CONF-860931--14

CONF-860931--14

DE87 004993

RESULTS OF TRANSIENT OVERPOWER EVENTS ON BREACHED AND UNBREACHED FUEL PINS*

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April 1986

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INVITED PAPER to be presented at the International Conference on Reliable Fuels for Liquid Metal Reactors, sponsored by the American Nuclear Society, Tucson, Arizona, September 7-11, 1986

*Work supported by the U.S. Department of Energy, Reactor Systems Development and Technology, under contract W-31-109-Eng-38, and the Power Reactor and Nuclear Fuel Development Corporation, Japan.

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INTRODUCTION

The understanding of UO_2-PuO_2 fuel pin performance during off-normal conditions is required to assure the reliability of such pins in a Liquid Metal-cooled Reactor (LMR). As part of the joint US-Japanese Operational Reliability Testing Program, fuel pin irradiation tests have been performed by Argonne National Laboratory (ANL) to study two types of off-normal events. These event types are a mild transient overpower on a breached pin and a single extended overpower event on unbreached pins to determine the cladding breaching threshold.

Occasional fuel pin failures are likely to occur in commercial liquid metal-cooled reactors despite highly reliable designs and high levels of quality control. Experience has shown that operation with simple "gas leakers" can be easily tolerated.[1] Experience with fuel pins that are operated in the run-beyond-cladding-breach (RBCB) mode is beginning to show that even more severely breached fuel pins that are emitting delayed neutron

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(DN) signals can be operated under normal steady-state conditions as well as startup and shutdown conditions without significant problems.[2,3] The objective of the overpower test on a breached pin was to assess the effects of a limited, duty-cycle overpower event on breach enlargement, fuel and fission product release, and possible failure propagation. This test, designated TOPI-2, was conducted in EBR-II under the Breached Fuel Test Facility (BFTF)[4] to provide additional DN signal information and to obtain data on the release of fuel and fission products. The test was composed of a single breached pin in the center of an assembly of 18 unbreached pins.

The objective of the extended overpower tests on intact pins was to determine the pin cladding breaching thresholds vis-a-vis the Plant Protection System (PPS) trip settings, typically at ~10-15% overpower. These tests emphasize slow operational-type transients in light of earlier work[5,6] which suggested that irradiated mixed-oxide fuel pins may be particularly vulnerable in the slow ramp-rate regime. An overview of the extended overpower test series was previously reported.[7] More recent results on two of the tests in this series are included in this paper. These two tests, designated TOPI-1A and TOPI-1B, were each conducted on a 19-pin assembly with various pin design, operation and burnup variables. The overpower ramp rates for the TOPI-1A and -1B tests were 0.1%/s and 10%/s, respectively.

BREACHED PIN TEST

TEST DESCRIPTION

The testing strategy to achieve an overpower event on a breached pin was to irradiate a group of pins with pre-thinned cladding some of which would fail at burnups between 4 and 6 a/o during the K2A test.[3] One or more of the K2A pins were expected to become delayed neutron (DN) emitters after steady-state operation as gas leakers. After these pins had operated as DN-emitters for a few days to establish a behavior baseline, the K2A test would be terminated and a nearly breached or slightly breached pin (leaking only gas) would be removed and subsequently subjected to a nominal 15% overpower event in the TOPI-2 test. The overpower event was to occur after DN emission comparable to that from the sibling pins in the K2A test had been established. Comparison of the resulting DN emission and the TOPI-2 pin's physical performance with sibling K2A pins would establish the effects of the overpower transient.

The TOPI-2 test pin became a gas leaker during its irradiation in the K2A test at a burnup of ~5 at.%. Gamma-scans of the plenum indicated that the TOPI-2 test pin had lost about 20% of its fission gas inventory during its irradiation in K2A.

It was anticipated that the TOPI-2 test pin would convert from a gas leaker to a DN emitter during a short steady-state operation. After the pin became a DN emitter, irradiation was to continue for 5 days and then a 15% overpower transient sequence was to be performed. The sequence would consist of a power increase at a rate of 4%/s to 15% overpower, the reactor power was to be maintained at 115% for 5 min and then returned to nominal full power at a rate of 4%/s. However, the test pin operated for 16 days with no indication that it would convert to a DN emitter. The 15% overpower transient sequence was then performed and was successful in producing a DN signal from the fuel pin. About three days later, after DN emission had stabilized, the sequence was repeated to meet the test objective of performing a limited overpower transient on a DN emitting fuel pin. High DN signals caused the test to be terminated shortly after the power was returned to full power after the 5-min hold at 15% overpower.

Because of an unanticipated decrement in fission rate in the TOPI-2 test assembly, the linear power of the test pin during the steady-state portion of the test was 6% less than its power rating during K2A, 318 W/cm vs. 334 W/cm. When the reactor power was increased 15% for the TOPI-2 transient, the test pin power was only 9% higher than its K2A power.

FISSION GAS AND DN RELEASE

Shortly following the startup of the TOPI-2 test, the test pin released a burst of fission gas that confirmed that the test pin was a gas leaker. The Xe-138 activity in the cover gas indicated that fission gas was released continually during the first two days of operation. The Xe-138 activity then dropped asymptotically to background levels until the first overpower sequence was performed. During this initial operation there was no DN signal on either the Fuel Element Rupture Detector (FERD) or the DN detector in the BFTF (FDND).

During the ramp up to 115% for the first overpower sequence, there was a slight increase in the DN signal on both the FERD and the FDND. The DN signal remained slightly elevated until the reactor power was returned to nominal full power. About 35 min after the overpower transient was initiated, the DN signal rose rapidly on both detectors. The peak signal was about 400 cps on the FERD. The DN signal then declined over the next 68 h to a level of 185 cps on FERD.

There is a delay of about 9 min between the time fission gas is released from a fuel pin under the BFTF and the time the activity is first detected by the cover-gas activity monitoring system. Assuming this time delay, it appears that the Xe-138 activity began to increase as the reactor power was raised. The Xe-138 activity in the cover gas peaked at a level of 240 nCi/ml about 15 min after the beginning of the transient. The cover gas activity declined over the 68 h that followed the first transient with the Xe-138 activity being about 150 times the normal background level at 30 nCi/ml just before the second transient was performed.

The second 15% overpower transient was initiated about 68 h after the first transient. The reactor power, DN signal (FERD), and Xe-138 activity during the second transient are shown in Fig. 1. During the ramp up to the 15% overpower, the DN signal rose rapidly and then peaked at about 1540 cps on the FERD shortly after the high power level was reached. The DN signal then dropped to about 1200 cps on the FERD during the 5-min steady-state operation at the overpower level. However, during the overpower operation the signal was not very stable and several peaks near 1500 cps were recorded. As the power was reduced back to nominal full power, the DN signal again increased rapidly. Very shortly after the power began to level-off at nominal full power, the DN signal exceeded the preset administrative limit of 1600 cps on the FERD and an anticipatory reactor shutdown was initiated. The FDND in the BFTF indicated that the large peak recorded by the FERD was actually composed of two peaks, one occurring on the comedown to nominal full power and the other occurring just after the anticipatory scram began (see Fig. 2). The maximum DN signal that was recorded on the FERD was about 4200 cps. During the second transient the fission gas activity essentially duplicated the behavior during the first transient. Again, shortly after the transient was started the Xe-138 activity rose until it reached a peak of about 250 nCi/ml, and then it declined after the reactor shutdown owing to the action of the cover gas cleanup system.

PIN EXAMINATIONS

Examination of the test fuel pin after irradiation showed that there was a primary crack through the pre-thinned region of the cladding and two secondary cracks under the spacer wire at an orientation 105 to 120° clockwise from the primary crack. The primary crack was about 20 mm (0.81 in.) long and 0.86 mm (0.034) in. wide. The second crack was 16 mm (0.65 in.) long and 0.25 mm (0.01 in.) wide. The third crack was about 16 mm (0.63 in.) long and 0.2 mm (0.008 in.) wide. The mid-length of the second crack was about 25 mm below the mid-length of the first crack. The breaches are shown in Fig. 3.

Diameter measurements on the intact sibling pins showed no measurable change as a result of the two overpower transients during the TOPI-2 irradiation. Diameter measurements on the test pin showed significant diameter increases in the regions of the cracks in the cladding. The maximum diameter change for the TOPI-2 pin was 5.2% at the axial location of the primary breach.

Cross-sections from the TOPI-2 and K2A sibling pins are shown in Fig. 4. The columnar and exquiaxed grain zones were slightly greater in the K2A pin than in the TOPI-2 pin. There also was less residual as-fabricated porosity in the outer zone of the fuel in the K2A pin than the TOPI-2 pin, while the central void was slightly larger at the core midplane in the TOPI-2 pin than in the K2A pin. There was no fuel micro-tearing in the transient-tested pin, nor was there a significant circumferential crack network. These two sibling pins operated under nearly identical conditions during their irradiation in the K2A test, but the TOPI-2 pin was operated at a slightly lower power during the steady-state portion of the TOPI-2 test. The slight differences in microstructure in these two intact pins have been attributed to slight variations that may have existed in the original pellet densities or in local subassembly operating conditions, not to any restructuring that occurred during the two 5-min periods of overpower operation.

Comparable cross-sections from the TOPI-2 test pin and one of the breached K2A test pins are shown in Fig. 5. The microstructures show that sodium ingress has a significant effect on the fuel. Prominent features in both pins were the presence of fuel-sodium reaction product between the fuel and cladding; large, irregularly shaped central voids; and large, blocky grains near the central void near the core midplane. The differences between the pins are subtle but indicative of the effects of the overpower transients.

Typical areas of the fuel-sodium reaction product in these fuel pins are shown in Fig. 6. One of the characteristics of the reaction in these pins was the transition of the product from a pure product to a product with islands of unreacted fuel, and then to a product only in the grain boundaries. This transition over a wide zone was strong evidence that the reaction had not come to chemical equilibrium after RBCB irradiation periods of three and five days for the TOPI-2 and K2A pins, respectively.

The irregularly shaped central voids and large, blocky grains adjacent to them are believed to be indicative of fuel liquidity and relocation. The partial filling of the void at some elevations in the K2A pin while the void at these elevations in the TOPI-2 pin tended to be open is probably indicative of a somewhat higher temperature and greater fuel relocation in the TOPI-2 pin.

One of the prominent features in most of the cross-sections from the TOPI-2 pin was the circumferential void space that was present just inward from the reaction zone. The voided area was greatest at the breach elevation but diminished in extent toward the midplane where it existed only in embryonic form. The circumferential void/crack was present in the K2A test pin only in the upper elevations and not at all in the unbreached pins. It is believed that this circumferential crack/void is a result of the sodium-fuel reaction and was accentuated by the second overpower transient. It is believed that the reaction product in this region decomposed as the ~1150 C stability isotherm moved outward during the second overpower transient. At the outer periphery of the void/crack zone is an area of fine-grained fuel (see Fig. 6) that is thought to be the fuel component of decomposed reaction product. Also, some areas of the void contain what appears to be vapor-deposited fuel, particularly at the ends of radial cracks. These areas would have had to be a void at the end of the second overpower transient for this material to deposit there.

Direct measurements on the BFTF's deposition sampler showed that fuel loss from the test pin was negligible.[8]

BREACHED PIN BEHAVIOR

The data obtained during the test on DN signals and fission-gas release when combined with the results of the pin examinations makes possible a reasonable understanding of the behavior of a breached pin during an overpower event.

The pre-thinned fuel pins used in the K2A test and the TOPI-2 test failed during steady-state operation and initially released only small quantities of fission gas. This behavior and the operation of the TOPI-2 pin for 16 days with little fission product release indicates that initial failure of the pin was a pure gas-pressure, stress-rupture breach with a very small defect size. The first overpower sequence opened that small defect, probably by differential thermal expansion between the fuel and cladding, slowly over a period of about half-hour allowing stored fission gas to be released. Sodium then entered the pin and reacted with the fuel forming fuel-sodium reaction product, a material with about half the density of the fuel. At the time of sodium ingress a slight gap between the fuel and the cladding likely existed at the location of the initial breach near the top of the fuel column. That gap and unhealed radial cracks in the fuel allowed the sodium to contact the fuel over a much greater area than the area of the breach alone. Sodium-fuel reaction at the fuel surface extended the small defect into an open crack. In addition to physically enlarging the defect, the fuel-sodium reaction would have reduced the oxygen/metal ratio (O/M) of the fuel, which would reduce its thermal conductivity and solidus temperature and raise its thermal expansion coefficient. The change in conductivity caused fuel temperatures to rise and enhanced the release of volatile fission products. The initial peak in the DN signal after the first overpower resulted from the opening of the defect into a crack and the physical changes in the fuel as a result of the sodium-fuel reaction. The DN signal then declined as the rate of reaction decreased and the reaction product filled the gap and partially sealed the breach.

The second transient probably initiated the secondary breaches under the spacer-wire by fuel-cladding mechanical interaction (FCMI) as a result of the reaction product in this area and the greater thermal expansion of the lower O/M fuel. These new cracks provided an immediate opportunity for additional sodium to enter the pin as there was no significant fission gas inventory to prevent the ingress of sodium. Reaction between fuel and the sodium that entered these new breaches contributed to the high DN signal during the overpower operation. The overpower operation caused some of the reaction product that was present prior to the transient to dissociate as a result of higher fuel temperatures moving the decomposition isotherm outward. This decomposition of the reaction product is believed to be responsible for the formation of the large circumferential void/crack in the fuel that was present in the TOPI-2 test pin during the latter stages of the test. The decomposition of the reaction product would enhance the release of volatile fission products, and therefore, be a strong contributor to the high DN signal during the overpower transient.

The two large peaks in the DN signal that accompanied the reduction in power from the 15% overpower to full power and the reduction from full power to zero power at the end of the second transient are obviously related to a phenomenon that occurs when the fuel cools. It is doubtful that these peaks were caused solely by the sweeping action of sudden fission-gas release from a freshly vented central void as this would not occur in two bursts.

A plausible explanation of these very high, short-lived DN peaks lies in the decomposition of the reaction product in the region of the circumferential crack/void during the overpower operation and the micro-cracking of the fuel pellets in this region during the two decreases in pin power at the end of the test. Another observed phenomenon in this region of the fuel pellets was the cracking of islands of fuel particles within the reaction product matrix. This cracking, too, would have added to the volatile fission product inventory available for rapid release at the time of cooldown.

It is important to note that these high DN signals from the TOPI-2 test could not have been generated by the loss of fuel from the pin that was swept past the DN detectors. Each of the two DN peaks during the power reductions at the end of the test would have required the loss of over 1 g of fuel. The metallography of the fuel pin showed that no large amount of fuel was lost from the pin and the examination of the deposition sampler has indicated essentially no fuel was lost.

The results of the TOPI-2 test show the effects of a nominal 15% over-power event on breached pin nominally operating at peak power of ~318 W/cm (~10 kW/ft). Under these conditions, some fuel melting evidently occurred. It is not possible to conclude at this time that similar results would have been obtained from a lower power pin, or, for that matter, from a higher power pin. Likewise, it is only possible now to conjecture on the behavior of a pin in which the fuel-sodium reaction had achieved completion, i.e., had achieved a uniform interface between the fuel and the reaction product.

BREACHING THRESHOLD TESTS

TEST DESCRIPTION

The TOPI-1A and TOPI-1B tests each employed a dedicated subassembly consisting of 19 intact fuel pins in a wire-wrap bundle configuration. The major variables in the test pins were: fuel smear density, cladding type and fuel burnup in the TOPI-1A test, and fuel smear density, cladding thickness and fuel burnup in the TOPI-1B test. The more aggressively designed pins with thin cladding and/or high fuel smear density were included in the TOPI-1B test to accentuate transient-induced effects. Summary descriptions of the test pin design and operating histories for the TOPI-1A and TOPI-1B tests are shown in Tables 1 and 2 , respectively.

The method of conducting breach threshold tests in EBR-II was described in Ref. 7. The power history for the TOPI-1A test consisted of a two-day steady-state preconditioning period followed by a 0.1%/s ramp to an assembly-average peak pin overpower of 62%. That for the TOPI-1B test was a seven-day preconditioning period followed by a 10%/s ramp to 98% peak overpower.

TEST RESULTS

The significant destructive examination results for the TOPI-1A test and the nondestructive examination results for the TOPI-1B test are presented below.

Cladding Integrity Limits

None of the TOPI-1A or TOPI-1B pins breached during the transients. Cladding integrity margins of >62% overpower for the 0.1%/s ramp and >98% overpower for the 10%/s ramp were thus established for the pins in the TOPI-1A and -1B tests, respectively. Three fuel pins from the TOPI-1A test were subjected to the second transient in the TOPI-1B test, and all three pins maintained their cladding integrity. The earlier concerns that mixed oxide fuel pins may be particularly vulnerable to slow transients at low overpowers were not substantiated in these two tests. As the PPS typically terminates a transient at ~10-15% overpower, the positive results from these two tests with much higher overpower severity demonstrated that mixed oxide fuels are capable of reliable operation in an LMR over a range of operational transient conditions.

In the TOPI-1B test, one of test pins, an aggressively designed pin with a 91% smear density, and a burnup of 10.1 a/o, apparently developed a gas leak during the first of the two reactor start-ups attempted for the TOPI-1B preconditioning period. This pin was left in the TOPI-1B test intentionally to observe the behavior of a gas leaker during an extended overpower event. During the ensuing restart, preconditioning and transient, although more fission gas was released, no DN precursors were released from this pin. The fact that this pin did not become a DN emitter after a shutdown and restart attests to the benign behavior of gas leakers even during an extended overpower transient.

Thermal Performance

Of the TOPI-1A test pins that were destructively examined, only one high-burnup pin and one near-fresh pin showed centerline fuel melting. The extent of melting in both pins was limited, <5% areal. In the case of the high-burnup pin, fuel melting was affected by fission-products which have been known to decrease the fuel solidus temperature by eutectic formation.[9] The intermediate burnup pins exhibited higher thresholds of power-to-melt in the transient.

The most pronounced thermal-mechanical effect of the applied overpower transient in the TOPI-1A pins is perhaps fuel grain-boundary separation, or microcracking. Such cracking was found in virtually every one of the preirradiated TOPI-1A pins that were destructively examined. Most of the microcracks were found in a circular band in the equiaxed grain-growth region where favorable conditions, including a high population of grain-boundary gas bubbles before the transient, were present. Apparently these gas bubbles coalesce and interconnect during the transient thereby weakening the boundary. Upon cooldown these weakened boundaries tear in response to differential thermal contraction forces. Fig. 7 illustrates the microcracks in the fuel pin after the transient and the lack of similar cracks in the steady-state sibling. The contribution of microcracking to local fuel volume changes was studied using a quantitative stereology technique. The analysis results for this pin and its sibling shown in Fig. 7 are illustrated in Fig. 8. Because microcracking represents a significant form of "fuel swelling," the extent of fuel microcracking can significantly affect the FCMI loading on the cladding on subsequent startups.

The inter-linkage of grain-boundary fission gas bubbles during the transient would be a factor in fission gas release. The gas release data for the three TOPI-1A pins for which sibling data are available are given in Table 3. The incremental release for the three pins was about the same, ~7-9%. Whether this gas was released during the transient or on cooldown cannot be determined from this test.

Cladding Strain

The cladding diameter profiles for the TOPI-1B pins before and after the transient test were measured with either linear or spiral profilometry.[7] The linear profilometry, performed on three of the TOPI-1B test pins that had no spacer wires, yielded more accurate strain data bacause of its multi-angle measurement capability.

The measured incremental strain profiles for TOPI-1B test pins P43-B15 and P40-D103 are illustrated in Figs. 9 and 10, respectively. In pin P43-B15, which had 0.38-mm-wall cladding, despite the high fuel smear density (91% TD), the overall incremental strain was small with a maximum of ~0.1% occurring near the midplane. In pin P40-D103, the incremental strain was substantially greater (~0.3% max.) owing primarily to the thinner 0.25-mm-2all cladding. The sharp rise of the incremental strain profile at the top of the fuel column in pin P40-D103 suggests that cladding loading was due mainly to fuel-cladding mechanical interaction. The overall profile showing greater incremental strain near the top end of the fuel column may be correlated with the reduction of cladding strength with increasing operating temperature.

Unfortunately, the pins in the TOPI-1A and 1B tests that received linear profilometry did not contain comparable design and operating variables, thus making it impossible to evaluate directly the effects of the two different ramp rates. However, the next test in the series, TOPI-1C, has been conducted at a ramp rate of 0.1%/s and direct cladding strain comparisons with the TOPI-1B test will be made.

CONCLUSIONS

The primary conclusion that can be drawn from the TOPI-2 test is that a breached fuel pin can be subjected to a duty cycle overpower transient without severe degradation of the breach or the general condition of the pin. The total area of the breaches in the transient-tested pin was smaller than the area of the breach in either of similar pins operated under steady-state conditions.

A second conclusion that can be drawn from the TOPI-2 test is that under transient conditions the magnitude of the DN signal is a poor indicator of the size of the breach and the condition of the fuel pin. During the power reduction portions of the second transient, a DN signal was reached that was approximately four times that of a pin, in another test, that had six times the breach area of the TOPI-2 pin. The TOPI-2 results show that the exposed fuel area within the pin is more significant than the area of the breach.

The results from the TOPI-1A and TOPI-1B transient tests showed that mixed oxide fuel pins possess a significant cladding breaching margin over the PPS trip thresholds. Contrary to previously-expressed concerns, these fuel pins are capable of reliable operation in an LMR during slow, operational transients.

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Table 1. Summary Description of TOPI-1A Test Pins

	Pin Types				
	P43-A	P43-B	P43-C	P43-F	P40-C
No. of Pins	6	2	6	2	3
Pellet Density (%TD)	89.4	95.4	93.4	96.2	93.2
Dia. Gap (mm)	0.11	0.13	0.08	0.17	0.12
Smear Density (%TD)	85.4	90.7	90.6	89.8	88.8
Fuel O/M	1.94	1.94	1.94	1.96	1.95
Cladding Thickness (mm)[1]	0.38	0.38	0.38	0.38	0.38
SS Peak Cladding Temp (°C)	640	650	650	650	600
SS Peak Pin Power (kW/m)	26	26	27	29	32
Burnup (a/o)	4.1-16.4	5.8	6.1-12.3	10.5	0

[1]All pins had 5.84 mm OD, 20% CW Type 316 stainless steel cladding, except the P433-F pins which had 20% CW D9 cladding.

Table 2. Summary Description of TOPI-1B Test Pins

	Pin Types						
	P43-B	P43-C	P43-D	P43-E	P43-F	P14A	P40-D
No. of Pins	3	4	2	5	1	2	2
Pellet Density (%TD)	95.4	93.4	95.7	90.8	96.2	90.5	92.7
Dia. Gap (mm)	0.13	0.08	0.13	0.16	0.17	0.14	0.13
Smear Density (%TD)	90.7	90.6	91.0	85.6	89.8	85.6	88.2
Fuel O/M	1.94	1.94	1.94	1.94	1.96	1.94	1.96
Cladding Material	316	316	316	316	D9	316	316
Cladding Thickness (mm)[1]	0.38	0.38	0.25	0.25	0.38	0.38	0.25
SS Peak Cladding Temp (°C)	650	650	630	630	650	600	630
SS Peak Pin Power (kW/m)	27	25	29	28	29	16	30
Burnup (a/o)	3.9-5.8	10.0-12.0	2.6	3.6-6.4	10.5	1.7	2.9

[1]All pins had 5.84-mm OD, 20% CW Type 316 stainless steel cladding except the P43-F pin which had 20% CW D9 cladding.

Table 3. Incremental Fission-gas Release in TOPI-1A Test Pins

	P43-A9	P43-C33	P43-F104
Peak BU (a/o)	6.1	12.3	10.5
Fission-gas Release (%)	80	98	94
Release from SS Sibling (%)	73	90	85
Incremental Release (%)	7	8	9

Figure 1. Power and Fission Product Release Data During the Second Transient and Reactor Shutdown.

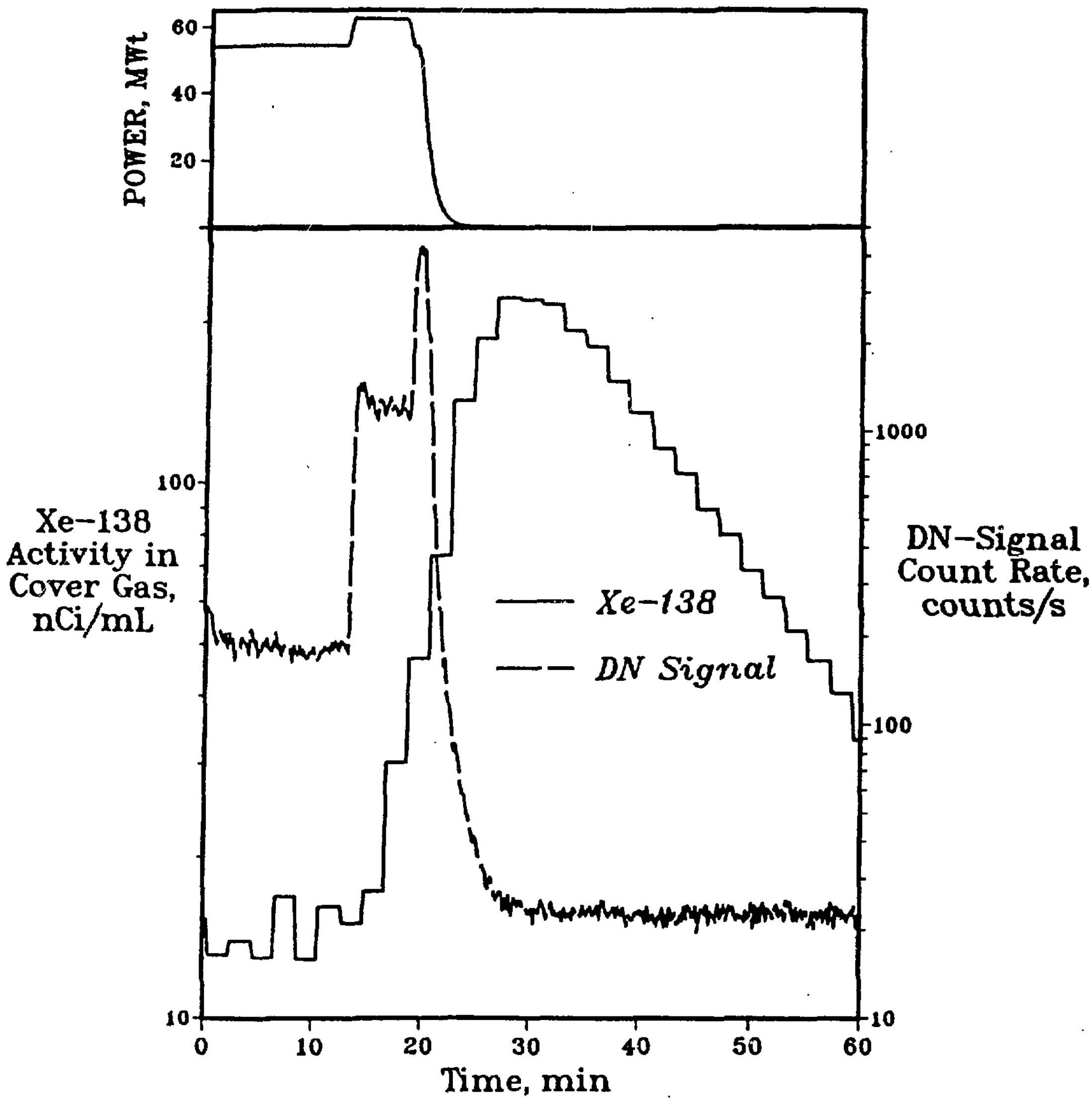
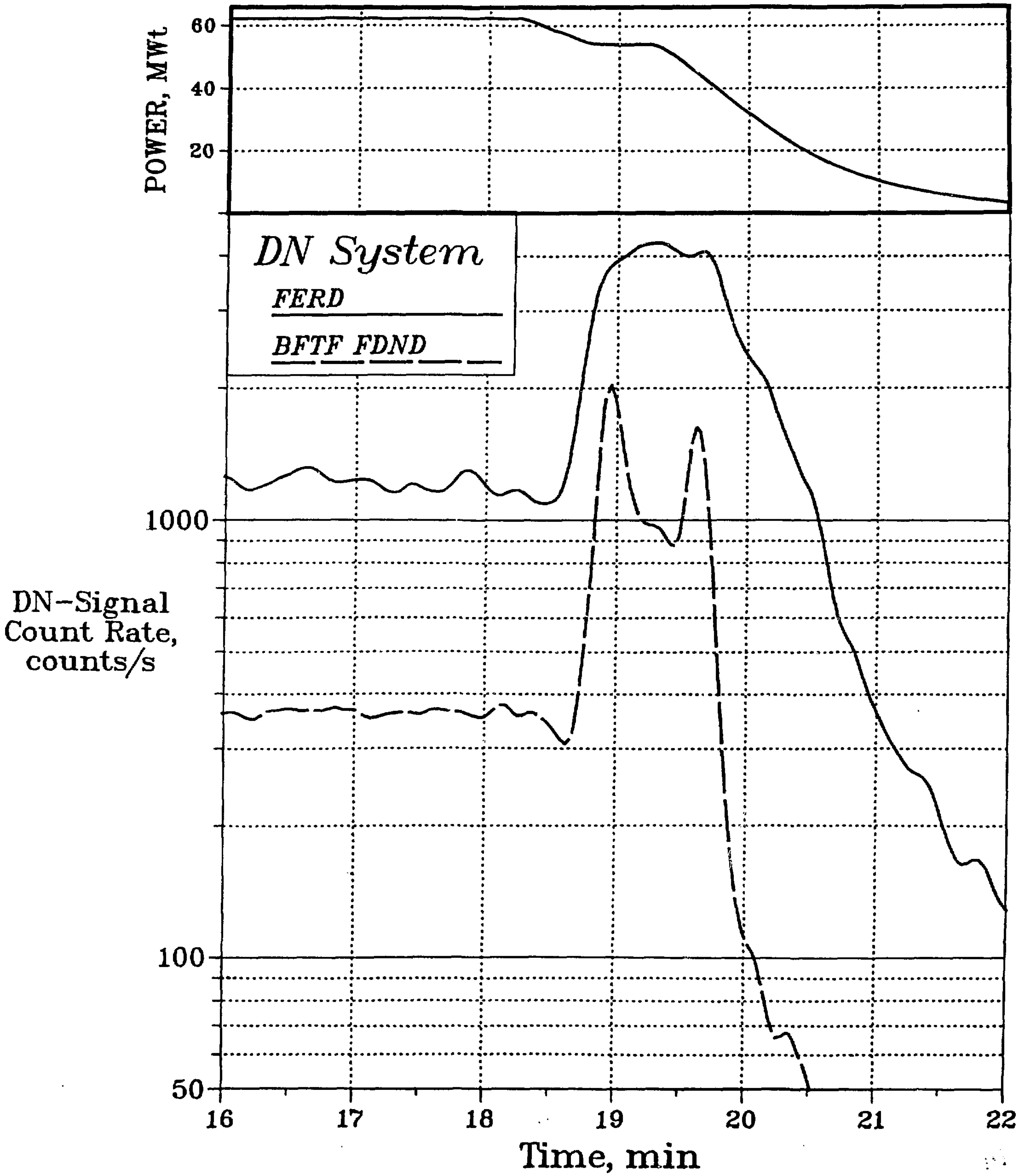


Figure 2. FERD and BFTF DN Signals at the End of the Second Transient and Reactor Shutdown.



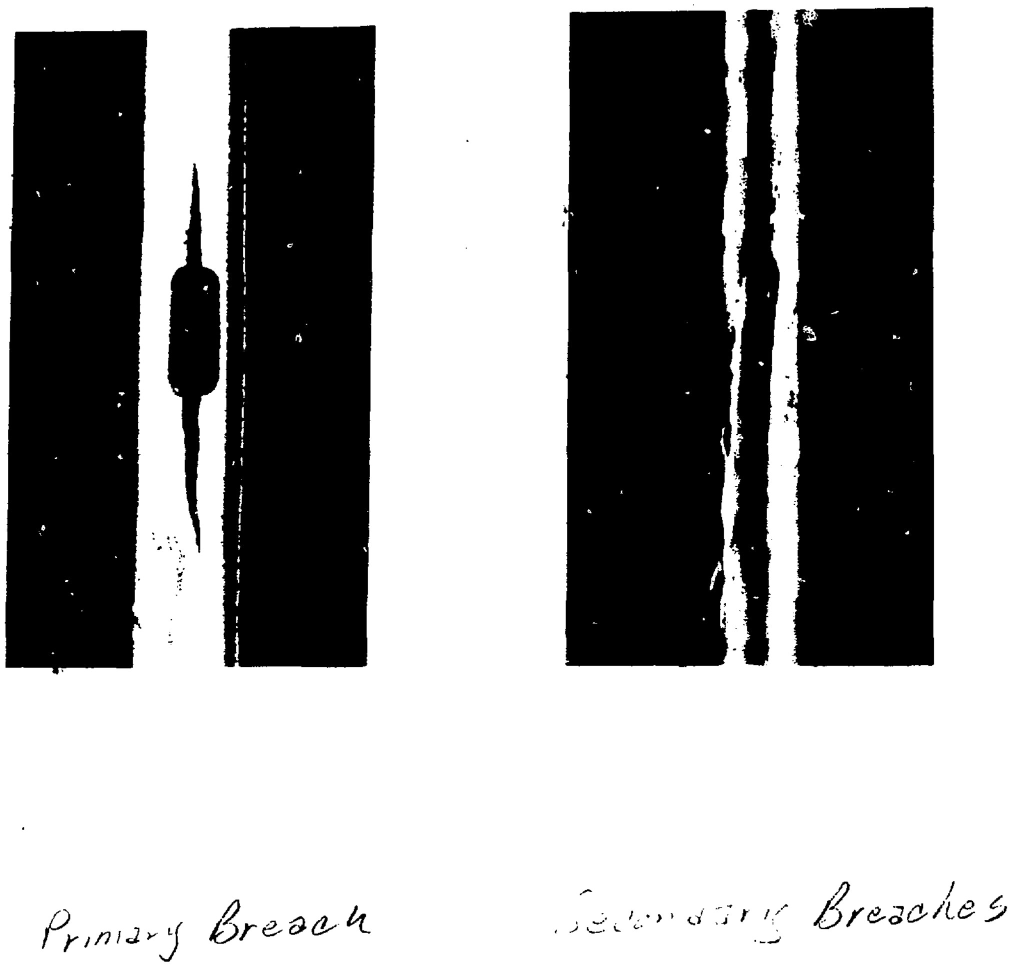


Figure 3. Primary and Secondary Breaches in the TOPI-2 Test Pin.

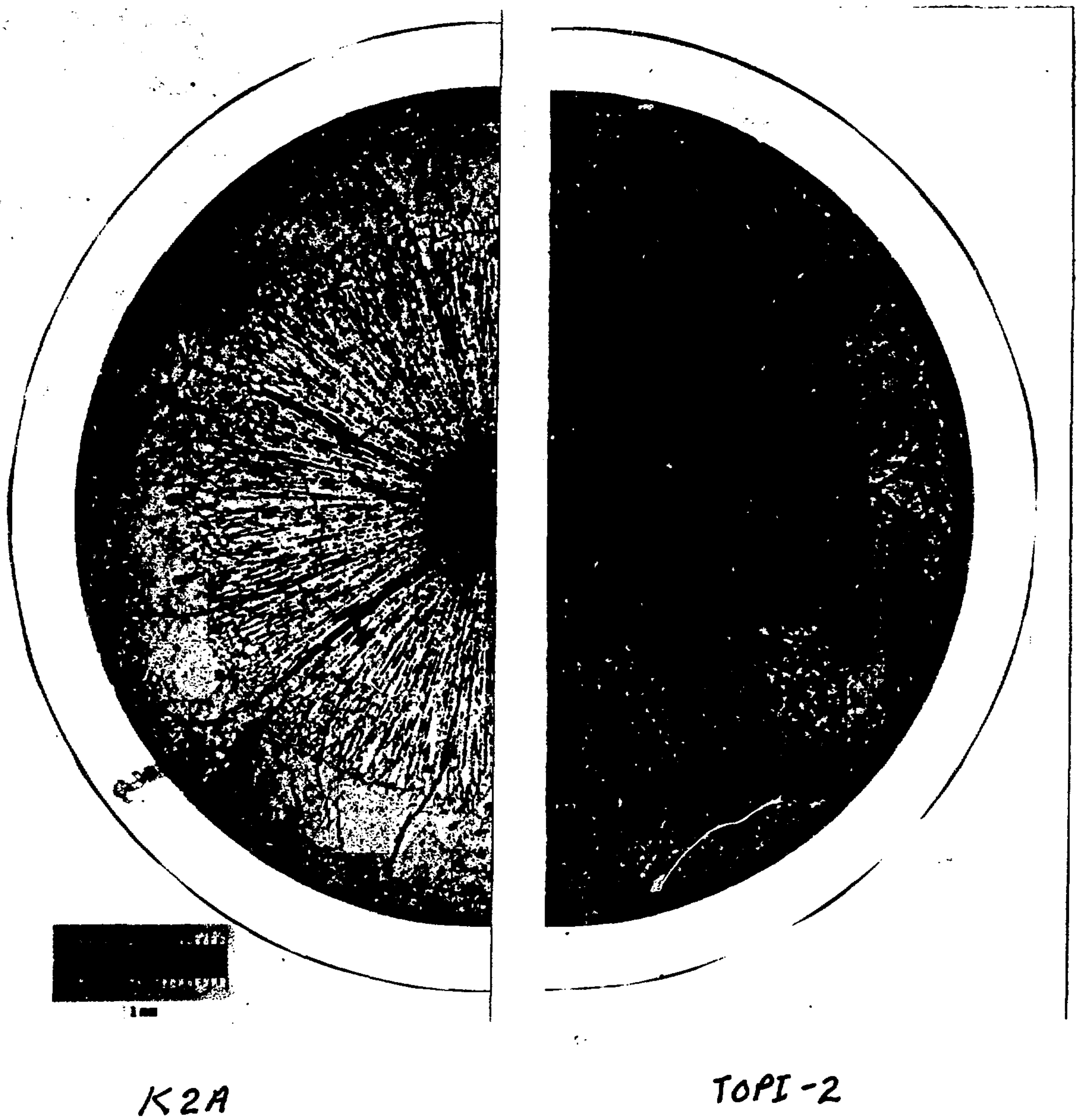
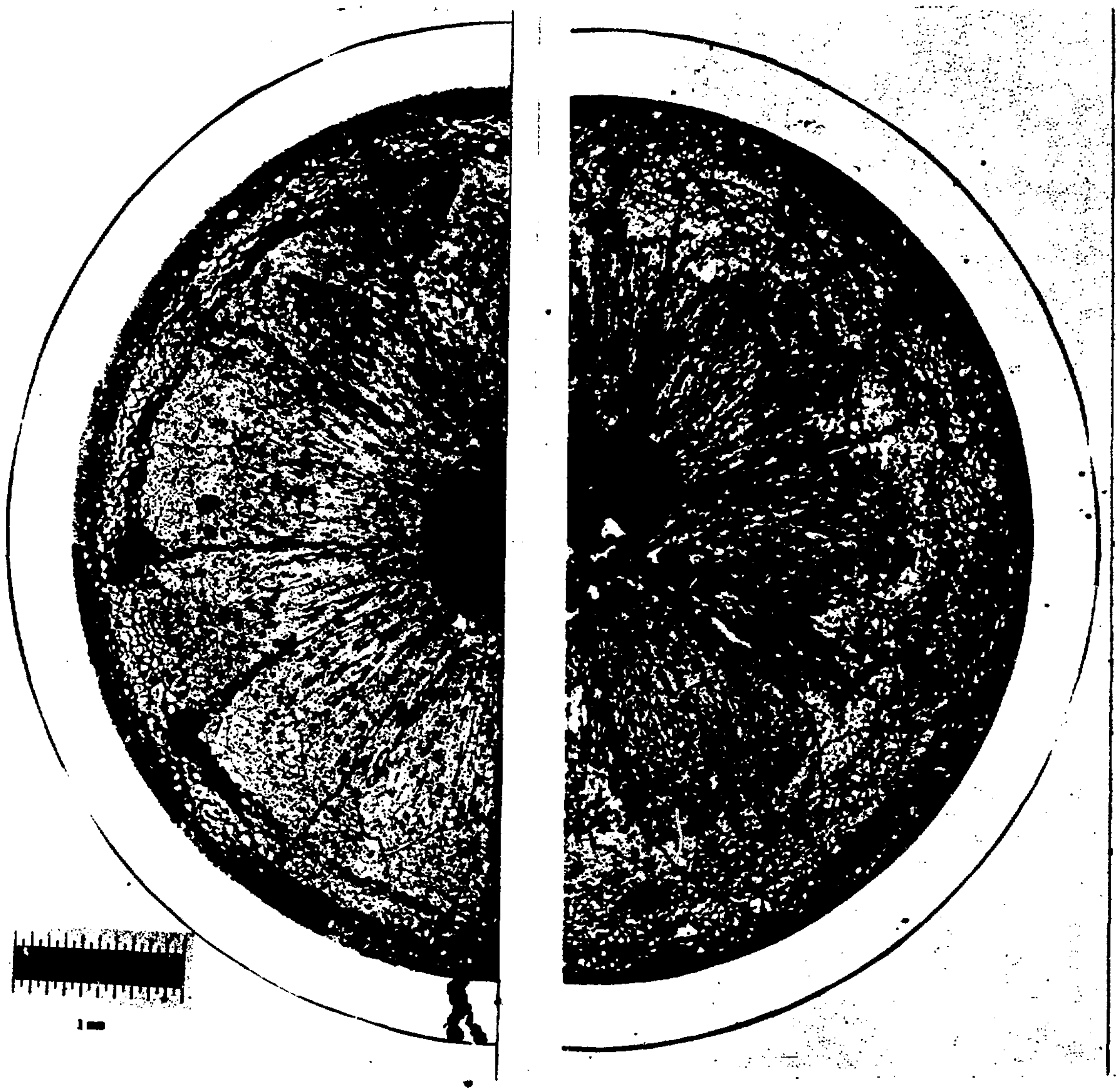
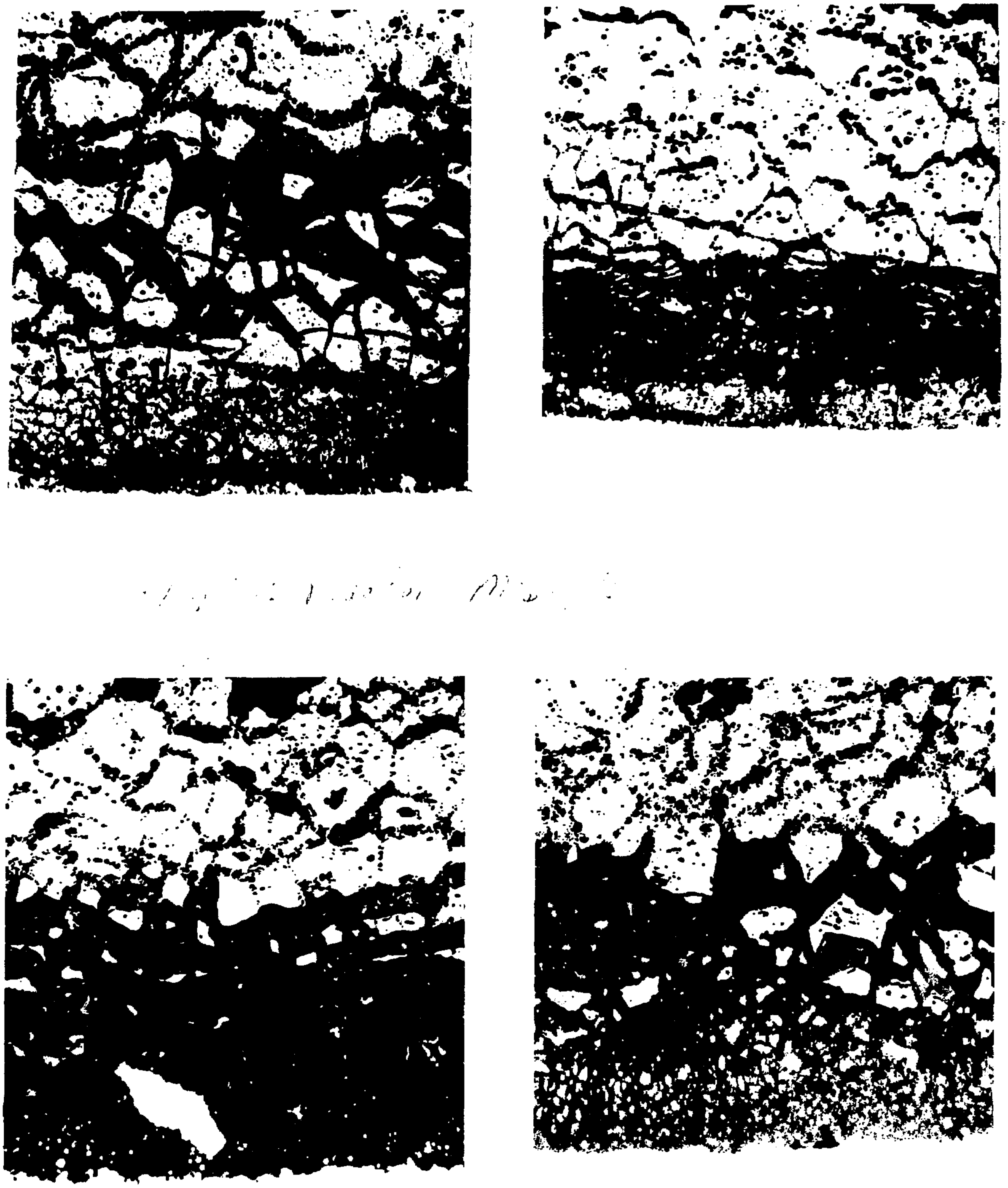


Figure 4. Mid-plane Cross-section of Unbreached Sibling Fuel Pins from the K2A and TOPI-2 Tests.



TOPI-2 K2A

Figure 5. Cross-sections from the K2A and TOPI-2 Test Pins Below the Primary Breach.



TOPI-2 K 2A

Figure 6. Reaction Product Zone at Selected Elevation of the K2A and TOPI-2 Test Pins.

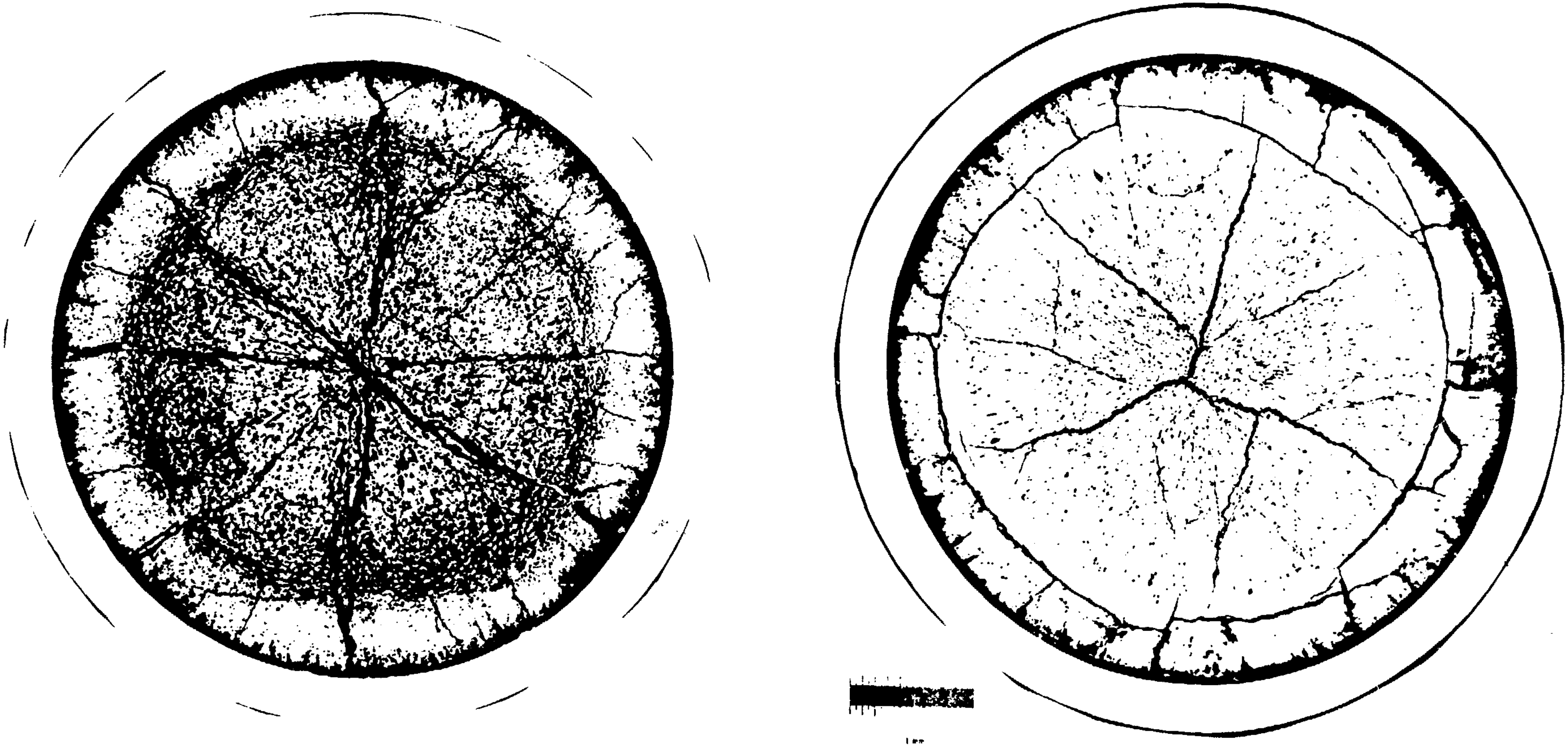


Figure 7. Comparison of TOPI-1A Test Pin P43-F104 (Left) and Its Steady-State Sibling (Right). Note the Formation of Microcracks at $X/L \simeq 0.7$ in P43-F104.

Figure 8. Void Fraction Distribution in TOPI-1A Pin P43-F104 vs. Its Steady-State Sibling. Note the Increase in Void Fraction in P43-F104 at X/L = 0.6-0.8 Due to Fuel Microcracking.

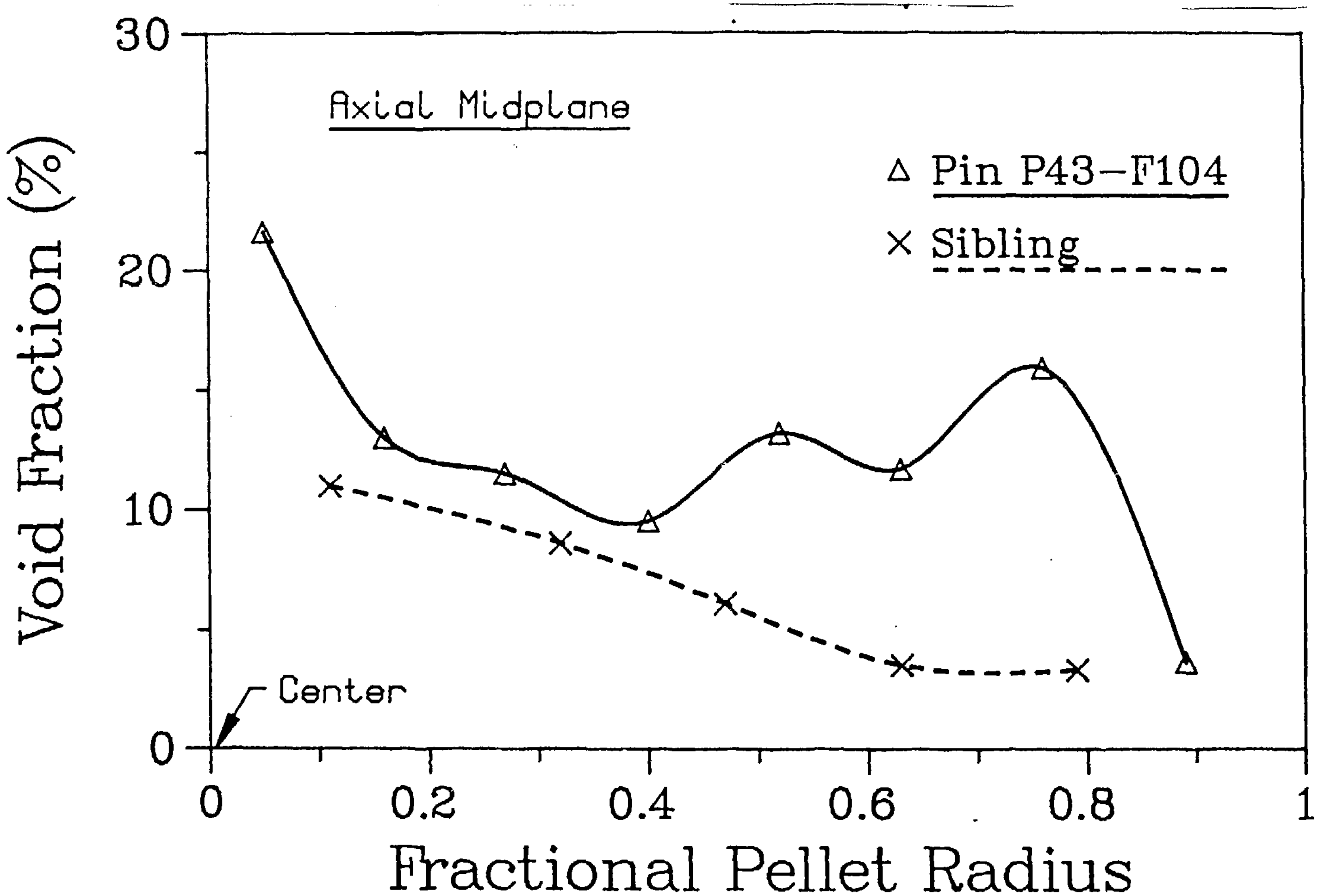


Figure 9. Profile of Incremental Strain Incurred in Pin P43-B15 During the TOPI-1B Transient.

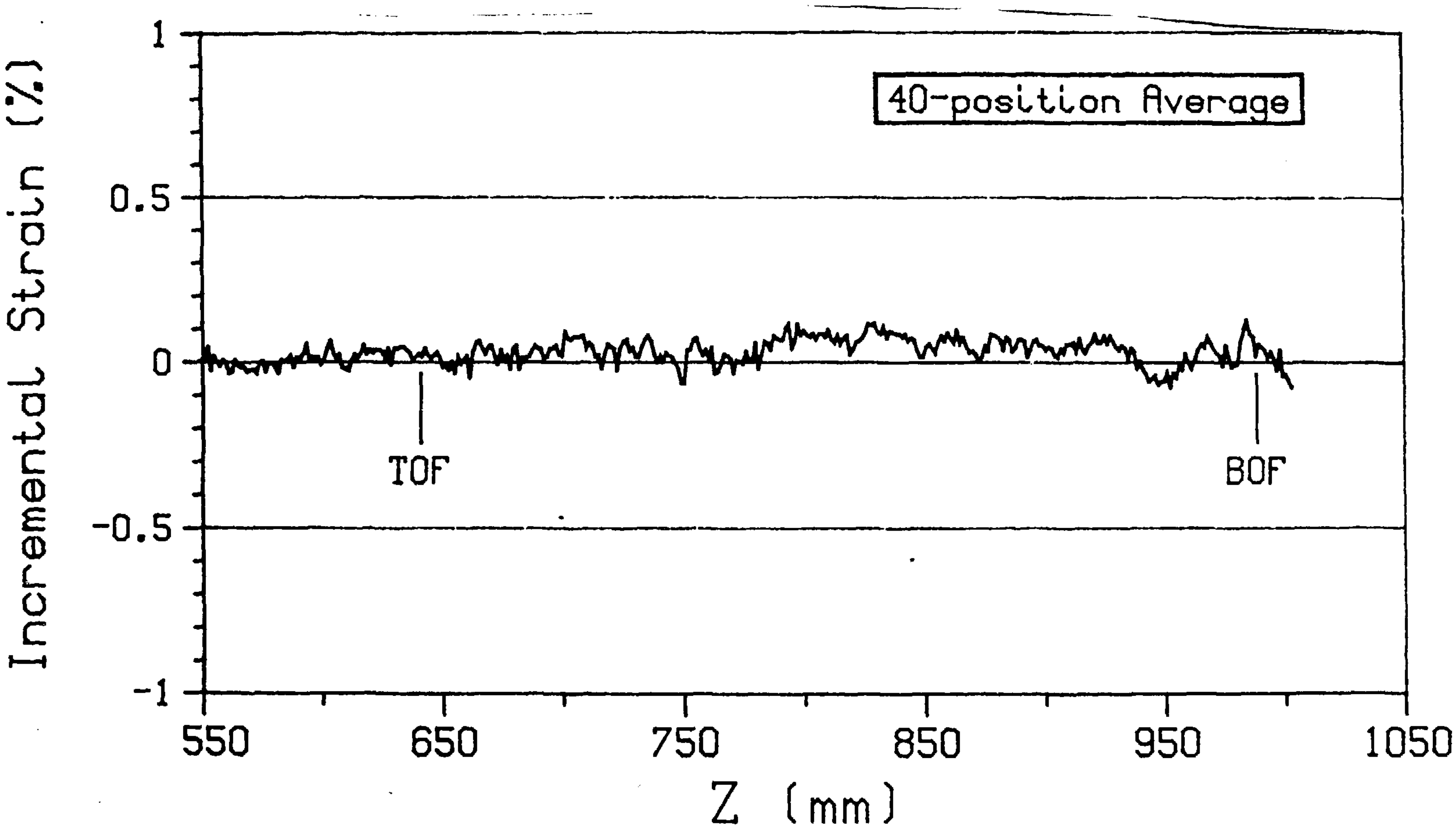


Figure 10. Profile of Incremental Strain Incurred in Pin P40-D103 During the TOPI-1B Transient.