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PERFORMANCE OF FAST REACTOR MIXED-OXIDE FUEL PINS DURING EXTENDED OVERPOWER TRANSIENTS*

by

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1 INTRODUCTION

The Operational Reliability Testing (ORT) program, a collaborative effort between the U.S. Department of Energy and the Power Reactor and Nuclear Fuel Development Corp. (PNC) of Japan, was initiated in 1982 to investigate the behavior of mixed-oxide fuel pin under various slow-ramp transient and duty-cycle conditions. In the first phase of the program, a series of four extended overpower transient tests, with severity sufficient to challenge the pin cladding integrity, was conducted.[1] The objectives of the designated TOPI-1A through -1D tests were to (1) establish the cladding breaching threshold and mechanisms, and (2) investigate the thermal and mechanical effects of the transient on pin behavior. The tests were conducted in EBR-II, a normally steady-state reactor. The modes of transient operation in EBR-II were described in a previous paper.[1] Two ramp rates, 0.1%/s and 10%/s, were selected to provide a comparison of ramp-rate effects on fuel behavior. The test pins chosen for the series covered a range of design and pre-test irradiation parameters.

In the first test (1A), all pins maintained their cladding integrity during the 0.1%/s ramp to 60% peak overpower.[1] Fuel pins with aggressive designs, i.e., high fuel-smear density and/or thin cladding, were, therefore, included in the follow-up 1B and 1C tests to enhance the likelihood of achieving cladding breaching. In the meantime, a higher pin overpower capability, to greater than 100%, was established by increasing the reactor power limit from 62.5 to 75 MWt. In this paper, the significant results of the 1B and 1C tests are presented.

2 TEST DESCRIPTION

Each of the 1B and 1C tests involved a subassembly of nineteen preirradiated fuel pins (up to 11 at.% burnup) arranged in a wire-wrapped bundle configuration. All pins had 5.86-mm dia., 20% cold-worked Type 316 or D9 cladding, and a 343-mm-long fuel column of $(U_{0.75}Pu_{0.25})O_2$ fuel pellets. Many of the pins had high fuel smear densities (~88 to 91%), and some had thin cladding (0.254-mm wall). The oxygen/metal ratio for all the fuels was nominally in the range 1.94-1.96. The key design and operating parameters of the test pins are shown in Table 1.

The ramp rates for the 1B and 1C tests were 10 and 0.1%/s, respectively. The achieved subassembly-average peak pin overpowers were similar, 98% in 1B and 100% in 1C. Prior to the transients, the fuel pins were preconditioned at their steady-state power/temperature conditions for seven days to restore the steady-state thermal and mechanical balance. The tests were terminated at the peak of the ramp with a reactor scram to freeze the condition of the as-tested fuel.

As the test subassemblies had no built-in instrumentation, the behavior of the test pins during the transient was monitored only by the in-reactor fission-gas (FG) and delayed-neutron (DN) detectors.[2] Following the tests, detailed nondestructive and destructive examinations were conducted on the fuel pins to collect fuel and cladding behavioral data.

3 RESULTS AND DISCUSSION

3.1 Breach Behavior

No pins breached in the 10%/s-ramp 1B test while two breached in the 0.1%/s-ramp 1C test. The temporal relationship between the initial FG and DN releases and pin overpower history in the 1C test, corrected for transit times, is shown in Fig. 1. Based on the fission-gas release data, the initial pin breach in the 1C test was determined to be at ~71-78% overpower, compared to the usual reactor trip settings of ~12-15%. The DN release trailed the fission-gas release and reached its peak immediately following the reactor scram. Such DN behavior could possibly be related to fuel cracking during cooldown.

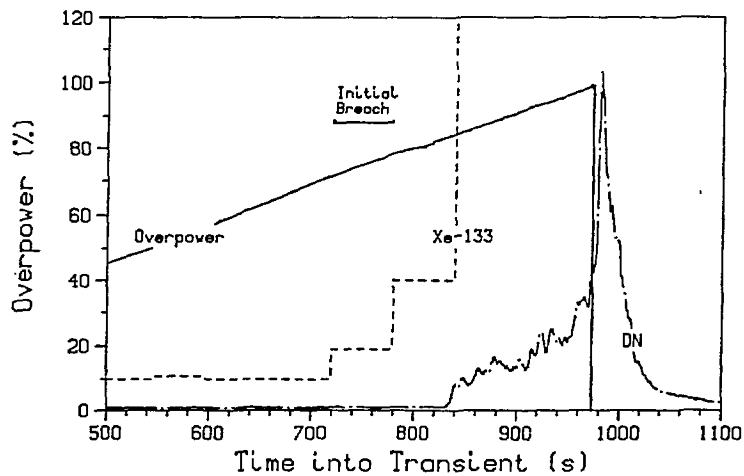

Fig. 1. Fission-gas and delayed neutron (DN) release history during the TOPI-1C test. Note the peak DN release occurred after the reactor scram, possibly relating to shutdown fuel cracking.

The breached pins in the 1C test were P43-D73 (5.6 at.% burnup) and P43-C52 (11.1 at.% burnup), both with aggressive designs (see Table 1). The breach in P43-D73 was a longitudinal crack at X/L of 0.76-0.82 and adjacent to the spacer wire of a neighboring pin. That in P43-C52 was a longitudinal crack, initiated underneath its own wire, between X/L of 0.58 to 0.68. Fuel losses from both pins were apparently small (~1 g max.) though this could not be precisely determined due to the countervailing effects of fission-gas release and sodium intake. Neither breach produced any noticeable effect on the neighboring pins.

One of the pins in the 1B test was known to be a gas leaker prior to the transient. Significantly, it did not become a DN emitter, nor did the breach deteriorate noticeably during the ensuing transient.

3.2 Cladding Strain Behavior

Cladding diameter profiles were measured with multiple-angle linear profilometry before and after the transient for three of the 1B pins and all of the 1C pins. As expected in both tests, the aggressively designed pins exhibited the greatest cladding incremental strains. The typical behavior of aggressive pins is illustrated in Fig. 2 for medium burnup 1C test pin P43-D69 (5.8 at.%). On the diameter profiles, the pronounced periodic minima correspond to the pellet-pellet interfaces, indicating that there was substantial fuel/cladding mechanical interaction (FCMI) in the pin from the prior steady-state irradiation. During the transient, additional stresses from differential thermal expansion, and probably fuel swelling, caused further straining of the cladding. The incremental strain was substantially greater in the upper half of the fuel column. The lack of any appreciable strain in the plenum region of the pin indicates negligible gas loading on the cladding in this medium burnup pin.

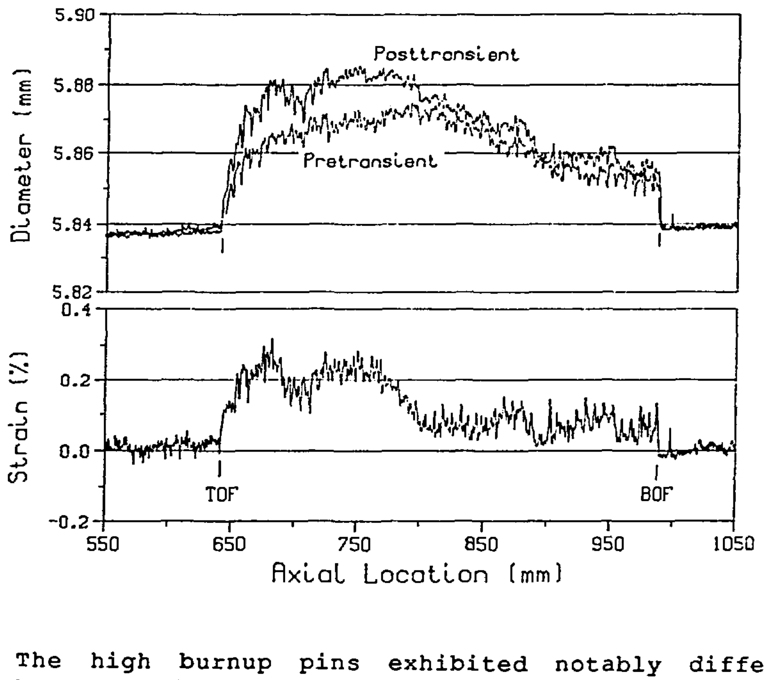

Fig. 2. The cladding diameter (top) and incremental strain (bottom) profiles of 1C Pin P43-D69. The fuel burnup was 5.8 at.%.

The high burnup pins exhibited notably different behavior, as illustrated in Fig. 3 for 1C pin P43-C48 (11.0 at.% burnup). The pronounced high strains (~0.25% max.) occurred in the lower half of the fuel column at locations where enhanced fission-product cesium activities were detected before the transient. This suggests the cladding loading mechanism to be related to the cesium buildup in the fuel/cladding gap (see below). There was a small (~0.05%), but near-uniform, strain in the plenum region above the fuel. This strain was apparently induced by the fission-gas pressure. Such strains were absent in lower burnup pins.

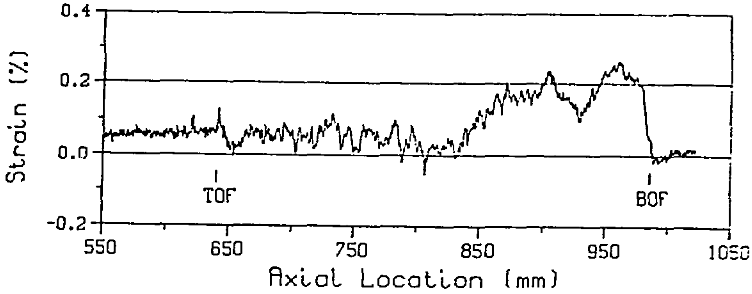

Fig. 3. The incremental strain profile of 1C Pin P43-C48. The fuel burnup was 11.0 at.%.

The correlations between cladding incremental strain and pin parameters are shown in Fig. 4. As expected, pins with thinner cladding, denser fuel, and higher burnup incurred the greatest cladding strain. Within the data scatter, there appear to be no significant differences between the 1B and 1C pin data, suggesting a lack of of ramp-rate sensitivity on cladding strain behavior in the range investigated.

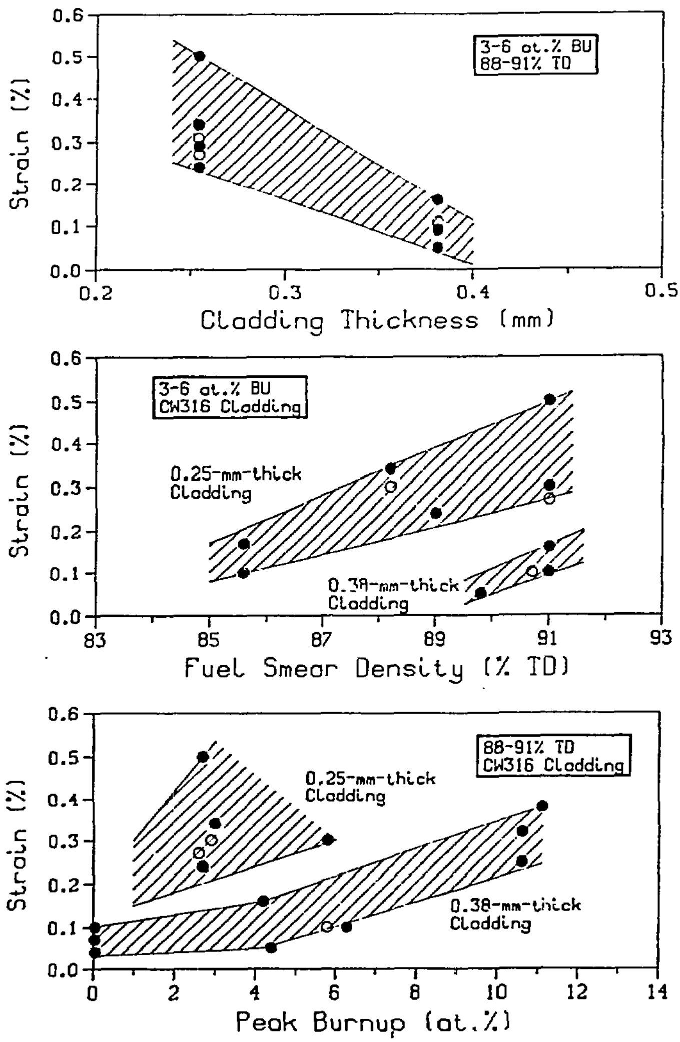

Fig. 4. Correlations between the cladding incremental strain and pin parameters.
o = 1B test
• = 1C test

3.3 Fuel Microstructure

The principal objective of the posttest metallographic examination was to relate microstructural features (e.g., transient fuel swelling, centerline fuel melting, and cesium deposit in the fuel/cladding gap) to cladding deformation and breach.

Transient fuel swelling, as evidenced by gas-driven grain-boundary microcracking in the equiaxed-grain-growth region (see Fig. 5), was generally more pronounced in the longer-duration 1C test than in the shorter-duration 1B test. This is apparently related to the time required for intergranular bubble growth.[3] In general, higher burnup fuels display greater transient swelling, due to the higher fission-gas inventory in the fuel.

Centerline fuel melting occurred in test pins with high transient linear power ($\geq$50 kW/m). The extent of fuel melting, however, was limited; the maximum areal melt fraction in pins destructively examined was ~7%. There were apparently no deleterious effects due to this limited amount of fuel melting; all redistribution of the molten fuel was confined in the central void region (see also Fig. 5).

In the lower portion of the higher burnup pins, cesium reacted with the fuel and formed a Cs(U,Pu,O) compound that caused tight fuel/cladding contact. The hypostoichiometric fuel (O/M = 1.94-1.96) in the 1B and 1C pins favored this reaction. The compound was probably non-pliant at the cooler, lower portion of the pin and apparently caused much of the cladding strain seen in Fig. 2. In the top half of the pin, cesium in the fuel/cladding gap probably formed more pliant cesium-molybdate compounds which might have "cushioned" the fuel/cladding mechanical interaction.

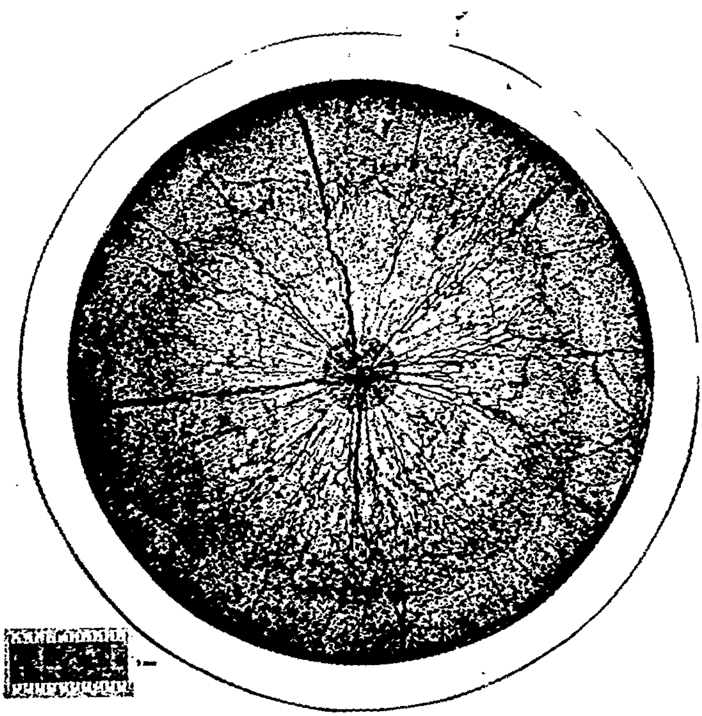

Fig. 5. Transverse section of 1C pin P43-C48 at X/L=0.60. Note the circumferential microcracking in the equiaxed-grain-growth region and fuel melting at center.

Table 1. Key design and steady-state irradiation parameters of test pins.

Pin Type	No. of Pins in Tests 1B	No. of Pins in Tests 1C	Design: Pellet Density (%TD)	Design: Diam. Gap (mm)	Design: Smear Density (%TD)	Design: Cladding Thick. (mm)	S.S. Irradiation*: EOL Peak Pin Power (Kw/m)	S.S. Irradiation*: Peak Burnup (at.%)
P14A	2	2	91.0	0.14	86.2	0.38	16	2
P40-C	0	3	94.4	0.13	89.7	0.38	-	0
P40-D	2	1	92.7	0.13	88.2	0.25	31	3
P43-B	3	2	95.4	0.13	90.7	0.38	27	4-6
P43-C	4	5	96.2	0.17	89.8	0.38	24-27	0-11
P43-D	2	4	95.7	0.13	91.0	0.25	27-29	3-6
P34-E	5	2	90.8	0.16	85.6	0.25	25-27	4-7
P43-F	1	0	96.2	0.17	89.8	0.38	24	11

*Peak cladding ID temperature for the pins during irradiation was ~600-650°C.

4 CONCLUSIONS

1. Irradiated mixed-oxide fuel pins, even with aggressive design parameters, can withstand a slow-ramp overpower transient to a severity significantly greater than the typical reactor trip settings.

2. The behavior of breached pins was benign, i.e., with minimal fuel loss and no apparent deleterious affects on neighboring pins. The breaches were readily detected with the in-reactor fission gas and delayed neutron detectors.

3. Fuel/cladding mechanical interaction, from differential thermal expansion and transient fuel swelling, was apparently the principal mechanism for cladding strain and breach. The condition of the fuel/cladding gap, as affected by fission-product cesium, can significantly influence the cladding strain behavior.

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