heterogenous fuel/blanket system in the CDE [4]. Neutron flux levels in the FFTF are comparable to many commercial LMR designs, thereby permitting prototypic blanket tests to be run using depleted uranium dioxide. This is not possible in many smaller test reactors.

All blanket irradiations are complete. Performance was very good for the Reference design and excellent for the HT9 design. There were no breached pins in any of the tests and high exposures were reached (table 1). The Reference radial blanket test was terminated early because of problems with duct bowing caused by the steep flux gradients near the core periphery. All the other blanket tests went full term and were ultimately limited by the increasing assembly temperatures (a result of breeding) reaching maximum levels allowed by safety analyses (e.g., margin to boiling sodium in postulated accident events). As with blankets in commercial LMRs, FFTF blankets had to strike a design balance between having enough coolant flow for end of life safety and limiting the maximum coolant flow rates to avoid thermal striping considerations at beginning of life. None of these blanket assemblies are scheduled for PIE.

8. Absorber tests

This program addressed B_4C absorber development for the Reference FFTF, CRBR, and advanced LMR control rods. Reference absorbers are based on an operating duration of up to 300 equivalent full power days (EFPD) and were characterized using a 61-pin, contact-instrumented (pin temperature and internal gas pressure) verification test. An Extended Lifetime test using enriched boron-carbide and 316 SS to achieve 600 EFPD duration was run in support of the CRBR. Four other tests were conducted for designs that exceeded a 900 EFPD in support of advanced LMRs. These later tests used both sealed and vented pins, D9 SS, and large-diameter (19.9 mm) cladding.

All the tests and the normal FFTF control rods have performed extremely well, some reaching world record exposures (table 1). Only one notable problem occurred. An advanced control rod design using a circular duct, rather than a hexagonal duct as employed by other tests, experienced a slight periodic precession of the pin bundle within the duct during operation, resulting in minor reactor power oscillations. This presented no reactor plant problems but would be considered undesirable for a commercial reactor. A previous paper [3] discussed FFTF control rod and absorber test performance, including PIE results on two of the earlier tests. The advanced absorber tests with record exposures (e.g., 330×10^{20} captures /cc) currently have no firm plans for PIE.

9. Discussion

Major progress and significant advancements in technology for LMRs has resulted from the activities of the FFTF testing programs. Record exposures have been achieved in many categories. The following are some selected general conclusions from these programs.

- The wire wrap pin spacer concept worked extremely well, showing minimal pin wear and providing predictable coolant distributions throughout life.
- The core reload forces for assemblies were predictable even with the diverse mix of duct materials being used.
- The allowable pin power to avoid melting of mixed oxide fuel was found to be significantly less (e.g., about 12%), although still adequate for LMRs, than previously inferred from similar tests in a less sophisticated test reactor [1].
- Pin tag gas compositions for each assembly provided a highly efficient method of locating breached pins.
- Pin breaches were benign, nonpropagating, and caused no problems in routine plant operation.
- HT9 was shown to be a solution to duct deformation and potential core management problems at high exposure. Use of HT9 for pin cladding also is highly promising, though higher exposure tests have not been examined.
- Partial fuel melting in mixed oxide pins near the beginning-of-life does not appear to significantly affect fuel pin lifetime [1].
- Sealed absorber pins can be designed to attain long lifetimes (e.g. 900 EFPD), while vented pins may provide even more lifetime capabilities.

Details of these conclusions can be found in papers noted in the references.

The PIE results from the WHC FFTF test programs are maintained in comprehensive computer data bases. This includes information from pin nondestructive examinations – pin profilometry and gamma scan data – and destructive examinations – plenum gas analyses, fuel burnup, cladding attack, and fuel microscopy measurements. For example, pin profilometry is available from over 450 pins irradiated in the FFTF, and fuel microstructural measurements are available from over 200 transverse pin samples.

PIE and documentation is complete on many Reference and Extended Lifetime tests (see table 1). However, as noted, a significant quantity of other data remains latent. Perhaps the most interesting are the data from the near-zero swelling HT9 experience; only one of the HT9 tests at maximum exposures is scheduled for PIE (i.e., none of the metal or blanket tests). Thus, a potential opportunity remains at this time for others to obtain these data, assuming agreements can be made with the US DOE. Whether or not the unexamined tests are tapped, the currently published results establish the success of the first 12 years of operation for the FFTF in providing a tremendous technology base for LMRs that in many areas is unmatched in relevance and scope.

Acknowledgements

These programs involved the technical staff and facilities from ANL, Los Alamos National Laboratory, Pacific Northwest Laboratory, Westinghouse Electric Corporation, General Electric Company, and others. The authors wish to acknowledge the excellent sustained support of the FFTF plant and fuel fabrication staff. Finally, the authors would like to acknowledge the engineers, technicians, secretaries, and managers of the WHC Applied Technology Group that have worked in many cases for more than a decade to make the bulk of these test programs the ultimate success reflected here. This work was funded under contract from the U.S. DOE.

References

[1] R.B. Baker, F.E. Bard and J.L. Ethridge, Proc. LMR: A Decade of LMR Progress and Promise (American Nuclear Society, Washington, D.C., 1990) p. 184.

[2] A.L. Pitner and R.B. Baker, Westinghouse Hanford Company Report, Richland, Washington, WHC-SA-1579-FP (1992); and in these Proceedings (Int. Symp. on Fuels for Liquid Metal Reactors, Chicago, IL, 1992), J. Nucl. Mater. 204 (1993) 124.

[3] A.L. Pitner, Proceedings LMR: A Decade of LMR Progress and Promise (American Nuclear Society, Washington, D.C., 1990) p. 230.

[4] A.E. Bridges, A.E. Waltar, R.D. Leggett, R.B. Baker and B.C. Gneiting, Proc. Int. Conf. on Fast Reactor and Related Fuel Cycle (Atomic Energy Society of Japan, Kyoto, 1991) p. 184.

[5] R.D. Leggett and L.C. Walters, Westinghouse Hanford Company Report, Richland, Washington, WHC-SA-1740-FP (1992); and in these Proceedings (Int. Symp. on Fuels for Liquid Metal Reactors, Chicago, IL, 1992), J. Nucl. Mater. 23.

[6] D.L. Porter and F.A. Garner, J. Nucl. Mater. 159 (1988) 114.

[7] B.J. Makenas, S.A. Chastain and B.C. Gneiting, Proc. LMR: A Decade of LMR Progress and Promise (American Nuclear Society, Washington, D.C., 1990) p. 170.