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BEHAVIOR OF LOW-BURNUP METALLIC FUELS FOR THE INTEGRAL FAST REACTOR AT ELEVATED TEMPERATURES IN EX-REACTOR TESTS*

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ABSTRACT

A series of ex-reactor heating tests on low burnup U-26wt.%Pu-10wt.%Zr metallic fuel for the PRISM reactor was conducted to evaluate fuel/cladding metallurgical interaction and its effect on cladding integrity at elevated temperatures. The reaction between the fuel and cladding caused liquid-phase formation and dissolution of the inner surface of the cladding. The rate of cladding penetration was below the existing design correlation, which provides a conservative margin to cladding failure. In a test which enveloped a wide range of postulated reactor transient events, a substantial temporal cladding integrity margin was demonstrated for an intact, whole fuel pin. The cause of the eventual pin breach was reaction-induced cladding thinning combined with fission-gas pressure loading. The behavior of the breached pin was benign.

I. Introduction

The Integral Fast Reactor (IFR) is an advanced liquid-metal reactor (ALMR) concept that features enhanced reactor safety, fuel cycle economy, and environmental protection. These advantages are, to a large extent, the direct result of using a metallic U-Pu-Zr alloy as the fuel material.[1,2] The U and Pu constituents in the fuel, however, tend to interact metallurgically with iron-based claddings at elevated temperatures during off-normal reactor events. Such interaction, in conjunction with fission-gas pressure loading, can potentially shorten fuel-pin lifetime and eventually cause cladding breach. To assess the independent and synergistic effects of fuel/cladding interaction on pin reliability, ex-reactor behavioral tests with irradiated test pins from the Experimental Breeder Reactor (EBR)-II are being conducted.

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In this paper, the recent results of ex-reactor behavior testing on low-burnup pins with U-26wt.%Pu-10wt.%Zr fuel and HT9 cladding are reported. This fuel type has been selected as the driver fuel for the General Electric PRISM (Power Reactor - Innovative Small Module),[1] the current reference USDOE ALMR design.

II. Experimental Procedure

Two furnace facilities, the Fuel Behavior Test Apparatus (FBTA)[3] and the Whole-Pin Furnace (WPF) System,[4] were used. The FBTA is a radiant furnace that provides isothermal heating of test specimens; the WPF is a similar, but taller radiant furnace with a prototypical axial temperature gradient that allows thermal testing of an entire fuel pin. Both facilities are located in the Alpha-Gamma Hot Cell Facility (AGHCF) at Argonne National Laboratory.

In the FBTA, short segments (≈10 mm long) of a test pin were individually heated to determine the mechanism and kinetics of fuel/cladding metallurgical interaction. The ends of the specimen were open and the cladding section was stress-free during the test. Following each test, the specimen was metallographically examined to evaluate fuel/cladding interaction. From high-magnification photomicrographs, the maximum depth of cladding penetration was established by comparing the thickness of the as-built cladding with that of the thinnest remaining cladding in the circumference.

In the WPF system, an intact fuel pin was heated to cladding breach. The pin was placed inside a stainless-steel test section that was evacuated before the test. Instrumentation in the test section consisted of multiple thermocouples for temperature control and cladding temperature measurements, together with pressure transducers for pin breach detection. Posttest examination of the fuel pin consisted of gamma scanning and neutron radiography to determine axial fuel redistribution, and metallography to establish the mode and mechanism of the pin breach.

III. Test Fuel Pins

Two fuel pins, T678 and T680, with identical design and irradiation history were used in the FBTA and WPF tests. Each pin consisted of a cast U-26wt.%Pu-10wt.%Zr slug (5.67-mm diam, 343-mm long) and HT9 cladding (7.37-mm OD, 0.42-mm wall). The gap between the fuel slug and cladding was filled with sodium to facilitate heat transfer early in life, i.e., before gap closure from fuel swelling. A plenum of 12.3 ml above the bond sodium accommodated the released fission gas. Irradiation of the two pins took place in EBR-II subassembly X430A to a peak burnup of 2.3 at.%. The peak pin power and peak cladding temperature during the irradiation were ≈49 kW/m and 560°C, respectively.

Pin T678 was sectioned to provide specimens for the FBTA tests and pin T680 was used in the WPF test. Sections of pin T678 were examined to determine the as-irradiated (i.e., pretest) condition of both pins.

IV. Test Descriptions

The test series consisted of six FBTA tests and one WPF test. The FBTA tests were conducted first to provide scoping information to aid the design of the WPF test. Two of the FBTA tests (90-22 and 90-24) simulated specific PRISM events: a 0.40$ unprotected transient overpower (UTOP) and a UTOP coupled with a loss-of-heat-sink (LOHS), respectively. The latter is an extremely severe occurrence and was chosen by NRC as a bounding event (1B) to challenge the PRISM safety capabilities. The other FBTA tests were constant-temperature, fixed-duration tests specifically designed to compare the compatibility performance of the U-26Pu-10Zr/HT9 PRISM-type fuel with the broader IFR data base.[5] The WPF test, designated FM-3, was a constant-temperature endurance test terminated at cladding breach. The test temperature of 820°C was selected to envelop a wide range of postulated reactor transients, e.g., plant-protection-system (PPS)-terminated events and anticipated-transient-without-scram (ATWS) events. The temporal relationship between the breach time of the FM-3 test pin and the durations of the reactor events defines the cladding integrity margin. The matrix for the FBTA and WPF tests is shown in Table 1.

Table 1. Test Matrix

Test No.	Test Temp. (°C)	Test Duration
	FBTA Tests	
90-17	800	1.0 h
90-18	750	1.0 h
90-19	800	5.0 min
90-21	800	2.0 h
90-22 (1)	815	2.0 min
90-24 (2)	815, 700	2.0 min, 36 h
	WPF Test	
FM-3	820	147 min (3)

(1) Simulating a 40$ UTOP event in PRISM.
(2) Simulating a UTOP (815°C for 2 min) plus LOHS (700°C for 36 h) event in PRISM.
(3) Time of cladding breaching.

V. Results and Discussion

A. Fuel/Cladding Reaction Mechanism

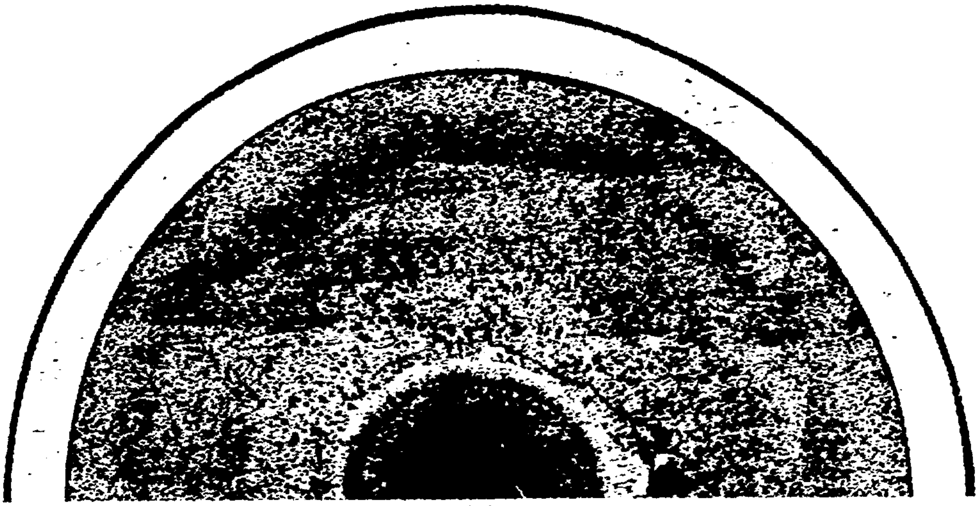
At elevated temperature, the HT9 cladding constituents, chiefly Fe, that diffuse into the U-26Pu-10Zr fuel cause the fuel to liquefy, forming a solid/liquid two-phase mixture. At the same time, cladding dissolution by the molten fuel/cladding alloy occurs.[4] Fig. 1 compares the partially liquefied fuel structure in the 800°C, 1.0-h test specimen (FBTA 90-17) with that of the as-irradiated sibling. The reacted cladding in the 90-17 specimen is shown in Fig. 2. At lower temperatures, such as in the 750°C, 1.0-h (90-18) test, there was no fuel liquefaction and therefore no liquid-phase interaction between the fuel and cladding.

B. Cladding Penetration Rates

The deepest cladding penetration in the 800°C, 1.0-h (90-17) test specimen was 55 μm, corresponding to an "effective" cladding penetration rate of 1.5 x 10-2 μm/s. This penetration and the "null" rate for the 750°C, 1.0-h (90-18) test are substantially below the existing correlation

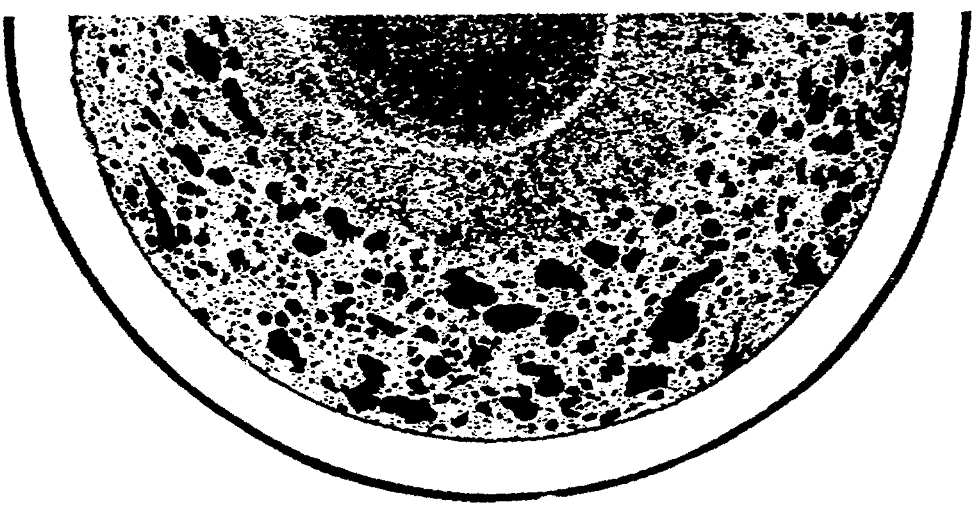
$$\text{Rate } (\mu m/s) = \exp\,[11.646-15665/T(K)],$$

currently being used for design and modeling purposes.[5]



(a)

MCT 277592



(b)

MCT 277871

Fig. 1. Transverse sections of fuel (a) after irradiation and (b) after the 800°C, LOH 90-17 FBTA test. Liquefaction of the fuel in the 90-17 specimen extended to approximately mid-radius.

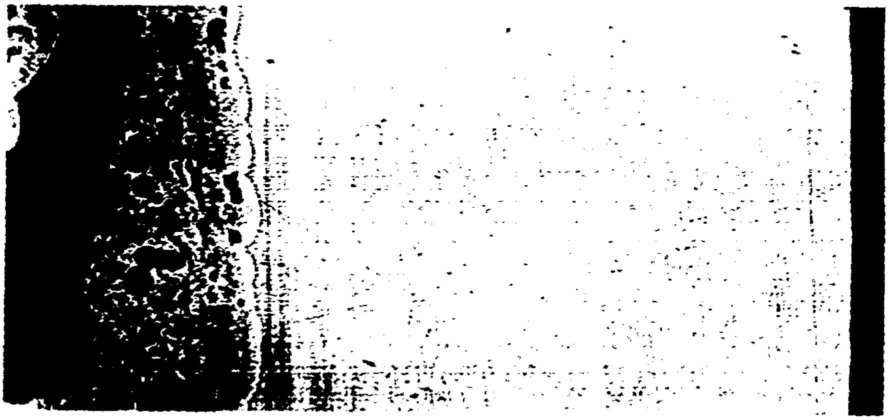


Fig. 2. Liquid-phase-fuel/cladding interaction in 90-17 specimen. Unreacted cladding is at right.

Tests 90-19 and 90-21 were conducted at 800°C with 5.0-min and 2.0-h durations, respectively. In conjunction with the 1.0-h 90-17 test, these three provided information on cladding penetration as a function of time at 800°C. The results are shown in Fig. 3. The "instantaneous" penetration of ≈20 μm at the onset of the heating cycle is likely related to the rapid melting of an interdiffusional layer formed during the steady-state irradiation. After this initial rapid interaction, the rate of cladding penetration leveled off with time. This decrease in penetration rate is indicative that the reaction kinetics were probably controlled by diffusion processes across the thickening reaction layer. Also shown in Fig. 3 are the results of other metallic fuel systems tested in the FBTA. In terms of cladding penetration, the behavior of the low-burnup U-26Pu-10Zr/HT9 specimens is comparable to that of U-26Pu-10Zr/316SS and superior to that of U-10Zr with 316SS, D9, or HT9 cladding.

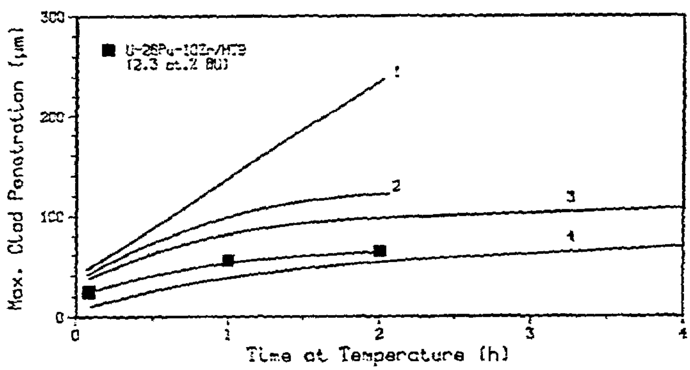
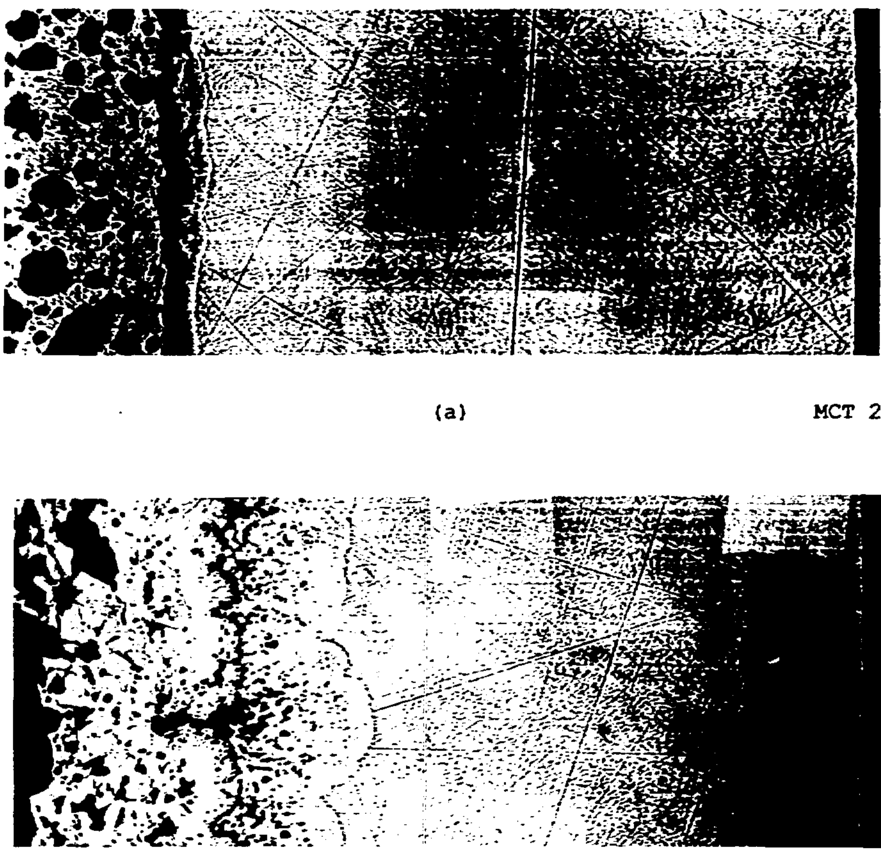


Fig. 3. Time dependence of cladding penetration at 800°C. Results from tests of other fuel systems are also shown: (1) U-10Zr/HT9 at 8 at.% BU, (2) U-10Zr/316 SS at 5 at.% BU, (3) U-26Pu-10Zr/316 SS at 5 at.% BU, and (4) U-10Zr/D9 at 17 at.% BU

C. Fuel Behavior during PRISM UTOP and Bounding Events

The PRISM UTOP event was simulated by a 2-min flattop at 815°C in FBTA test 90-22. Fuel surface liquefaction and cladding interaction was minimal. The condition of the fuel/cladding interface is shown in Fig. 4a. The depth of maximum cladding penetration was ≈19 µm, comparable to the "instantaneous" penetration shown in Fig. 3.

The NRC bounding event 1B was simulated in FBTA test 90-24 by a 2-min flattop at 815°C (UTOP) followed by a 36-h hold at 700°C (LOHS). The condition of the fuel/cladding interface after the test is shown in Fig. 4b. Apparently due to the sluggishness of Fe diffusion into the fuel at the modest LOHS temperature, there was no substantial additional fuel surface liquefaction. There was, however, noticeable further cladding penetration during the 36-h, 700°C hold. The maximum cladding penetration in the specimen was 121 µm, ≈28% of the original cladding thickness. Considering the extreme severity of this event, however, this amount of cladding wastage is regarded as only moderate.



(a) MCT 277844

(b) MCT 278023

Fig. 4. Fuel/cladding interface in FBTA specimens after (a) UTOP and (b) bounding event 1B.

D. Pin Cladding Integrity Margin

In the WPF FM-3 test, pin T680 was held at a peak cladding temperature of 820°C until cladding breach. Based on the pressure transducer data, shown in Fig. 5, breaching occurred at ≈147 min into the test. As the durations of the various PPS-terminated and ATWS events are typically less than two minutes, a large cladding integrity margin was demonstrated.

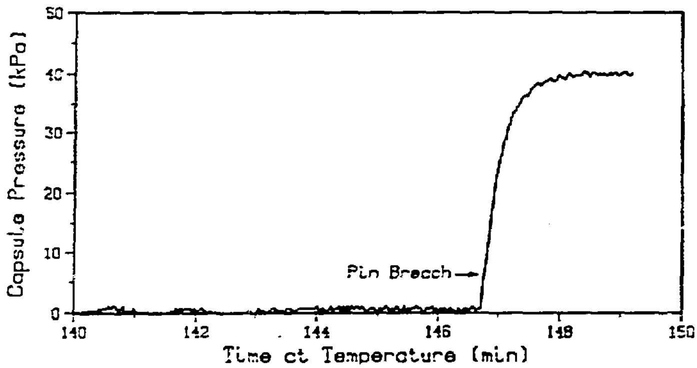


Fig. 5. Pressure transducer response in the FM-3 test. Pin breaching occurred at 146.7 min.

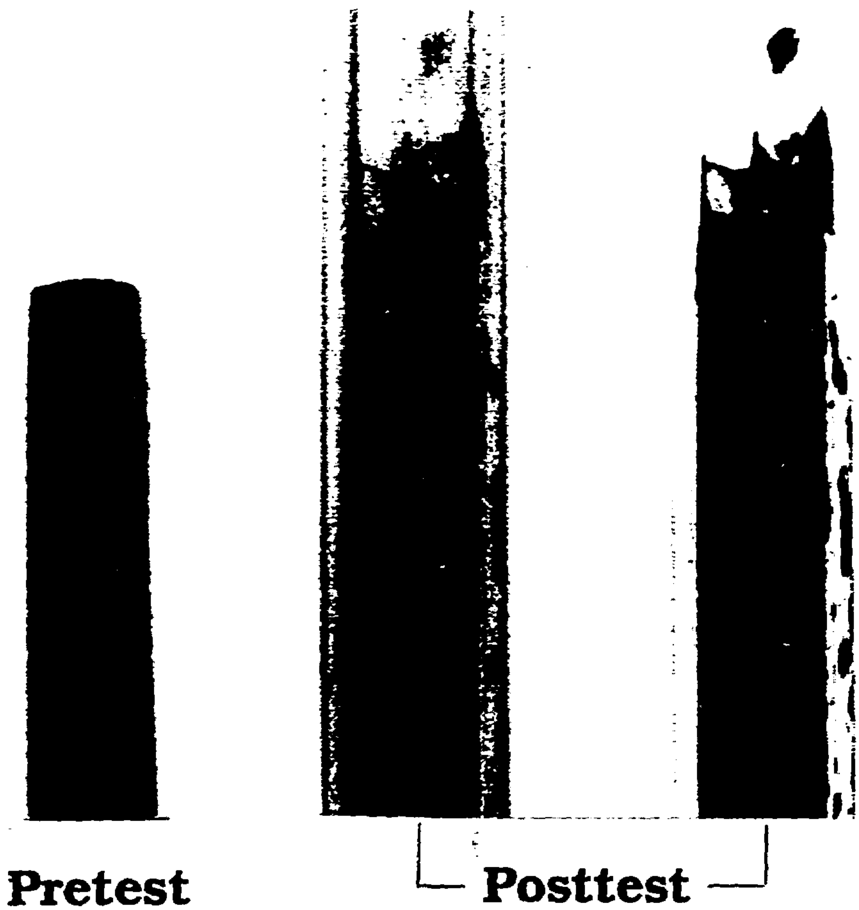
Prior to the FM-3 test, the FBTA data were used to estimate that 7.0 h would be required for complete cladding penetration due to fuel/cladding interaction only. Predictions of the pin failure time were also made with the FPIN2[6] and LIFE-Metal[7] codes that model both fuel/cladding interaction and cladding creep rupture. These codes predicted breaching times of 93 and 217 minutes, respectively. Compared to the 7.0-h failure time based on fuel/cladding interaction alone, the shorter breaching time would be due to the added effect of fission-gas pressure loading. When cladding creep from gas-pressure loading is considered, the codes yielded much closer predictions on the breaching time. The FM-3 data are currently being used to refine the predictive capability of both codes.

E. Pin Cladding Breaching Mode and Mechanism

Posttest neutron radiographs, shown in Fig. 6, indicated that cladding breaching occurred near the top of the fuel column where the cladding temperature was the highest during the test. Once-molten fuel debris, released from the breach and trapped in the gap between the pin cladding and the capsule wall, was apparent at the top location. A deposit of a foamy debris in the pin cladding above the original fuel top was also evident.

Metallography of the pin, Fig. 7, shows the transverse section just above the breach at $x/L=0.998$. Significant fuel/cladding interaction occurred along the entire circumference of the cladding; however, the interaction was not uniform.

Continued grinding of the section revealed an axial cladding crack with a length of <1 mm and an opening of ≤0.25 mm. A transverse section containing the crack at $X/L = 0.996$ is also shown in Fig. 6. The cladding breach mode was a benign crack, not a burst rupture. At the breach site, ≈80% of the original cladding thickness had reacted with the fuel, indicating that fuel/cladding interaction (i.e., cladding wall thinning) played a dominant role in the cladding breach, with fission-gas pressure loading causing the final rupture of the thinned cladding.



MCT 279867

Fig. 6. Neutron radiographs of the top end of the FM-3 fuel. Two exposures of the posttest radiographs are shown.

X/L = 0.998 (MCT 279622)

X/L = 0.996 (MCT 279625)

Fig. 7. Transverse sections of the FM-3 test pin just above the cladding breach (top) and at the breach (bottom).

VIII. Conclusions

Fuel/cladding compatibility tests on low-burnup, PRISM-type U-26Pu-10Zr/HT9 fuel showed the behavior to be excellent and consistent with the broader FBTA data base for IFR fuels. The WPF pin integrity test demonstrated a very substantial temporal margin to cladding breach. The breaching mechanism was predominantly fuel/cladding interaction with fission-gas pressure loading causing the final rupture.

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