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Review of Behavior of Mixed-Oxide Fuel Elements In Extended Overpower Transient Tests in EBR-II*

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ABSTRACT

From a series of five tests conducted in EBR-II, a substantial data base has been established on the performance of mixed-oxide fuel elements in a liquid-metal-cooled reactor under slow-ramp transient overpower conditions. Each test contained 19 preirradiated fuel elements with varying design and prior operating histories. Elements with aggressive design features, such as high fuel smear density and/or thin cladding, were included to accentuate transient effects. The ramp rates were either 0.1 or 10% $\Delta P/P/s$ and the overpowers ranged between ≈60 and 100% of the elements' prior power ratings. Six elements breached during the tests, all with aggressive design parameters. The other elements, including all those with moderate design features for the reference or advanced long-life drivers for PNC's prototype fast reactor Monju, maintained their cladding integrity during the tests.

Posttest examination results indicated that fuel/cladding mechanical interaction was the most significant mechanism causing the cladding strain and breach. In contrast, pressure loading from the fission gas in the element plenum was less important, even in high-burnup elements. During an overpower transient, FCMI arises from fuel/cladding differential thermal expansion, transient fuel swelling, and, significantly, the gas pressure in the sealed central cavity of elements with substantial centerline fuel melting.

Fuel performance data from these tests, including cladding breaching margin and transient cladding strain, are correlatable with fuel-element design and operating parameters. These correlations are being incorporated into fuel-element behavior codes. At the two tested ramp rates, fuel element behavior appears to be insensitive to transient ramp rate and there appears to be no particular vulnerability to slow ramp transients as previously perceived.[1]

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INTRODUCTION

Slow-ramp overpower transients in a liquid-metal-cooled reactor (LMR) can initiate from credible events such as malfunctioning of a single control rod. These events are more plausible to occur than rapid reactivity insertions commonly associated with core disruptive accidents. The ramps for these types of mild "operational" transients would be a few percent per second or less and be terminated by the reactor's trip protection system, usually set at an overpower of ≈10-15%. For economical operation of an LMR, it is imperative that mixed-oxide fuel elements withstand these operational transients without a degradation of reliability. To evaluate this performance capability, including the margin to cladding breach, a series of five slow-ramp, extended overpower transient tests was conducted between 1983 and 1992 in the Experimental Breeder Reactor-II (EBR-II). These tests were part of the comprehensive Operational Reliability Testing (ORT) Program jointly sponsored by the U.S. Department of Energy and the Japanese Power Reactor and Nuclear Fuel Development Corporation (PNC).

In early transient overpower (TOP) tests[2-4] conducted mainly in TREAT and SLSF, due to the reactor limitations on reactivity and heat rejection capabilities, the ramps were necessarily fast in order to attain meaningful overpowers. Most of the transients were conducted in the range of ≈10-100%/s, more akin to core disruptive accidents. Few data existed on the possible vulnerability of mixed-oxide fuel elements to slow-ramp transient before this program. Such vulnerability was postulated in an earlier analysis[1] and was thought to be partially the cause of the cladding breaching in a TREAT test[5] which simulated a ≈3% $\Delta P/P/s$ transient to 25% overpower. This important issue on ramp susceptibility for the more probable, slow-ramp transients, therefore, needed to be addressed experimentally.

Recently, substantial fuel element design improvements[6,7] were made to extend the lifetime of mixed-oxide fuel elements. These improvements derived mainly from better (i.e., stronger and lower swelling) steels for cladding and innovative designs (i.e., annular pellets and fuel columns with a central blanket section) for fuel. A major objective of the extended overpower test series was to demonstrate the performance capability of fuel elements with these advanced features.

This paper reviews the major transient performance issues pertaining to irradiated mixed-oxide fuel elements based on the results obtained from this series of extended overpower transient tests.

TEST DESCRIPTION

The extended overpower test series consisted of five assembly tests, designated TOPI-1A through 1E. A summary description of the combined test matrix is shown in Table 1. Each test was an assembly containing nineteen preirradiated mixed-oxide fuel elements with varying design and prior power and operating histories. The fuel elements for the first three tests were of the early designs with smaller diameter (5.84 mm OD) Type 316 or D9 claddings. In the last two tests, fuel elements with the advanced features were included -- larger element diameters (7.0-7.5 mm OD), advanced claddings (PNC316, PNC1520, and PNC-FMS)*, annular fuel pellets, and axially heterogeneous fuel columns. Detailed descriptions of the fuel elements can be found in Refs. 11-13. Depending on linear power, cladding temperature, cladding thickness, and fuel-smear density, the test elements were classified as having aggressive, moderate, or conservative designs. In the 1A through 1C tests, the nineteen fuel elements were arranged in wire-wrapped bundles in hex cans; in the 1D and 1E tests the fuel elements were contained in individual flow tubes for independent cladding temperature control.

EBR-II proved to be an outstanding facility for operational transient testing. The fast flux environment eliminated flux depression in fuels and bundles (as in TREAT or SLSF) and provided prototypical radial temperature profiles in the fuel. Equally important was the ability to operate the reactor at a partial power for an extended period of time to precondition the test fuel elements before the transient. (The elements for each had been irradiated in outer-row positions in EBR-II to the target burnup under normal steady-state conditions, then reconstituted into a test assembly and moved to the peak-power core center. In a designated reactor run, the test elements were preconditioned at a partial reactor power, which reproduced in the test elements the nominal steady-state linear powers, for two to seven days. At the end of the preconditioning period and without interruption, the reactor power was ramped to the target level, yielding in the test elements the desired overpowers.) The extended preconditioning at the nominal linear powers of the elements healed the cracks in the fuel from the prior shutdown, thus restoring the steady-state mechanical balance between the fuel and cladding. This ability to precondition was important and allowed the study of fuel/cladding mechanical interaction under prototypical conditions during the transients.

Although the individual test assemblies were not instrumented, the reactor's fuel element rupture detectors (FERDs)[9] and the Ge-Li argon scanning system (GLASS)[10] in the primary system yielded valuable information on the releases of delayed-neutrons (DN) and fission gas, respectively, in case of a fuel element breach.

Except for the 1B test, which had a ramp rate of 10% $\Delta P/P/s$, all other tests had a ramp rate of 0.1% $\Delta P/P/s$. These two ramp rates enveloped the broad spectrum of possible operational transients. The individual element overpowers were ≈60-100% of the element's prior power-rating in all five tests.

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*PNC316: an improved Type 316 stainless steel; PNC1520: a version of austenitic steel with lower swelling and greater creep rupture strength than PNC316; PNC-FMS: a tempered ferritic/martensitic steel with very low swelling characteristics. See references 6 and 8.

Table 1. Key Parameters for the TOPI Test Series

Test Series	1A	1B	1C	1D	1E
Element Diameter, mm	5.8	5.8	5.8	5.8, 7.0, 7.5	7.0, 7.5
Cladding Type	316, D9	316, D9	316, D9	316, D9 PNC316	D9, PNC316 PNC1520, PNC-FMS
Fuel-Smear Density, % TD	85-91	86-91	86-91	81-90	81-90
Prior History(1)	SS	SS	SS	SS, SS + TOP	SS, SS + TOP
Peak Burnup, at.%	4.1-16.4	1.6-12.0	3.3-11.1	2.5-9.3	3.6-15.2
EOL Linear Power, kW/m	22-28	15-31	15-29	30-46	28-45
Transient Cladding Temperature, °C	710-775	680-795	670-750	760-890	680-820
Ramp $\Delta P/P/s$, %	0.1	10	0.1	0.1	0.1
Overpower, %	57-67	95-104	93-106	64-99	55-82
No. of Breaches	0	1	2	1	2

(1)SS: Steady-State irradiation only. SS+TOP: Steady-State plus periodic duty-cycle transients.

CLADDING BREACH BEHAVIOR

One of the major goals of the test series was to induce a small number of cladding breaches for the purpose of developing fuel-element failure correlations. Because the approved operating procedures mandated a prompt reactor shutdown when a substantial DN signal was detected by the FERDs, the number of breaches in each test was small, no more than one or two. Prompt shutdown was also desirable from the standpoint of preserving the condition of the breached element(s). In the entire test series, a total of six breaches were attained. A summary of these breaches is shown in Table 2.

All six breached elements had aggressive design parameters, including high-fuel-smear density. Two of the breaches, one each in the 1B and 1D tests, were probably anomalous due to abnormal circumstances that the elements had experienced before the transient tests. The breach in the 1B test[11], an aggressively-designed element at high burnup, probably occurred before or during the preconditioning, based on the GLASS data. But significantly, the breached element did not turn into a DN emitter during the transient and the cladding crack remained small after the test. The anomalous breach in the 1D test[12] was apparently related to the high overtemperature the element encountered during a segment of the prior steady-state irradiation.

The other four breaches, two each in the 1C and 1E tests, were true transient-induced failures. The breaches in the 1C test[11] occurred at a significant overpower, >71%, based on the FERD data and the breach behavior was benign, i.e., resulting in minimal fuel losses and did not affect the neighboring elements in the bundle. The breaches in the 1E test,[13,14] while also occurring at a high overpower (>≈72%), resulted in substantial cladding rupture and fuel relocation. The contributing cause for the substantial fuel and cladding damage was evidently the individual flow tubes which intensified the effects of sodium voiding from fission gas release thus exacerbated fuel melting. Both breached elements in the 1E test were clad in the PNC-FMS material which has only moderate creep rupture strength at high temperatures.

Table 2. Summary Description of Breaches

Test	1B	1C	1C	1D	1E	1E
Element No.	P43-C45	P43-D73	P43-C52	WT-129	UW11047	UW11048
Element Diameter, mm	5.8	5.8	5.8	5.8	7.5	7.5
Cladding Type	316	316	316	316	PNC-FMS	PNC-FMS
Fuel-Smear Densiry, % TD	90	91	90	90	90	90
Cladding Thickness, mm	0.38	0.25	0.38	0.38	0.40	0.40
Peak Burnup, at.%	10.1	5.6	11.1	9.7	4.6	4.8
EOL Linear Power, kW/m	24.3	27.2	24.3	34.7	43.2	44.5
Transient Cladding Temperature, °C	700	745	690	877	783	775
% Overpower at Breach	(1)	>71	>71	29-35(2)	>72	>72

(1) Apparent breached before or during preconditioning.
(2) Experienced appreciable overtemperature during prior steady-state irradiation.

None of the elements with designs similar to those of the reference or advanced long-life drivers for PNC's prototype fast reactor Monju breached in the test series. In fact, many elements with features more aggressive than the Monju designs survived the 60-100% overpower transients. A significant breach margins over the reactor's trip system settings of ≈10-15% overpower was thus demonstrated. The substantial breach margins indicate that the premature failure in the slow-ramp TREAT test was probably an aberration and that irradiated mixed oxide fuel elements are not susceptible to slow-ramp transients as originally postulated.

FUEL/CLADDING MECHANICAL INTERACTION

The test data clearly show fuel/cladding mechanical interaction (FCMI) to be the most significant mechanism for cladding strain and breach during a slow-ramp overpower transient. In contrast, pressure from the gas in plenum is less important, even in high-burnup elements. As expected, FCMI is more pronounced in elements with high-smear-density fuels.

FCMI during an overpower transient arises from fuel/cladding differential thermal expansion, fission-gas-bubble-driven fuel swelling, and, significantly, gas pressure in the sealed central cavity of high-power elements with substantial centerline fuel melting. Fuel/cladding differential thermal expansion was undoubtedly occurring in all elements during the tests, although the evidence can only be inferred indirectly. On cladding strain profiles, for instance, differential thermal expansion would result in a transient incremental strain only in the fuel column region and no strains in the nonfuel region, such as the plenum. An example is shown in Fig. 1 for the strain profile of a 1C element with very aggressive design features (both high fuel smear density and thin cladding) and no significant fuel centerline melting.

Fission-gas-bubble-driven fuel swelling is evidenced by grain-boundary separation, or microcracking, in the fuel, as shown in Fig. 2. The cracks form on the grain boundaries in response to the coalescence of grain boundary gas bubbles and differential thermal expansion stresses[15]. Most of the microcracks are found in a circular band in the equiaxed grain-growth region where favorable conditions, including a high population of grain-boundary gas bubbles, were present before the transient. Since microcracking represents a significant form of transient fuel swelling, the extent of fuel microcracking can substantially affect the FCMI loading on the cladding.

Centerline fuel melting and the resultant central cavity pressurization exerts a strong effect on the cladding mechanical behavior, as has been noted in earlier TREAT experiments.[16] In some fuel elements, evidence indicated that the central cavity was sealed, i.e., isolated from the top plenum, due to the fuel restructuring (crack healing) and the deposition of volatile fission products in the fuel/cladding gap. When fuel centerline melting occurs during a transient, the gas pressure in the central cavity increases from (1) the rising fuel temperature, (2) the additional gas released from the solid fuel that becomes molten, and (3) the reduced cavity volume due to fuel phase change ($\approx$10% $\Delta V/V$ upon mixed-oxide melting). This increased pressure, using the remaining solid fuel outside of the melt zone as the force transmitter, can exert a substantial mechanical loading on the cladding.

If the cavity pressure is sufficiently large, it may fracture the solid fuel cap just above the liquid fuel, force the insulator pellet upward, and allow the molten fuel to move upward into the void. An illustration of this is shown in Fig. 3 for an element (WT179) from the 1D test. When this happens, the pressure in the central cavity is effectively relieved. Apparently relating to this relief, the data for many elements show a tradeoff between molten fuel upward movement and cladding strain, i.e., high-cladding strain with no fuel movement and low strain with fuel movement. Depending on when this burst, or relief, occurs during the transient, the abatement on cladding loading and strain varies. In Fig. 4, the cladding strain profile for the WT179 element is compared with that of the sibling element WT180 whose cavity pressure was apparently not relieved during the entire transient (i.e., no molten fuel extrusion into the plenum). As can be seen, although there is transient strain in the WT179 cladding, its peak magnitude is nonetheless only about half of that in WT180. It is possible that the relief in the WT179 element occurred late in the transient, after the cladding had already incurred the substantial plastic deformation. In several other elements in the tests, possibly because the expulsion happened early, little transient strains resulted.

The good correlation between the strain profiles and the postirradiation location of the segments of the central void in both pins strongly suggests that these segments were pressurized during the transient and were frozen in place upon solidification. The implication of this is that molten fuel does not necessarily slump under gravity during a transient and that it can be supported by internal gas pressure.

As long as there is a sodium flow, the molten fuel that is expelled to the plenum will solidify against the cladding and cause no further damage to the cladding. (A melt-through of the cladding by the molten fuel is considered unlikely,[16] as is also evidenced in Fig. 3.)

It is probable that both breaches in the 1E test were the consequence of central cavity pressurization. Both elements had the PNC-FMS cladding which has only moderate elevated-temperature creep rupture strength. The cladding was further degraded by extensive fuel/cladding chemical interaction (≈12% thickness reduction) during the steady-state irradiation because of the high O/M (1.99) in the fuel. Posttransient radiographic data showed the positions of the fuel tops were unchanged in both elements. Apparently, instead of raising the top of the central cavity, the pressure was rupturing the cladding and expelling the molten fuel into the flow channel.[13] A third element in the 1E test, with the same PNC-FMS cladding but annular fuel pellets, not only survived the transient but incurred essentially no transient cladding strain because the central hole provided a gas pathway to the plenum and no central cavity pressure developed.

RAMP EFFECTS

A small number of elements with the same designs appeared in both the 1B (10% ΔP/P/s) and 1C (0.1% ΔP/P/s) tests. As the two tests had about the same peak overpower (≈100%), some comparisons can thus be derived to determine the effects of ramp rate. In terms of transient cladding strain, data from both tests fall within the same band and show no noticeable ramp dependency. The data base on cladding breaching from the two tests, unfortunately, was too small (only two valid breaches) to offer a clear reading on ramp sensitivity. The fact that many common element groups in both tests maintained their cladding integrity at comparable high overpower suggests that the dependence of cladding breaching thresholds on ramp rate, if any, is small and significantly lower than first anticipated.[1] In any case, the substantial breach margins demonstrated in these tests indicate that irradiated mixed oxide fuel elements are not particularly susceptible to slow-ramp transients in the 0.1-10.0 ΔP/P/s range at overpowers just above PPS trip levels.

BEHAVIOR OF FUEL ELEMENTS WITH ADVANCED DESIGNS

With possibly the exception of the two PNC-FMS cladding breaches in the 1E test, fuel elements with advanced features generally displayed excellent performance in the test series.

The breaches in the PNC-FMS-clad elements was evidently the combination of two factors: overly aggressive fuel element design (high fuel smear density and linear power) for the PNC-FMS cladding and an excessive cladding wastage from fuel/cladding chemical interactions due to the high fuel O/M. As shown by the third FMS-clad element in the 1E test, even a slight relaxation in the design, such as using annular fuel pellets, can bring on a very substantial performance improvement. It should be noted that even with the aggressive design and large cladding wastage, the two 1E elements breached at overpowers substantially greater than the reactor trip settings.

Both PNC316 and PNC1520 cladding materials have excellent creep rupture strength. As expected, elements clad in them consistently show the best cladding strain behavior among the test elements. Indeed, none of the elements clad in either PNC316 or PNC1520 materials breached in the test series, in spite of the high steady-state burnups and severe transient conditions.

To minimize the reactivity swing at high-burnup operation, it is necessary to use large-diameter pellets for the advanced designs. In the test series, no discernible performance penalties associated with the larger element diameters were noted. Whereas the advanced elements with solid fuel pellets performed well in terms of fuel melting and cladding strain, the ones with annular pellets performed even better.

The element with a heterogeneous fuel column in the 1E test displayed no unusual behavior. Centerline melting occurred in both the top and bottom fuel sections but did not propagate into the middle blanket section. Melting in the top fuel section resulted in a lift-off of the top fuel pellet, a feature common in many test elements with homogeneous fuel columns. Centerline melting of the bottom fuel section did not produce an unfavorable effect because of the axial location of the blanket section was not affected by the .

CONCLUSIONS

A significant cladding breaching margin was demonstrated for irradiated mixed-oxide fuel elements in the ramp rate range of 0.1-10% $\Delta P/P/s$. Only six elements breached during the tests, all with aggressive design parameters. Four of the breaches were genuinely transient-induced and all occurred at overpowers >70%. The other elements, including all those with moderate design features for the reference or advanced long-life drivers for PNC's prototype fast reactor Monju, maintained their cladding integrity in the overpower range of ≈60-100% during the tests.

Test data indicated that FCMI was the most significant mechanism causing the cladding to strain and breach. In addition to differential thermal expansion and transient fuel swelling, the central cavity pressurization apparently plays an important role in FCMI. The cavity pressure can not only stress the cladding, but also expel the molten fuel upward into the plenum, or in case of a cladding breach, into the coolant. Cavity pressurization can be mitigated or eliminated by using annular fuel pellets.

Fuel elements with advanced features performed very well in the tests, with possibly the exception of the PNC-FMS-clad elements with aggressive design parameters. Even those elements did not breach until the overpower is ≈72%.

At the ramp rates tested, fuel element behavior appears to be insensitive to transient ramp rate, i.e., there appears to be no particular vulnerability for mixed-oxide fuel elements in slower ramp transient, as previously perceived.

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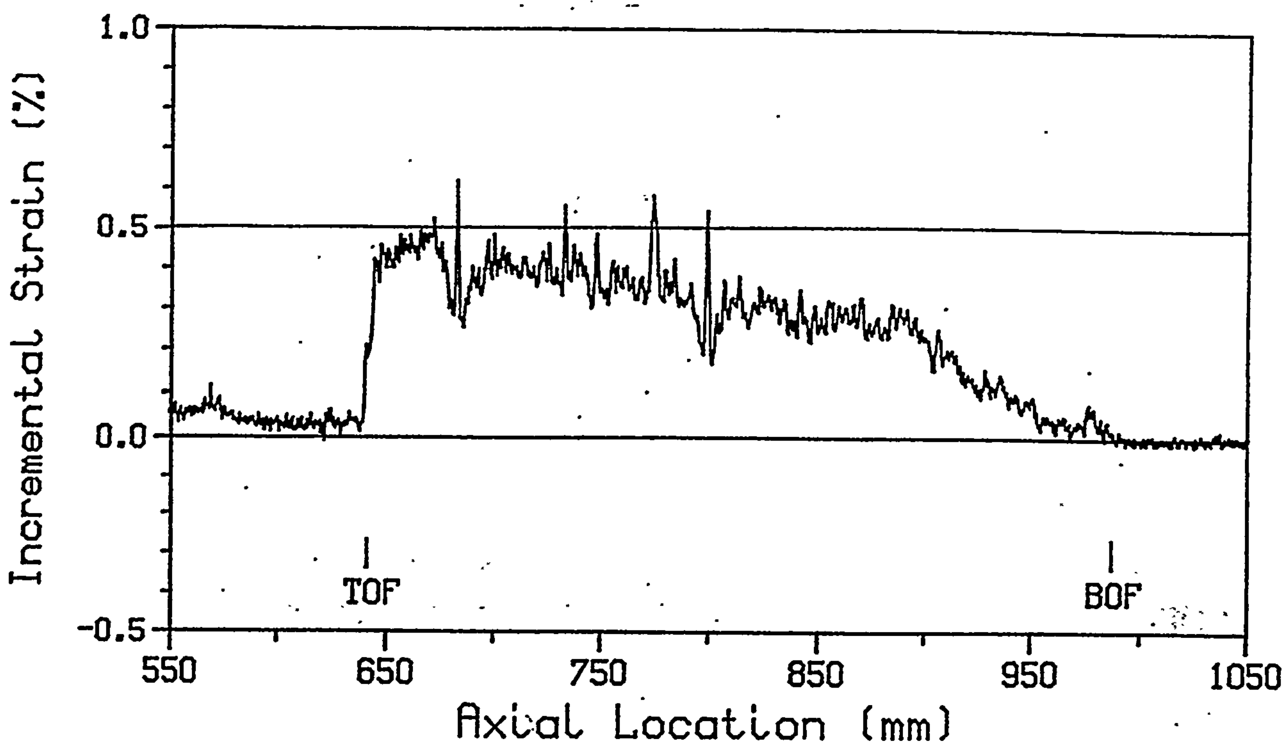

Fig. 1 Transient cladding strain for an element (P43-D79) from the 1C test. The element had high fuel smear density (91% TD), thin cladding (0.25 mm) and incurred no significant fuel melting. The cause for the strain was mainly fuel/cladding differential thermal expansion. TOF and BOF denotes top-of-fuel and bottom-of-fuel.

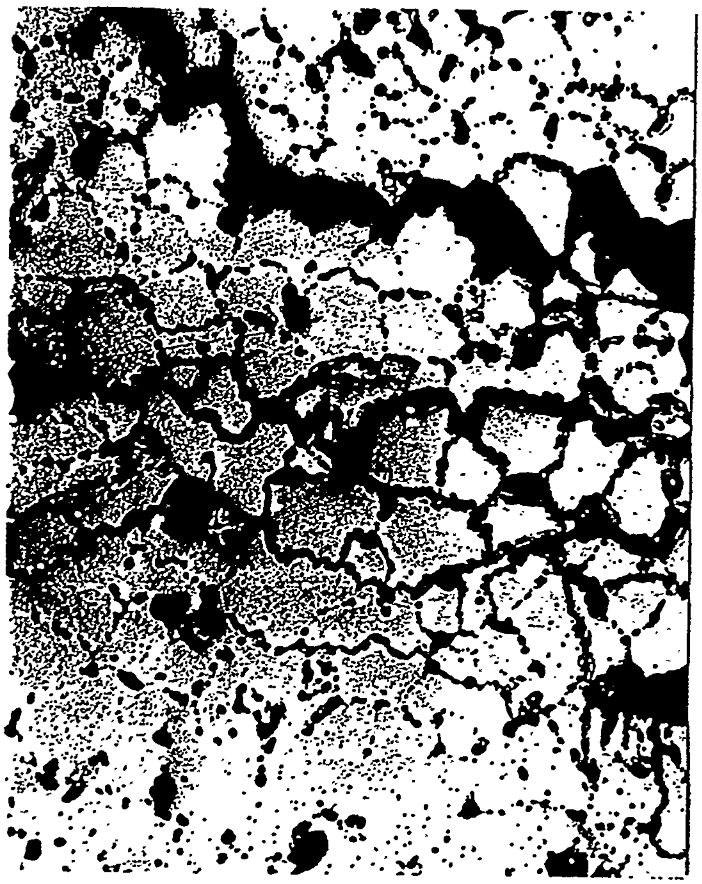

Fig. 2 .Transient-induced microcracking in the equiaxed grain-growth region of a medium burnup fuel (P43-A9, from the 1A test). Fuel center is to the top right. (N-7353)

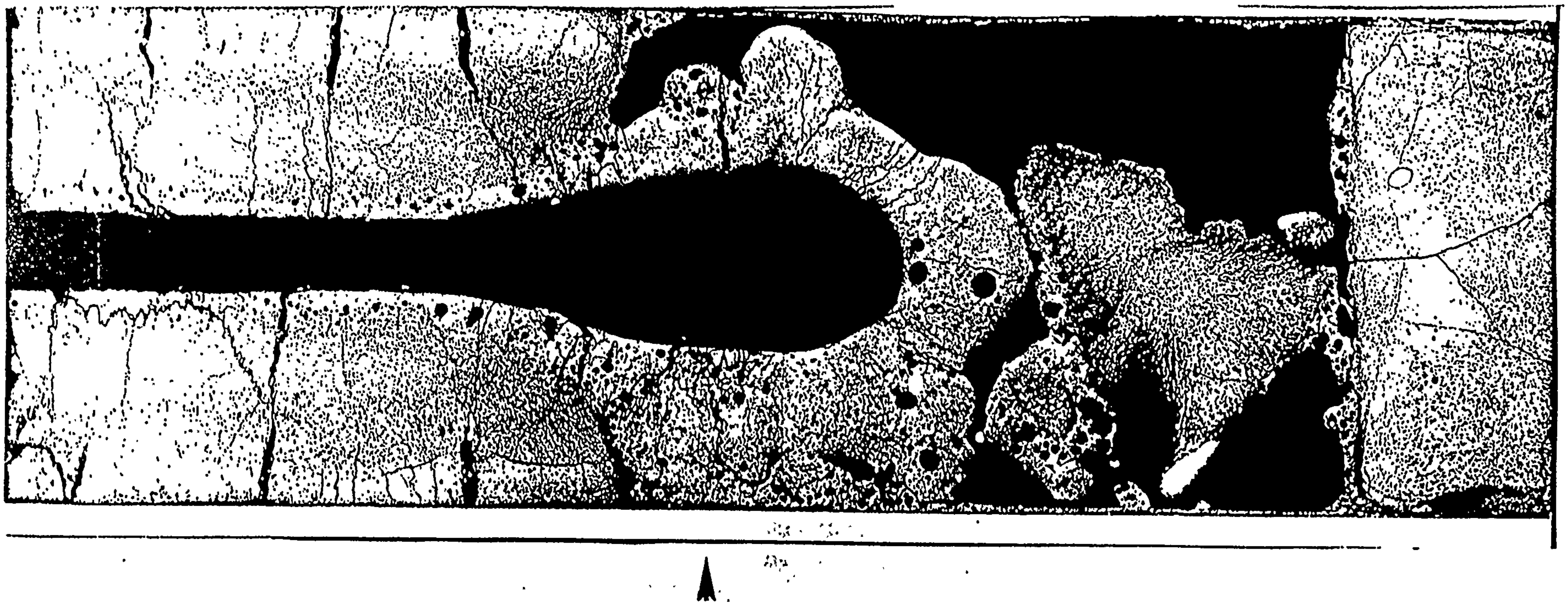

Fig. 3 Longitudinal section of an element (WT179 with PNC316 cladding, from the 1D test) showing expulsion of molten fuel (and part of the original fuel top, nonmelted) into the plenum and the liftoff of the insulator pellet. Note the benign solidification of the once molten fuel against the cladding wall. Arrow denotes approximately the original fuel top.

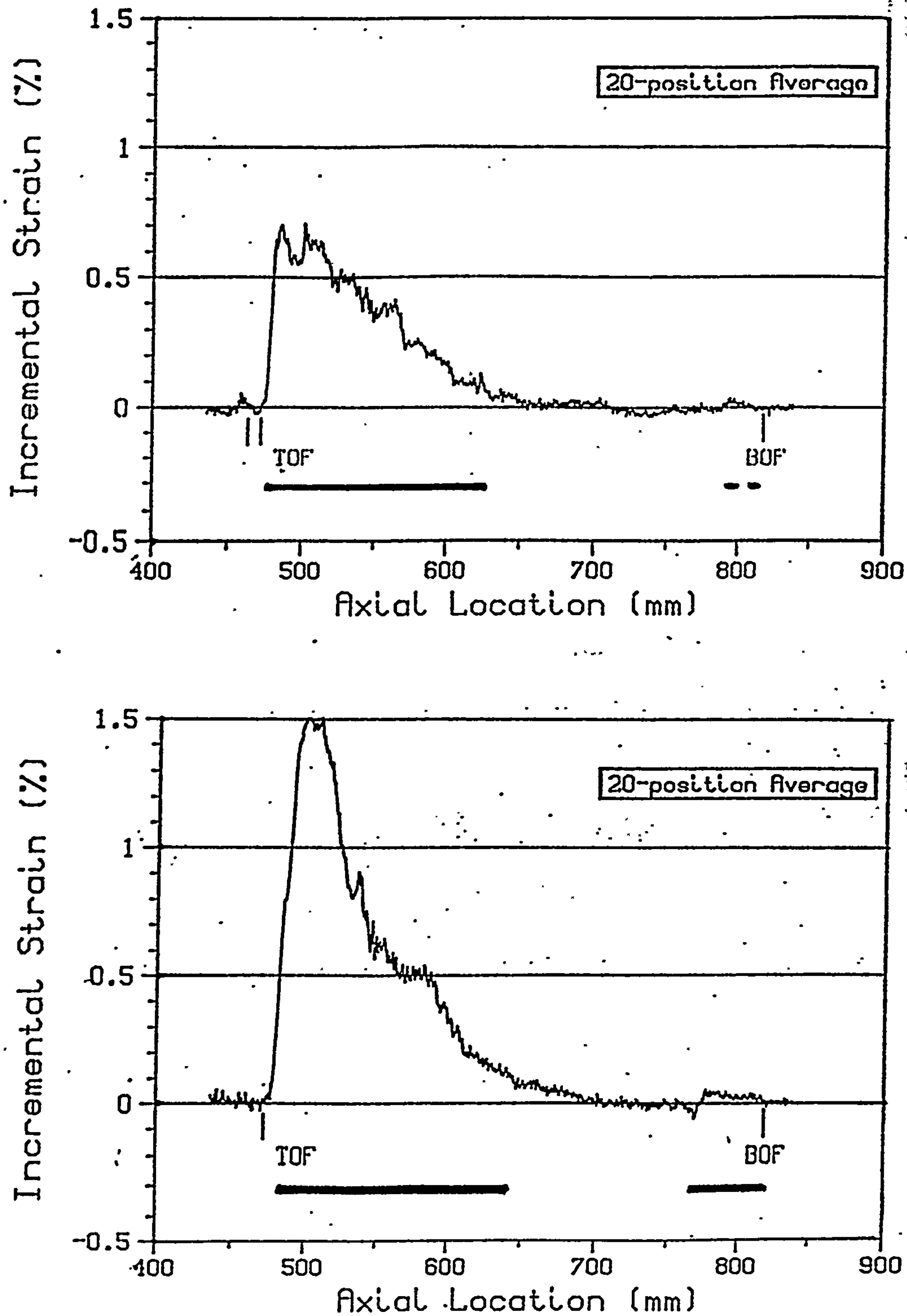

Fig. 4 Comparison of transient cladding strains between elements WT179 (top, with cavity pressure relief from molten fuel expulsion into the plenum) and WT180 (bottom, with no pressure relief). Both elements had PNC316 cladding and same aggressive design features. The horizontal bars denote the locations of the central cavities (determined from the posttransient radiographs).