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RELIABILITY OF FAST REACTOR MIXED-OXIDE FUEL DURING OPERATIONAL TRANSIENTS*

by

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Reliability of Fast Reactor Mixed-Oxide Fuel During Operational Transients *

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ABSTRACT

Results are presented from the cooperative DOE and PNC Phase I and II operational transient testing programs conducted in the EBR-II reactor. The program includes second (D9 and PNC 316 cladding) and third (FSM, AST and ODS cladding) generation mixed-oxide fuel pins. The irradiation tests include duty cycle operation and extended overpower tests. The results demonstrate the capability of second generation fuel pins to survive a wide range of duty cycle and extended overpower events.

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I. INTRODUCTION

Since October 1981, the United States Department of Energy (DOE) and the Power Reactor and Nuclear Fuel Development Corporation of Japan (PNC) have been conducting a cooperative program of operational transient testing of fast reactor mixed-oxide fuel in the EBR-II reactor.(1) The Phase I portion of this program was completed in 1990 and a Phase II effort, currently in progress, was initiated in September, 1987. The objective of this program is to determine the performance capability of reference and advanced mixed-oxide fuel pins during steady-state irradiation coupled with a range of operational and overpower transients which challenge the breaching thresholds of the pins. The fuel performance information is needed as input for reactor licensing, development of design criteria, calibration and validation of fuel pin performance codes (CEDAR and LIFE), and as a basis for making reactor operating decisions.

The completed Phase I program on mixed-oxide fuel pins with three cladding alloys (Type 316, D9 and PNC 316) is described in Table 1. A parallel program on oxide blanket rods is described in references 2 and 3 and will not be reviewed in this paper.

The Phase II program is described in Table 2. The purpose of this program is to extend the burnup of the Phase I pins to above 15% and to investigate advanced cladding materials and fuel pin designs for advanced liquid metal reactors.

— refs: superscript?

II. PHASE I DUTY CYCLE TESTS (2,4,5)

The results of the Phase I duty cycle tests (TOP series) were recently reported (5). The most significant accomplishments of these single pin tests include the following:

r- smaller solid dot.

- Demonstration of the capability of aggressively-designed mixed-oxide fuel pins (90% TD fuel smear density and peak time-averaged cladding temperatures of 650°C) to survive the duty cycle power histories shown in Figure 1. Peak burnup and fast fluence levels were 8% and 8 X 10^{22} n/cm^{2} (E>0.1Mev) respectively,

- Comparison of the irradiation behavior of PNC 316 and D9-C1P clad fuel pins revealed that the low swelling and high strength characteristics of PNC cladding are well suited for reactor application. In contrast, the low swelling and low strength characteristics of D9 cladding allow a more sensitive assessment of fuel behavior effects. Figure 2 shows a comparison of the cladding strain behavior of aggressive PNC and D9 clad fuel pins.

- Comparisons of the lifetime capability (based on CDF values) of individually shrouded TOP series fuel pins and wire-wrapped bundles of pins indicated the possibility that pin-pin and pin bundle-duct effects limit the burnup capability in wire-wrapped bundles.

Thirty-three of the Phase I TOP-series fuel pins were reconstituted into two new assemblies, TOP-4AAA and -4BBB, and returned to EBR-II for continued irradiation. The TOP-4AAA assembly was irradiated under steady-state conditions, whereas the TOP-4BBB assembly was exposed to steady-state plus periodic 15% overpower transients. The results of the Phase II burnup extension tests are described later in this paper.

III. TIGHT BUNDLE PERFORMANCE (6)

The objective of the TOB-10 test was to investigate the effects of pin-bundle interactions on fuel performance during steady-state plus periodic overpower transients by comparison of the behavior of 5.84 mm OD fuel pins in a tight 37-pin wire-wrapped bundle (TOB-10) with the behavior of identical pins in single pin tests (TOP-4B and -4BB). Table 3 provides a summary comparison of the TOB-10 and the single pin tests. In essentially all respects, the single pin operating conditions were calculated to be more severe than that of TOB-10. This is reflected by the peak cladding strain measurements. However, the depth of FCCI was greater for the D9-C1 clad TOB-10 pins (peak of 80 µm) than the similar TOP-4B (peak of 60 µm) pins suggesting that the thermal conditions in TOB-10 were more severe than calculated.

Figure 3 shows a cross-section of one of the two TOB-10 D9 cladding breaches. Careful consideration was given to the possible breach mechanisms that could account for the bulged cladding at the breach site, the extensive fuel-sodium reaction, and the near simultaneous release of fission gas and DN emitters for both of the TOB-10 breaches. These three characteristics could be explained by an FCMI-induced breach of the fuel pin cladding sufficiently large to allow rapid ingress of sodium. Such immediate fuel/sodium ingress would account for the near-simultaneous fission gas and DN signals. The fuel/sodium reaction may also account for the bulging of the cladding.

In summary, the results of the TOB-10 bundle test versus the single pin TOP-4B and 4BB tests are consistent with a previously reported conclusion (5) that pins in bundles behave differently than pins irradiated individually. However, the current uncertainty in TOB-10 operating conditions, reflected, on the one hand, by the cladding strain data indicating peak cladding temperatures of ~630°C and the FCCI data, on the other hand, indicating higher peak cladding temperatures (>700°C), limits quantitative assessment of the TOB-10 breaches. The high FCCI may be related to the periodic overpower events.

IV. EXTENDED OVERPOWER TRANSIENTS (7,8,9,10)

The results of the first three extended overpower tests, TOPI-1A, -1B and -1C, have been reported in detail (7,8,9). The main findings are shown in Figures 4 and 5. Figure 4 shows the conditions of the three tests and a 1981 conservative LIFE code prediction of overpower capability versus ramp rate. Based on the observation of two breached pins in the TOPI-1C tests, with the initial breach occurring at ~75% overpower, an experimental margin-to-failure line is shown on Figure 4. The 1981 LIFE code calculations (1) were made using a transient cladding failure correlation incorporating fuel-adjacency effects (12). However, PNC has demonstrated that fuel-adjacency effects are related to embrittlement and stress-corrosion cracking of the cladding in the hot cell due to reaction between uncontrolled moisture in the cell atmosphere and fission product Cs on the cladding surface (13). These early predictions, therefore, tended to underestimate the overpower capability of the pins, as shown by the experimental results,

Figure 5 shows some of the incremental cladding strain data derived from the TOPI-1B and -1C tests. Fuel pins with thin cladding, high smear density and high burnup exhibited the greatest incremental strains. The transient induced cladding strains are associated with differential thermal expansion and possibly fuel swelling.

The extended overpower transient tests demonstrated a substantial margin of overpower capability at low ramp rates relative to typical reactor trip settings. Furthermore, the tests showed that the behavior of the breached pins was benign, i.e., with minimal fuel loss and no apparent deleterious effects on neighboring pins.

Preliminary results of the TOPI-1D test were recently reported (10). This transient overpower test was performed at a ramp rate of 0.1%/s to 100% overpower on fuel pins irradiated in the Phase I duty cycle tests. The most interesting results obtained are shown in Figure 6. The peak incremental strains (in the axial region

0.8<X/L<1.0) increase with increasing transient overpower, independent of the pre-transient strains.

V. TRANSIENT OVERPOWER TEST OF A BREACHED PIN (8)

The purpose of the TOPI-2 test was to determine the effects of a 15% overpower transient on a breached mixed-oxide fuel pin emitting delayed neutrons (DNs). Tests in EBR-II have shown that pins can be operated in the breached condition for long periods (>100 days) with little or no fuel loss or other adverse consequences (14). Accordingly, the TOPI-2 test was designed to determine the behavior of a breached pin during an overpower transient including effects on breach size, fission product and fuel release and the possibility of breach propagation. The TOPI-2 pins were 5.84mm in diameter and made with 20% cold-worked D9 cladding.

The test pin (AKB-22) ~~in~~ for the TOPI-2 test was initially electro-discharge machined to produce a thinned region of cladding (0.11 mm thick) covering an area 6.4 mm X 1.5 mm about 13 mm from the top of the fuel pin. After 5% burnup in the K2A test, the AKB-22 pin had a pinhole in the pre-thinned region.

The TOPI-2 test consisted of 18 environmental pins and the AKB-22 pin. The six adjacent pins had not been previously irradiated. The TOPI-2 peak operating conditions at steady-state were 32 kW/m with a cladding temperature of 627 °C. At 15% overpower, the peak cladding temperature increased to 670°C.

At the start of the TOPI-2 irradiation, fission gas release was detected from the test. Irradiation continued for 16 days without a DN signal. A 15% overpower transient was conducted to induce a DN signal. The desired effect was achieved with DN counts near 200 cps over the period 20 to 65 hours after the transient. At this time, the second 15% overpower transient was initiated. Figure 7 shows the results obtained during the second transient.

Nondestructive examination of the AKB-22 pin revealed a small crack (20mm long and 0.9mm at the widest point) at the thinned region. A second crack (17mm long and 0.3mm wide), 120° away was centered 13mm below the primary crack and a third crack, just below the second crack, 105° from the primary crack, was 16mm X 0.2mm.

Detailed comparisons of the visual appearance, gamma scan and profilometry data for the AKB-22 pin and sibling breached pins not exposed to an overpower transient, indicated that a breached pin can be subjected to at 15% overpower transient without severe degradation of the breach or general condition of the pin.

VI. PHASE II BURNUP EXTENSION TESTS

The extended burnup of the Phase I 7.0mm OD mixed-oxide fuel pins with D9 and PNC 316 cladding has been completed. The D9-clad pins were irradiated to a peak burnup and fast fluence of 13% and 12.9X10^{22} n/cm^2, respectively. Two D9-clad pins breached, one at 10.8% burnup and the other at 12.2% burnup. The PNC 316-clad pins were irradiated to 17% burnup and a fast fluence of 17X10^{22} n/cm^2 without cladding breach.

The currently available data for the Phase II burnup extension tests are summarized in Figure 8 and Table 4. Significant differences in behavior of the ~~two~~ D9 and PNC 316 claddings are evident at high burnup. The average cladding strain rate for PNC 316-clad fuel pins is 40% of that for the D9-clad pins. Based on the successful irradiation of the PNC 316-clad pins to 17% burnup and the available cladding strain data, it appears that the aggressive PNC 316-clad pins could achieve EBR-II burnups above 20%.

Table 4 provides additional information regarding the burnup extension tests. The D9 cladding breaches at 10.8% and 12.2% burnup are consistent in that ~~with~~ the lower burnup breach occur~~ring~~ed in the pin with the higher Phase II SOL cladding temperature. Figure 9 shows the cladding strain profiles for an aggressive D9 clad pin (WT186) from the TOP-4BBB assembly at 7 and 10.8% burnup. The breach location for a sibling pin (WT185) and the location of a peak in the Cs profile are also shown on Figure 9. The local cladding strain peaks are related to pellet/pellet interfaces, with valleys at the interfaces in the top portion of the pin.

Preliminary analyses of the breaches indicate that the CDF values were above 1.0. This result provides additional support for the conclusion that single pin tests exhibit higher burnup capability than pin bundle tests.

VII. ADVANCED CLADDING MATERIALS

The Phase II program includes the fabrication and irradiation testing of a new series of (7.5mm OD X 0.4mm wall) mixed-oxide fuel

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(INSERT)

pins with PNC advanced cladding alloys. The alloys include a ferritic martensitic (FMS) alloy, a 20% Ni austenitic stainless steel (AST) and an oxide dispersion-strengthened (ODS) ferritic stainless steel (15). Fuel pins with FMS and AST cladding have been under irradiation for about two years and are currently at 8% burnup and $7X10^{22}$ n/cm^2 (E>0.1Mev). The ODS clad fuel pins will start irradiation later this year.

The fuel pins with advanced cladding alloys are being irradiated in two 19-pin assemblies as single pin tests (referred to as SPA-1 and -2, Source Pin Assemblies). The fuel pin design and operating variables include:

a little smaller.

- Annular and solid pellets,
- Peak cladding temperature of 650 °C except for FMS at 620 °C,
- Peak power ratings of 36 and 46 kW/m, and
- Homogeneous and several axially heterogeneous fuel pins.

The FMS and AST fuel pins at 5% burnup (SPA-1A) are available for an extended overpower transient (TOPI-1E) and ~~whole pin furnace~~ in-cell transient ~~WPFT~~ overheating tests. Upon completion of the "steady-state" irradiation program, FMS and AST pins will be available at 5, 10 and 15% burnup and ODS pins will be at 10% burnup. Additional extended overpower (TOPI-1F and -1G) and ~~[illegible]~~ ToH tests will be carried out on these pins.

VIII. SUMMARY AND CONCLUSIONS

The cooperative DOE and PNC Phase I and II operational transient testing programs have provided an extensive data base on the behavior of mixed-oxide fuel pins with second generation (D9 and PNC 316) LMR cladding materials. Testing is in progress to develop a similar data base for third generation (FMS, AST and ODS) cladding alloys. The major accomplishments of the program include the following:

- Demonstrated mixed oxide fuel capability to survive a wide range of duty cycle power histories,
- Showed the excellent behavior of PNC 316 cladding for high burnup reactor applications,
- Demonstrated the higher burnup capability of individually tested fuel pins compared to bundles of fuel pins,
- Showed that LMR fuel pins have a substantial margin of overpower capability at low ramp rates relative to typical reactor trip settings, and
- Demonstrated that a breached pin can be subjected to a 15% overpower transient without severe degradation.

IX. ACKNOWLEDGEMENTS

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Table 1
Summary of Completed Phase I Program (1) *

Test Designation	Test Type	Description	References
TOP-4A,-4AA	38 Single Pins	Steady-state tests to 8% burn-up	2,4,5
TOP-4B, -4BB	38 Single Pins	Steady-state plus periodic 15% transient overpower to 8% burnup	2,4,5
TOP-7	19 Single Pins	Alternating irradiation cycles at 100 and 60% power to 8.5% burnup	2,4,5
TOB-10	37 Pin Bundle	Tight bundle at steady-state plus periodic 15% overpower. Cladding breaches terminated the test at 7.5% burnup.	6
TOPI -1(A,B,C) -1D	3-19 Pin Bundles 19 Single Pins	Extended transient overpower tests at ramp rates of 0.1 and 10%/s to peak overpower levels of 100%.	7,8,9,10
TOPI-2	19 Pin Bundle	A 15% overpower test ~~including~~ on a breached pin exhibiting a DN signal.	8

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* References 2 and 3 describe the parallel oxide blanket program.

Table 2
Description of Phase II Program

Test Designation	Test Type	Description
TOP-4AAA	19 Single Pins	Extend steady-state irradiation of Phase I pins. Peak burnup of 17% achieved.
TOP-4BBB	19 Single Pins	Extend steady-state plus periodic 15% transient overpower irradiation of Phase I pins. Peak burnup of 17% including two overpower transients achieved.
SPA-1, -2	38 Single Pins	Steady-state irradiation to 5,10 and 15% burnup of fuel pins with advanced cladding alloys.
TOPI-1(E,F,G)	57 Single Pins	Extended transient overpower tests at ramp rates of 0.1 and 10%/s to peak overpower levels of 100%.
~~WPF~~ TOH	10 Whole Pin Furnace Tests	Hot cell experiments to determine pin behavior during transient overheating. ~~experiments~~.

Table 3
Comparison of the TOB-10 (37 Pin Bundle) and the TOP-4B and -BB (Single Pin) Tests

a. Operating Conditions

	TOB-10	TOP-4B and -4BB
Peak SOL Power, kW/m	37.4	37.8
Peak SOL Clad ~~MWT~~ Midwall Temp., °C	625	650
Peak Burnup, %	7.9	9.5
Peak Fast Fluence, 10^{22} n/cm^2	5.5	6.5
Peak Overpower, %	31	30
No. of Overpower Events	5	6,7
Cladding Breaches	2 in D9 2 in D9	----

b. Cladding Strain

	TOB-10		TOP-4B and -4BB	
Pin Type*	Number of Pins	Peak Strain, % (X/L)	Number of Pins	Peak Strain, % (X/L)
D9,A	0	--	3	0.8 (0.9)
D9,M	19	0.3 (0.9)	2	0.8 (0.9)
316,M	9	1.0 (0.6)	5	1.1 (0.6)
316,C	8	0.4 (0.6)	4	0.8 (0.6)

c. Fuel Cladding Chemical Interaction (D9-C1) Cladding

	TOB-10	TOP-4B
No. of Pins Examined	2	1
Maximum Depth of FCCI, µm	80	60

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*A refers to aggressive pin designs, M to moderate and C to conservative.

Clean up the [illegible], Make bottom lines all same level.

Table 4
Phase II Burnup Extension Tests

Phase I Assembly	Phase II Assembly	Pin Type	Phase I/II SOL Clad Mid-Wall T, C	Phase I Burnup, %	Phase I Fast Fluence, 10^{12} n/cm	Phase I Clad Strain, %	Phase II Burnup, %	Phase II Fast Fluence, 10^{22} n/cm	Phase II Clad Strain, %	Average Cladding Strain Rate % / %Burnup
A,AA	4AAA	D9,A	665/650	7.0	6.1	1.7	12.2	10.8	Breach	>0.6
		D9,M	640/615	7.9	6.9	0.7	12.8	11.4	2.4	0.3
		PNC,A	665/650	7.4	6.4	0.5	12.5	11.0	2.1	0.3
B,BB	4BBB*	D9,A	650/670	7.1	6.0	0.5	10.8	9.5	4.5,Breach	1.1
		PNC,A	650/670	7.3	6.1	0.4	12.5	11.5	2.0	0.3
7	4AAA	D9,A	645/640	8.4	8.0	1.0	13.0	12.9	3.8	0.6
	4BBB*	D9,M	645/640	8.5	7.9	2.0	12.7	12.4	4.4	0.6
	4BBB*	D9,A	645/640	8.4	8.0	0.4	12.5	12.4	1.6	0.3

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*During ~10,000 hours of Phase II irradiation, two 15% overpower transients were conducted.

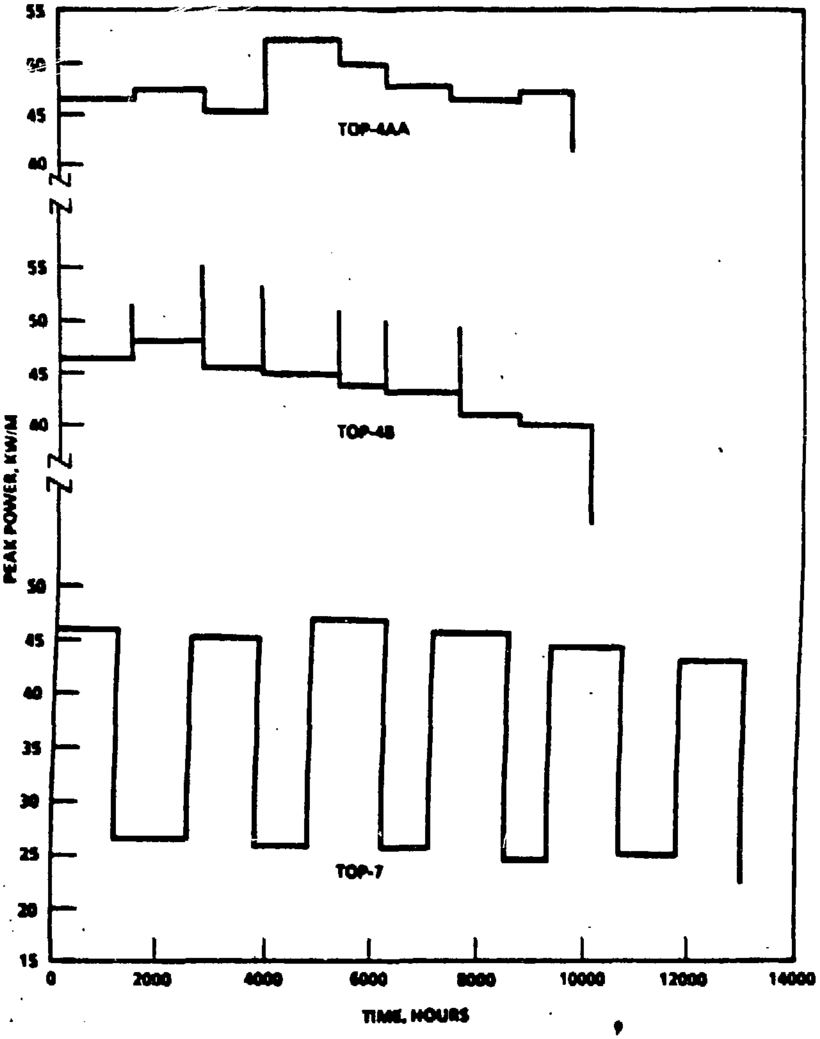

Fig. 1. Power Histories for Aggressive TOP Fuel Pins.

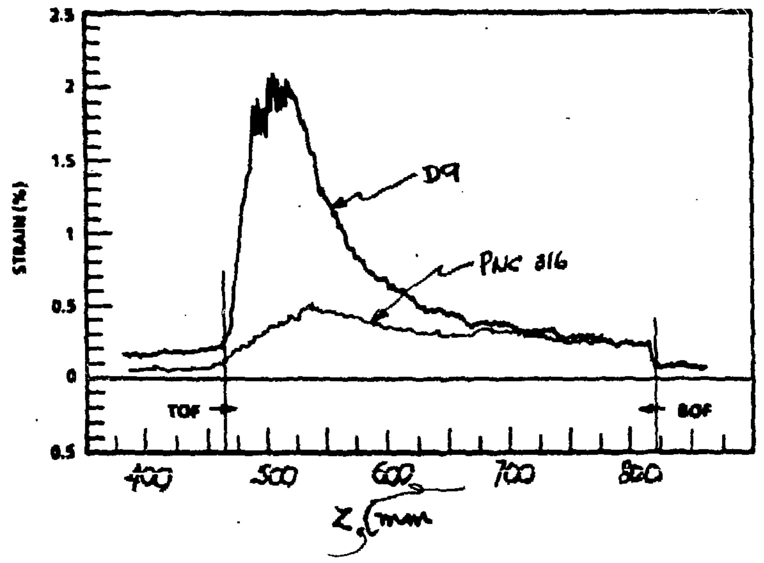

Figure 2 Linear Profilometry For Aggressive TOP-4A Fuel Pins (7.3% Burnup, 6.4×10^{22} n/cm^2)

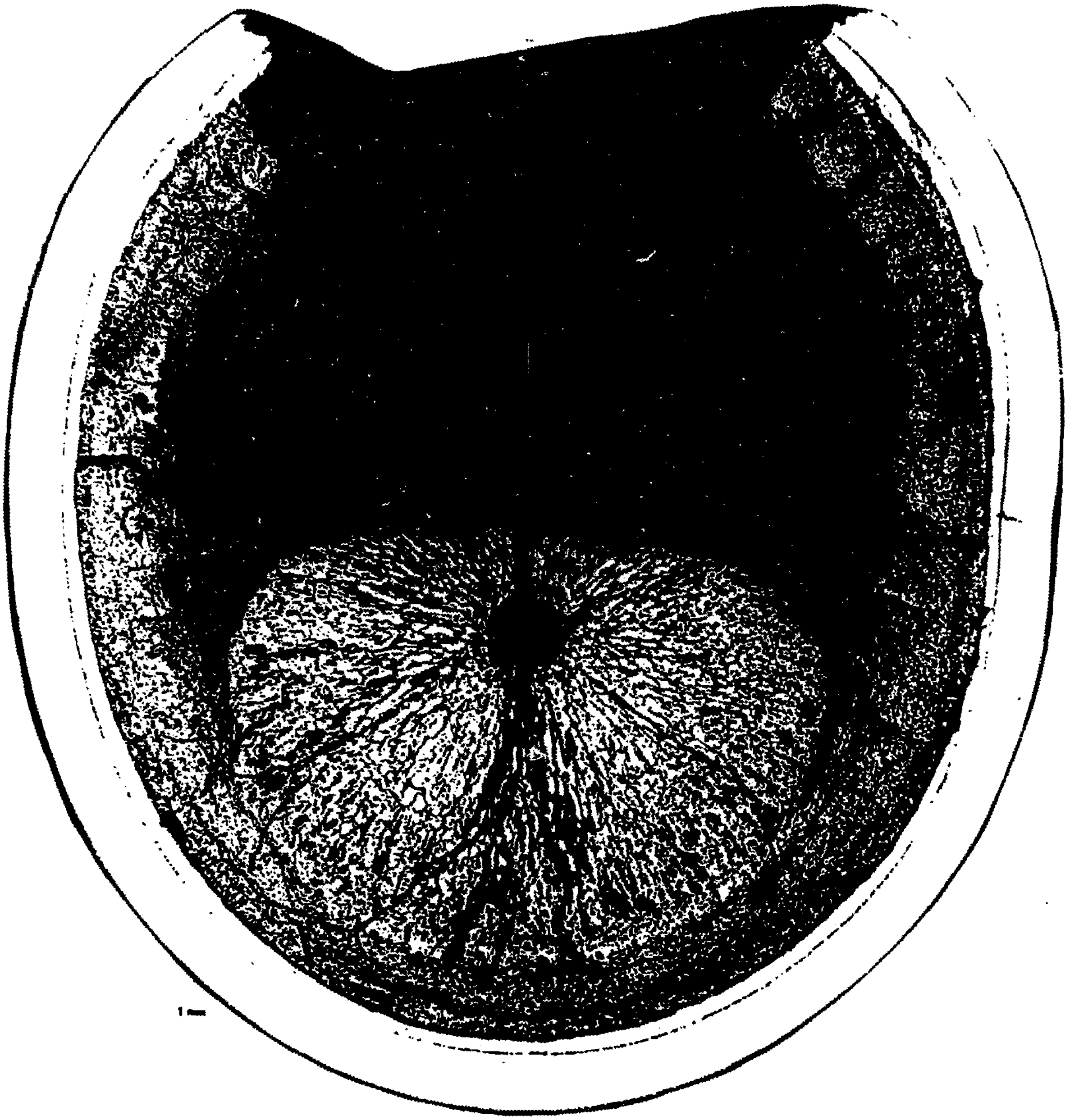

Figure 3 Breached TOB-10 Pin (D9 Cladding) at 7.6% Burnup

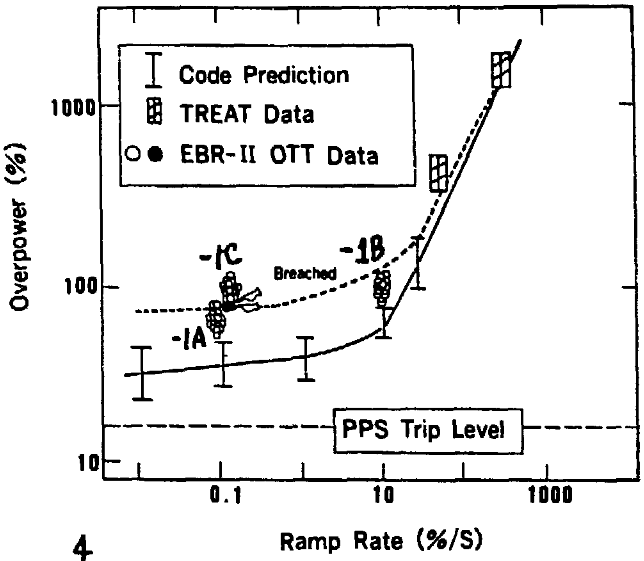

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Fig.7 Margins to failure demonstrated by ^extended overpower transient tests(TOPI-1A,-1B and -1C)

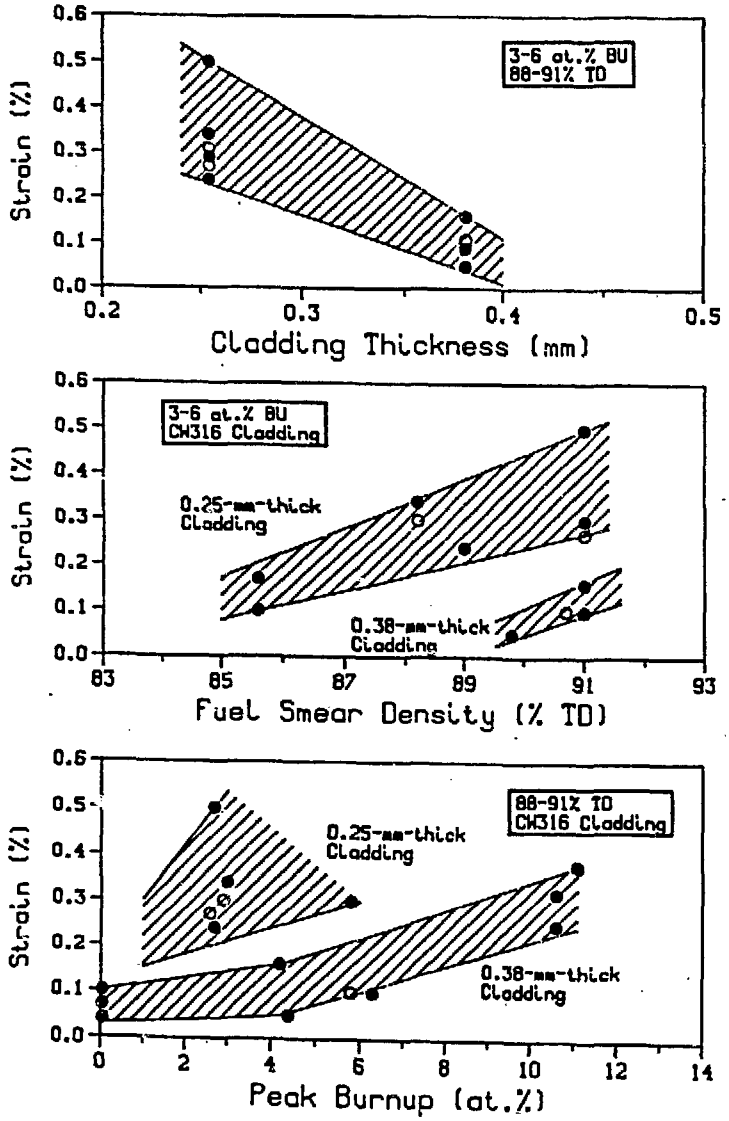


Fig. ~~4.~~ 5 Correlations between the cladding incremental strain and pin parameters.
o = 1B test
• = 1C test

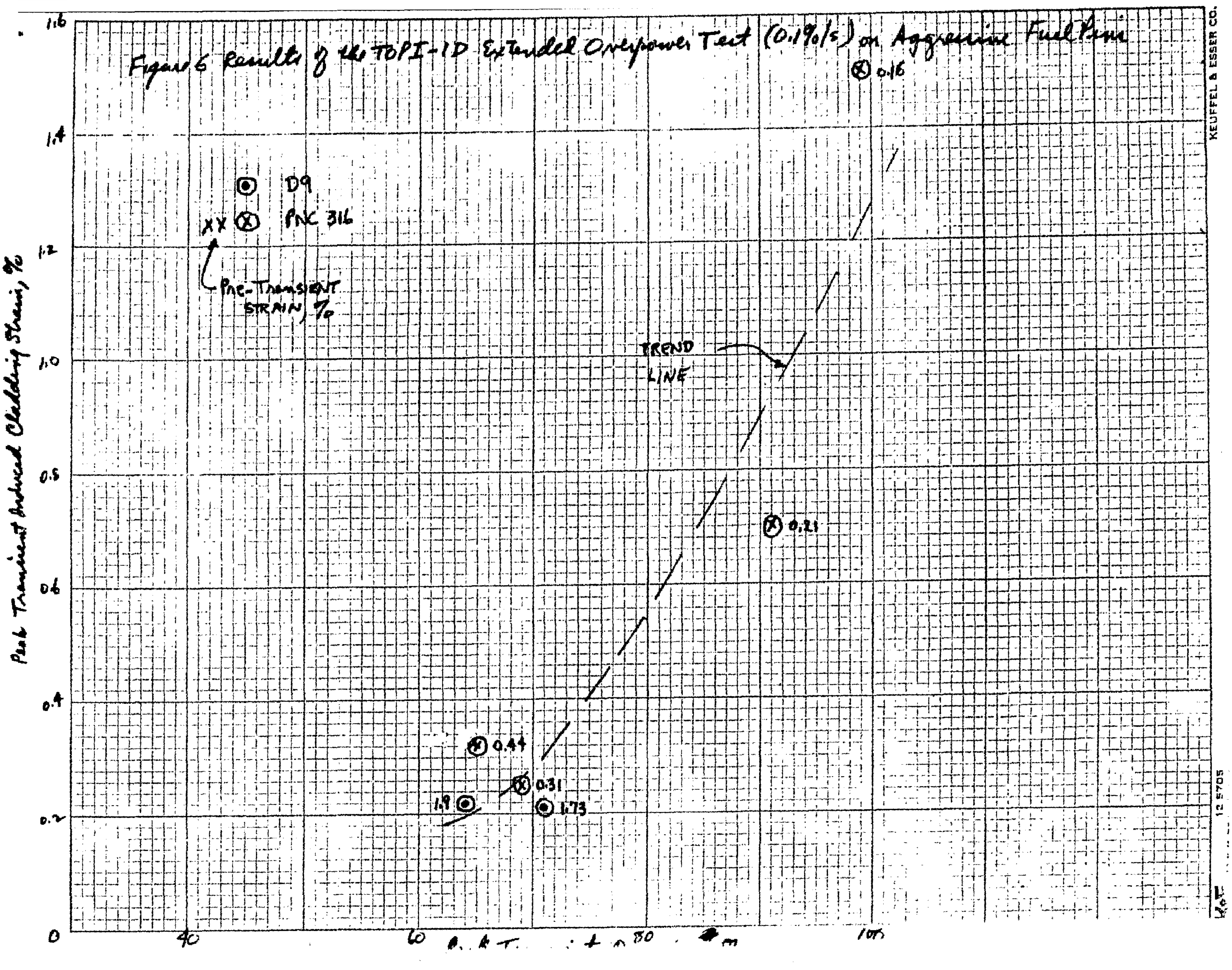
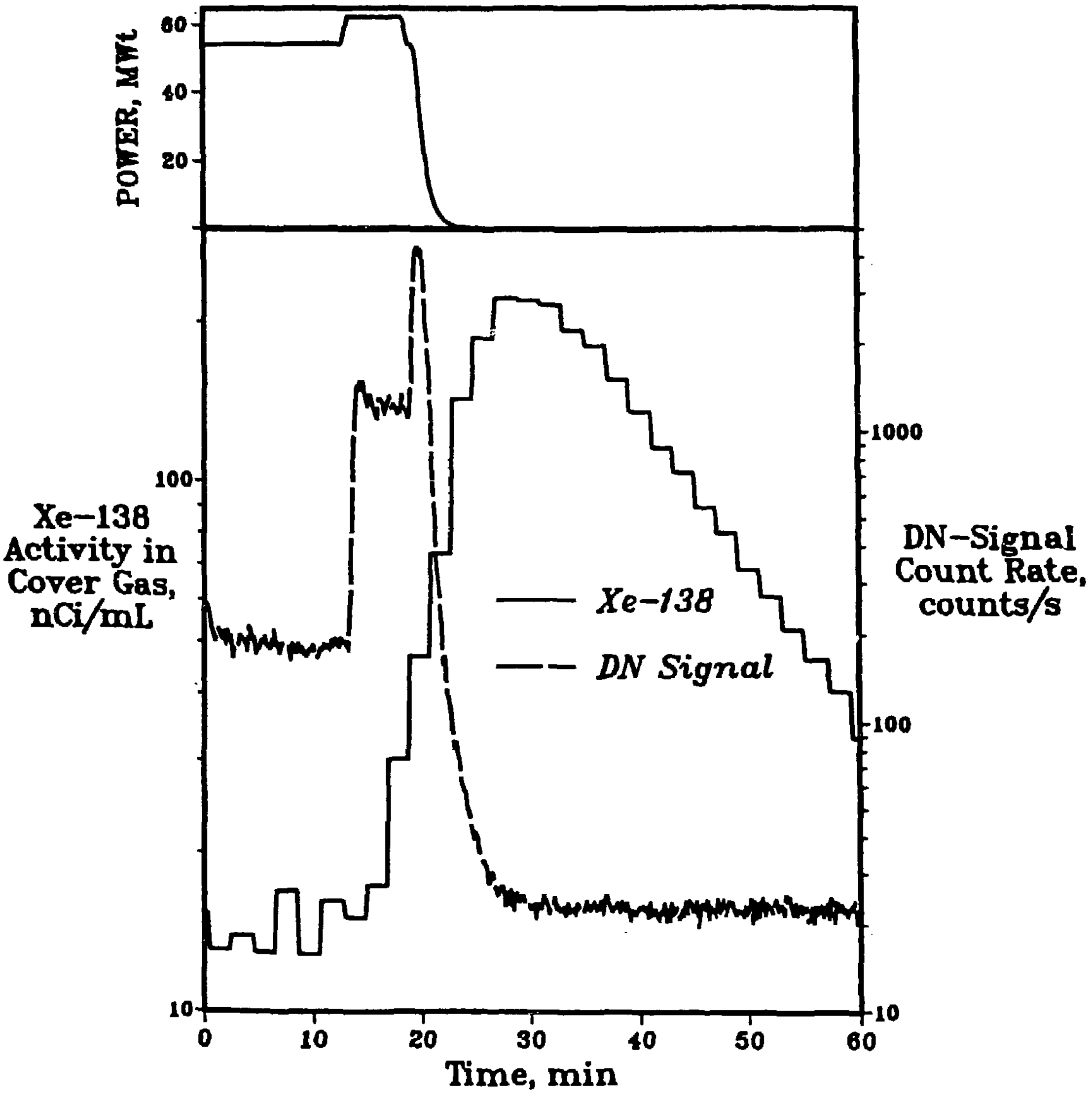


Figure 6 Results of the TOPI-1D Extended Overpower Test (0.1%/s) on Aggressive Fuel Pins

Fig. ~~10~~ 7. Power and Fission Product Release Data During the Second Transient and the Reactor Shutdown



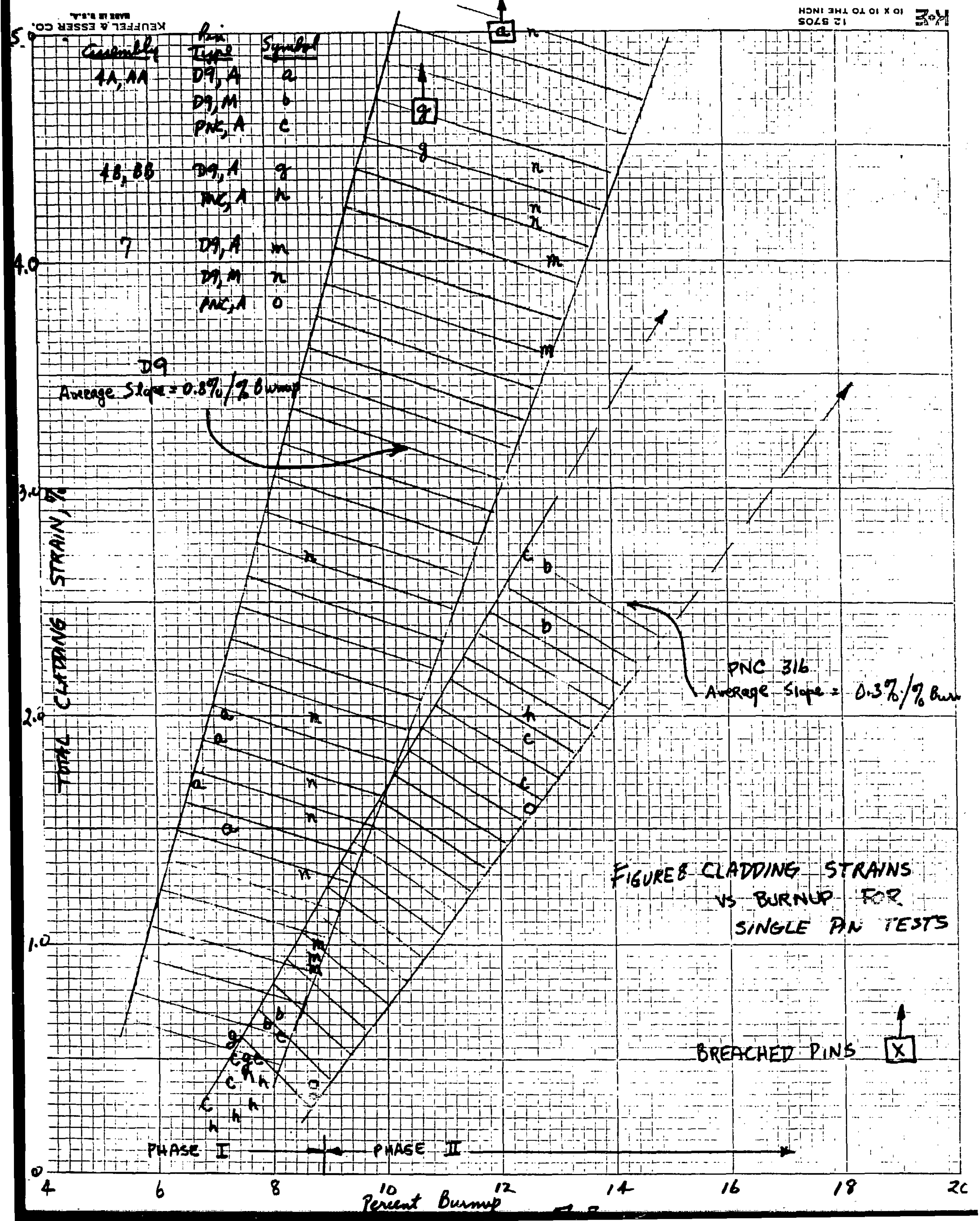


FIGURE 8 CLADDING STRAINS VS BURNUP FOR SINGLE PIN TESTS

Figure 9 Linear Profilometry for a Phase II High Burnup Pin ~~TOP 4BBB Pin~~ (WT-186)