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BREACHED PIN PERFORMANCE IN REFERENCE DESIGN FUEL PINS

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All of the 19 Hanford Engineering Development Laboratory (HEDL) mixed oxide (75% UO_2, 25% PuO_2) FFTF reference design experiments[1] in EBR-II have now been completed. Many of the experiments were deliberately irradiated to high burnup in order to determine failure mechanisms and cladding breaches occurred in 20 of the 1156 stainless steel clad pins irradiated in these subassemblies. The results from the examinations of 12 of these pins were reported previously.[2,3,4] The examinations of the four most recent breached pins are the subject of this paper. The most recent estimates of operating conditions for all 16 of these pins are given in the meeting transactions and in Table I. Four additional breached pins were designated for the Run-Beyond-Cladding-Breach program.[5]

The cladding breaches have, in general, been attributed to two causes: wear and local cladding hot spots (Figure 1). Two cladding breaches early in the irradiation program were attributed to wear (Figure 2) but no additional wear-related breaches have occurred in the more recent tests. The occurrence of serious cladding/wire wrap wear has been eliminated by reducing bundle clearance. Local cladding hot spots continue to be the major cause of breach. The mechanism of hot spot formation has not been determined but may be related to the displacement of pins during reconstitution of subassemblies. The four most recent breaches all occurred at the upper quarter of the fuel column (Figure 3) and all attained a burnup in excess of 10 atom percent. Three of the four (P-14-29, P-23B-31B, P-23C-12A) experienced a significant local cladding overtemperature, evidenced from metallographic examination. The fourth pin (P-23C-7A) appears to have experienced a slight overtemperature which may have shortened its life relative to its siblings.

P-14-29

The P-14-II subassembly consisted of 37 fuel pins (Figure 4) clad with 20% CW type 316 SS from an FFTF Core 1 heat. These fuel pins were previously irradiated to a burnup of 85 MWd/kgM in the 61 pin subassembly P-14. P-14-II was removed from EBR-II as a fission gas leaker after attaining a peak burnup of 104 MWd/kgM and a peak fluence of 8×10^{22} n/cm^2 (E > 0.1 MeV) and pin P-14-29 was identified as the breached pin.

Pressurization of P-14-29 with helium in an alcohol bath revealed a microscopic crack at 330 mm (13.0 in.) from the bottom of the fuel column. A partial crack that extended several mils into the cladding from the outer surface, was observed during metallographic examination at that location. The crack persisted for an axial distance of 2.7 mm (0.109 in.). Creep voidage and some secondary crack formation were observed at the lower extremity of this same region. The through-crack observed during this examination was the tortuous connection to the inner cladding surface shown in Figure 5. The sibling fuel pin, P-14-44, was not located immediately adjacent to the breach site in P-14-29 and its examination demonstrated no evidence to suggest impending failure. Full length photography of other nearby fuel pins revealed no evidence of failure propagation or distorted wire wraps.

The cladding immediately adjacent to the breach in P-14-29 (an arc of ∿120 degrees) showed, when chemically etched, a microstructure indicative of a local cladding hot spot (Figure 6). Numerous large intermetallic precipitates were observed on grain boundaries. The breach crack had propagated along grain boundaries, which were depleted of smaller carbide precipitates, and along sigma precipitate-matrix interfaces. In areas where creep voidage could be observed, each void was generally adjacent to a large intermetallic precipitate, which suggests void nucleation at the precipitate--matrix interface.

Whether this cladding overtemperature was confined solely to P-14-29 is not clear at this time. Neither the center pin nor any pins from the innermost row, other than the breached pin, have yet been destructively examined. Further examinations of fuel pins are planned in order to characterize the temperatures throughout the P-14-II subassembly.

<u>P-23B-31B</u>

HEDL high cladding temperature experiment P-23B (Figure 4) sustained a cladding breach after attaining a peak burnup of 109 MWd/kgM and a peak fluence of 9.9×10^{22} n/cm^2, E > 0.1 MeV. Fuel pin P-23B-31B was identified as a leaker suspect because of a significant weight loss (0.60 gram).

The breach location in P-23B-31B was determined by pressurization of the pin with helium gas in a water bath. The pinhole crack was located at 327 mm (12.9 in.) from the bottom of the fuel column and in an orientation close to that of the fuel pin wire wrap (Figure 7). Metallographic examination demonstrated a single intergranular crack (Figure 8). The crack was open at the outer cladding surface with only a short tenuous connection to the cladding inner surface. A few secondary cracks were seen. The axial extent of cracking was approximately 1 mm. Etched metallography revealed a localized concentration of intermetallic sigma phase near the breach site. A similar concentration of intermetallic sigma phase was also apparent in a metallographic section 25 mm (1 in.) below the breach and in the same angular orientation as the breach. Such a concentration of intermetallic phase is again indicative of a localized cladding hot spot. No intermetallic second phase was seen anywhere else in the fuel pin cladding. The cladding local overtemperature was estimated to be approximately 50°C above the calculated midwall temperature of 671°C.

P-23C-12A

The 37 pin, high cladding temperature test, P-23C (Figure 4) was removed from EBR-II after being identified as the source of leaking fission gas and a delayed neutron signal. This subassembly had reached a peak burnup of 132 MWd/kgM and a peak fluence of 12.0×10^{22} n/cm^2 (E > 0.1 MeV). P-23C-12A (a corner pin) was identified as the probable leaker and was subsequently found to contain an 11.3 mm (0.4 in.) long crack at an orientation that faces the duct wall. The unusually large axial extent of the crack (Figure 9) and a large diameter change at the breach site are a direct result of post-breach operation of P-23C for ∿2 days. The crack faced an insulated duct wall and the wire wrap was positioned 180° opposite from the breach site. Metallographic examination demonstrated a single large open crack (Figure 10). No creep voidage and very little secondary cracking were noted. Fuel cracks contained a second phase material which is sodium or sodium fuel reaction product.

The chemically etched cladding near the breach site showed a different cladding structure than the remaining cladding at the same axial locations. Large intermetallic precipitates were not found at any location but the normally fine carbide distribution appeared to have coarsened significantly near the breach crack (Figure 11). Based on out-of-reactor annealing studies, a local cladding temperature of 650°C (vs. 525 expected) can be assigned to the breach site for this interim irradiation period of 3000 equivalent full power hours. The possibility of an even hotter, short-lived hot spot cannot be ruled out however.

P-23C-7A

Fuel pin P-23C-7A, in an interior location (Figure 4), with the same irradiation history as P-23C-12A, is believed to have breached two days after the P-23C-12A breach discussed above. The two breached pins were not adjacent to one another and the two cladding breaches were apparently unrelated. A pinhole breach was subsequently identified at the top of the fuel column. The breach is shown in Figure 12 and its position corresponded to a small local strain peak at the top of the fuel column (Figure 13). Only small amounts of secondary cracking and creep voidage were observed. Fuel-Cladding Chemical Interaction (FCCI) was slightly greater in the region of the breach crack. The cladding microstructure near and removed from the crack was comparable except for a small number (< 0.7% area fraction) of intermetallic precipitates at the breach site. The interim irradiation period of this experiment lasted 3000 hours and the onset of sigma phase precipitation would imply an average cladding midwall temperature of 656°C which is only slightly higher than the expected 631°C. Sibling pins have not yet been examined but spacer wires of the breached pin and neighbors appear to be in position to prevent pin-to-pin contact. If the small number of observed intermetallic precipitates is a true indicator of slight local overtemperature (and not a stress induced precipitation phenomenon), then the breach of P-23C-7A may have been somewhat premature relative to a true end-of-life failure.

A number of hot spot related breaches have thus been observed in the Run-to-Cladding-Breach Program. They have primarily occurred near the top (i.e., hottest end) of the fuel column and have been associated with cladding areas which contain creep voids and intermetallic precipitation. All of them have occurred in reconstituted subassemblies. The breaches have had no catastrophic effects on reactor operation, have had no tendency to propagate to neighboring pins and have demonstrated no circumferential crack extension. More severe hot spot temperatures (700-800°C) have been associated with cladding breach in fuel pins with low burnup and low plenum pressures while less severe temperatures (650°C) are associated with cladding breach for high burnups (> 11 atom percent) fuel pins.

REFERENCES

1. D. A. Cantley, et al, "HEDL Steady State Irradiation Testing Program," HEDL-TME-75-48, (1975).

2. J. W. Weber, M. Y. Almassy, and R. A. Karnesky, "HEDL Mixed Oxide Fuel Pin Breach Experience in EBR-II," International Conference on Fast Breeder Reactor Fuel Performance, 87 (1979).

3. J. W. Weber, M. Y. Almassy, "Cladding Breaches in Mixed-Oxide Fuel Pins," Trans. American Nuclear Society, 27, 227 (1975).

4. D. F. Washburn, "Mode of Failure of LMFBR Fuel Pins," Trans. American Nuclear Society, 21, 189 (1975).

5. D. F. Washburn, et al, "Mixed-Oxide Run-Beyond-Cladding-Breach Tests In EBR-II," International Conference on Fast Breeder Reactor Fuel Performance, 100 (1979).

6. J. W. Hales, "Second Phase Precipitation in Irradiated Type 316 Stainless Steel Cladding," Trans. American Nuclear Society, 28, 153 (1978).

TABLE I

IRRADIATION CONDITIONS AT END OF LIFE OF BREACHED PINS

Pin	Cladding	Fluence n/cm² x 10⁻²² (E > 0.1 MeV)	Internal Pressure MPa	Calculated Maximum Midwall Temperature °C	Peak Fuel Burnup Atom %	Peak Pin Power w/m	Breach Location From Top of Fuel* mm	Cause**
N/E-N122	20% CW 316	3.0	2.92	587	4.3	38.4	5	hotspot (585/780)
PNL 10-14	20% CW 316	4.9	4.29	542	6.4	28.0	11	wear
E/F-N054	20% CW 316	2.9	2.70	574	4.1	37.0	15	unknown
E/F-N078	20% CW 316	4.2	4.15	508	6.0	33.9	158	unknown
P-23B-1A	20% CW 316	4.9	3.19	614	5.7	36.7	18	hotspot (588/820)
P-12AA-63K	30% CW 316	2.2	3.43	643	3.8	34.4	26	hotspot
PNL 11-39	20% CW 316	9.7	7.62	534	11.3	32.3	51	wear
PNL 5-1	SA 304	8.2	8.67	461	13.0	33.8	68	hotspot
PNL 5-17	SA 304	9.4	10.25	473	15.0	34.5	109	hotspot
P-12AB-11B	20% CW 316	5.0	5.78	631	7.8	32.6	186	hotspot (517/810)
P-23A-37	20% CW 316	9.0	7.22	565	10.8	29.0	91	hotspot (549/700)
P-23B-73E	20% CW 316	8.8	6.66	667	10.1	29.8	31	hotspot (650/700)
P-23B-31B	20% CW 316	9.9	7.51	680	11.2	29.1	15	hotspot (671/721)
P-14-29	20% CW 316	8.3	7.36	582	11.0	32.5	13	hotspot (575/650)
P-23C-7A	20% CW 316	12.0	9.00	631	13.7	28.1	0	hotspot (631/656)
P-23C-12A	20% CW 316	12.0	8.00	546	13.7	27.9	89	hotspot (525/650)

*The preirradiation fuel column is 343 mm in length.
**(Calculated Temperature/Metallographically-Determined Temperature, °C) at the breach site.

BREACHED PIN PERFORMANCE
IN REFERENCE DESIGN FUEL PINS

19 - EXPERIMENTS

1150 - MIXED OXIDE FUEL PINS IRRADIATED

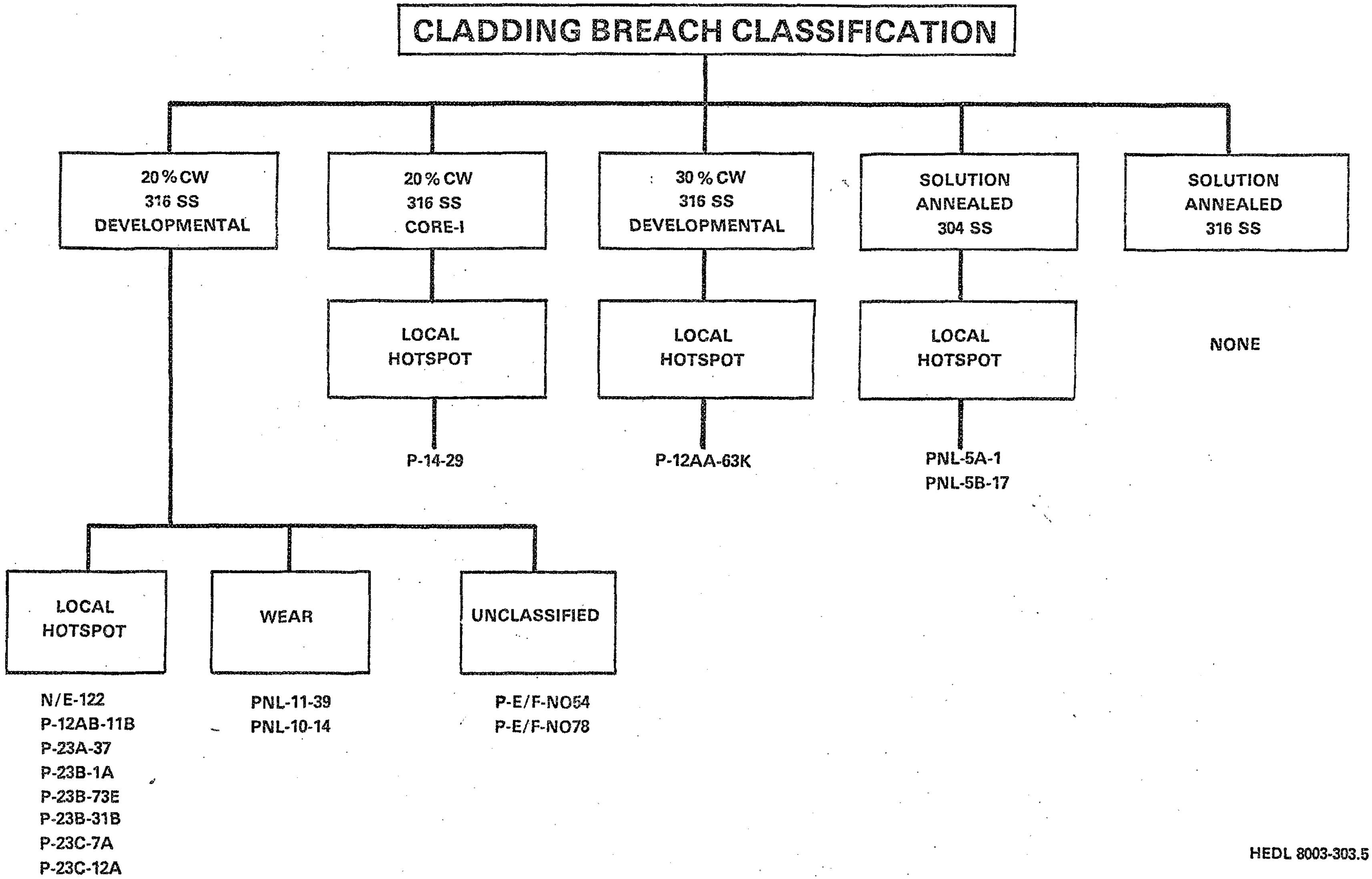
20 - CLADDING BREACHES

HIGH BURNUP BREACHED PINS

PIN	BURNUP
P-14-29	11 atom percent
P-23B-31B	11.2 atom percent
P-23C-12A	13.7 atom percent
P-23C-7A	13.7 atom percent

SUMMARY

1. Hot spots
2. Creep voids
3. Reconstitutions
4. Top of fuel
5. No circumferential propagation
6. Less severe hot spot temperatures necessary at high burnup



CLADDING BREACH CLASSIFICATION
20% CW
316 SS
DEVELOPMENTAL
20% CW
316 SS
CORE-I
30% CW
316 SS
DEVELOPMENTAL
SOLUTION
ANNEALED
304 SS
SOLUTION
ANNEALED
316 SS
LOCAL
HOTSPOT
LOCAL
HOTSPOT
LOCAL
HOTSPOT
NONE
P-14-29
P-12AA-63K
PNL-5A-1
PNL-5B-17
LOCAL
HOTSPOT
WEAR
UNCLASSIFIED
N/E-122
P-12AB-11B
P-23A-37
P-23B-1A
P-23B-73E
P-23B-31B
P-23C-7A
P-23C-12A
PNL-11-39
PNL-10-14
P-E/F-NO54
P-E/F-NO78
HEDL 8003-303.5

Figure 1.

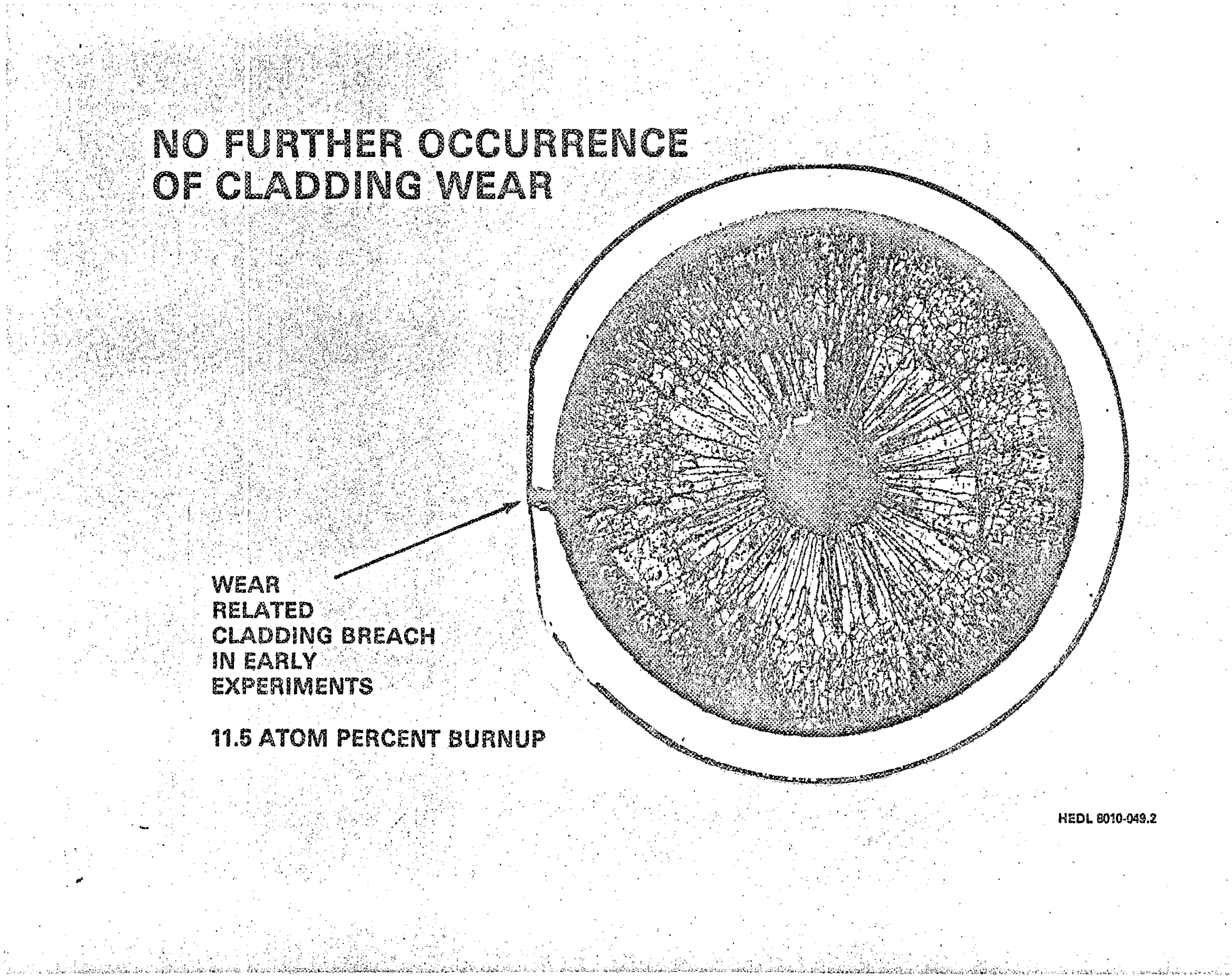

NO FURTHER OCCURRENCE
OF CLADDING WEAR
WEAR
RELATED
CLADDING BREACH
IN EARLY
EXPERIMENTS
11.5 ATOM PERCENT BURNUP
HEDL 8010-049.2

Figure 2.

LOCATION OF CLADDING BREACHES

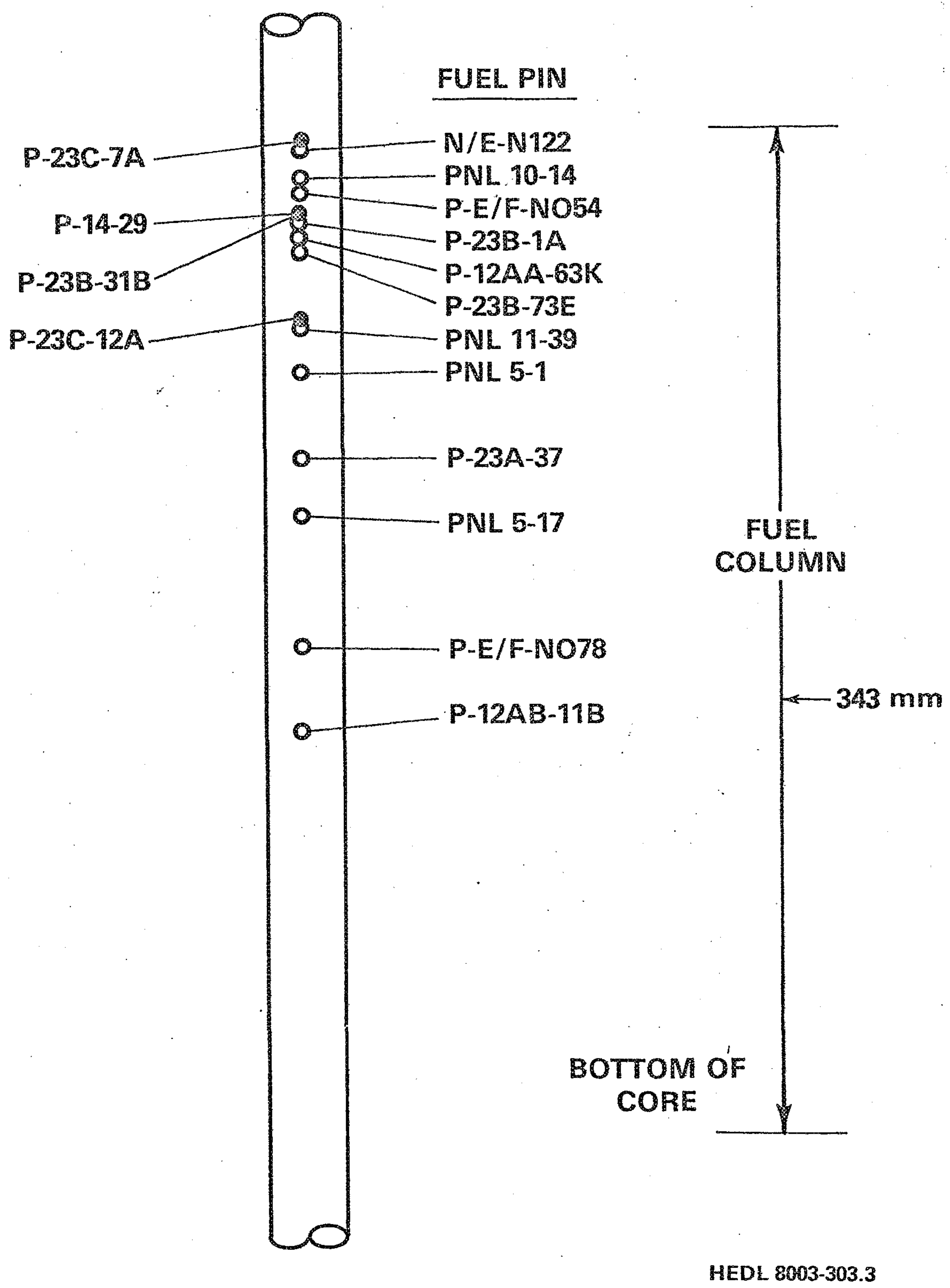


Figure 3.

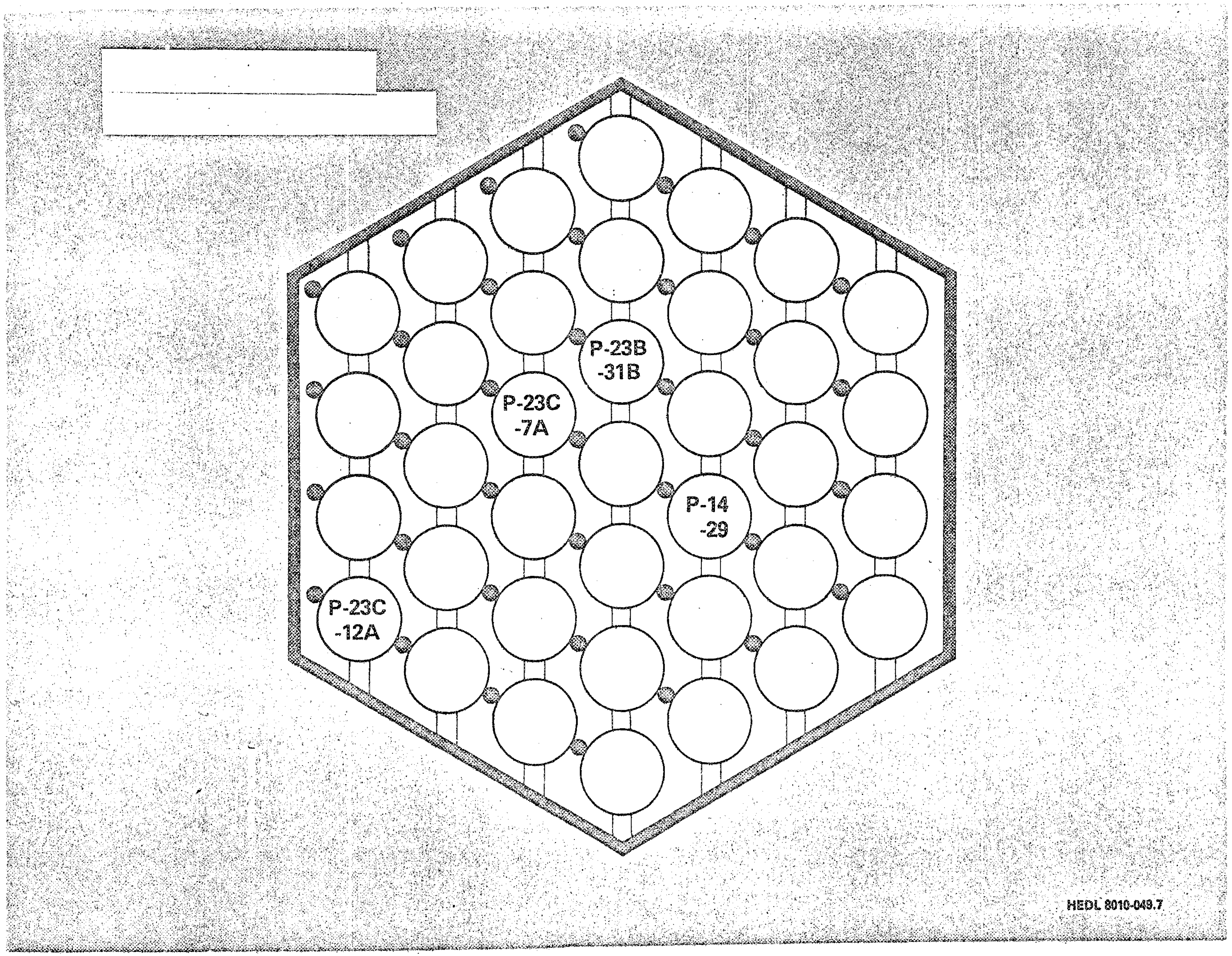
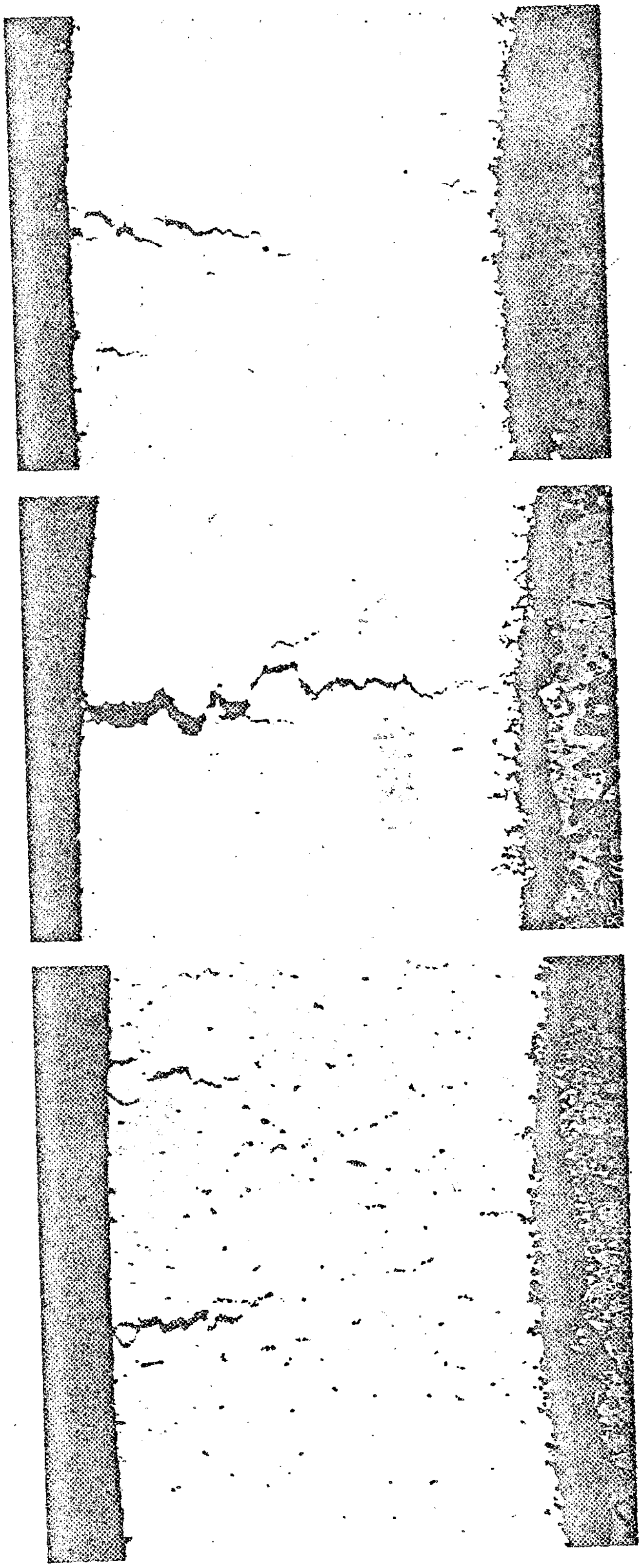


Figure 4.

P-14-29 CLADDING BREACH

FIRST CORE CLADDING

11 ATOM PERCENT BURNUP



a.

b.

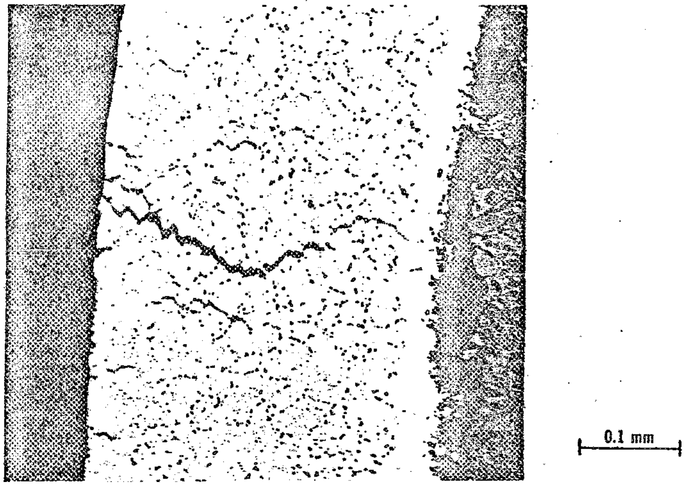
c.

HEDL 8002-307.1

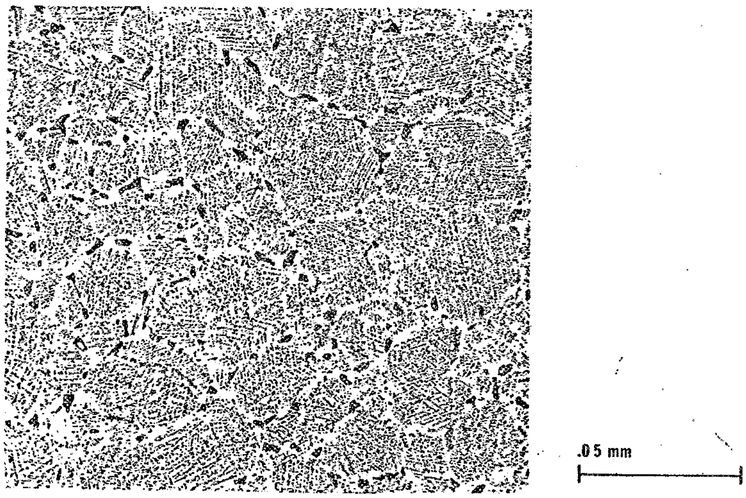
Figure 5.

BREACHED PIN P 14-29

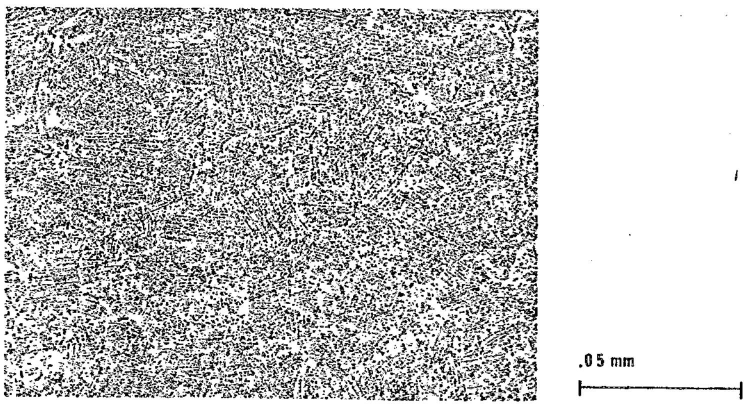
CLADDING MICROSTRUCTURE



a) The Breach Area Etched to Show Intermetallic Precipitates



b) Microstructure Near The Cladding Breach



c) Cladding Microstructure 90 Degrees From Breach Site

HEDL 7908-208.3

Figure 6.

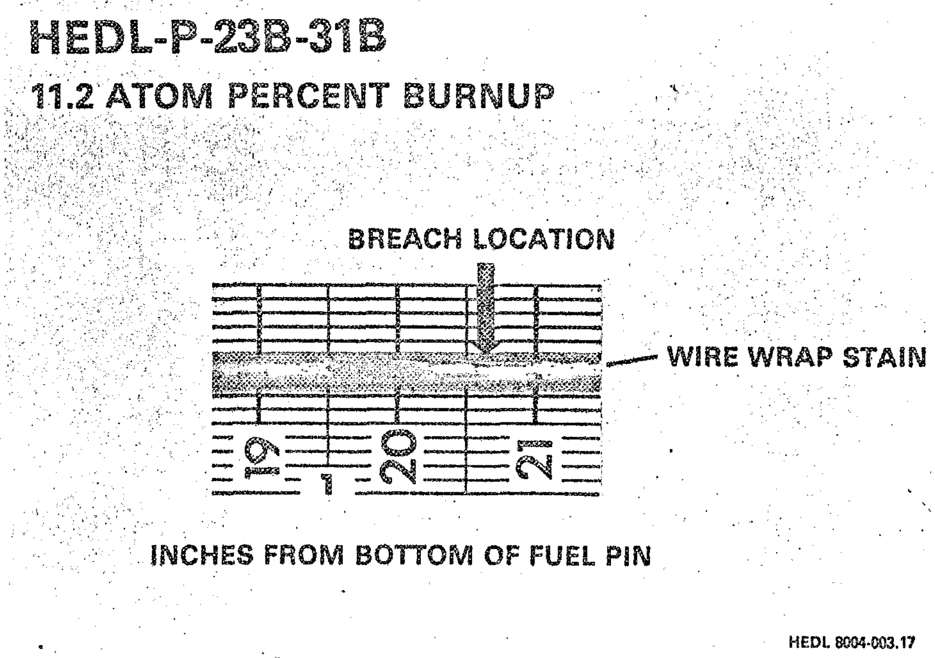
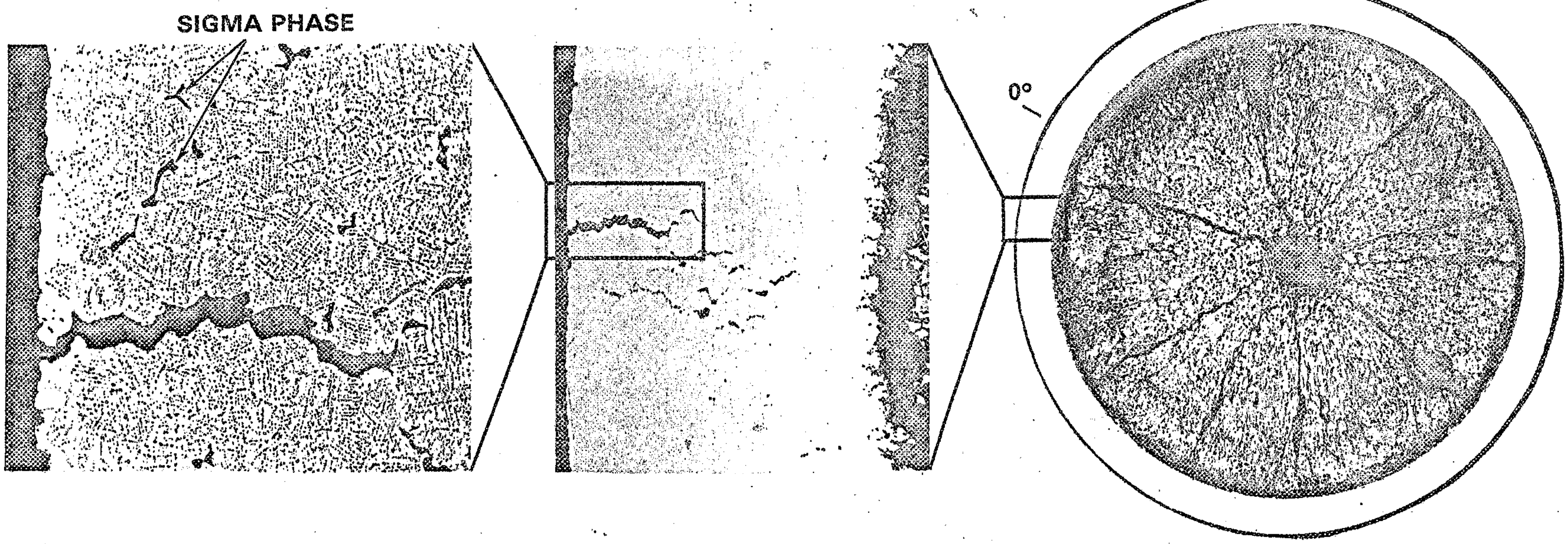

HEDL-P-23B-31B
11.2 ATOM PERCENT BURNUP
BREACH LOCATION
WIRE WRAP STAIN
19
20
21
INCHES FROM BOTTOM OF FUEL PIN
HEDL 8004-003.17

Figure 7.

HEDL-P-23B-31B



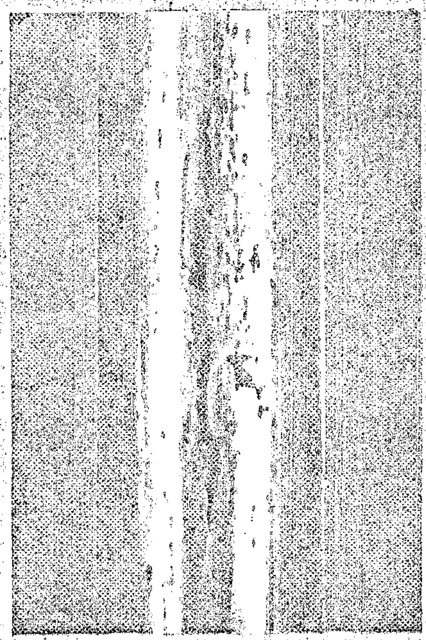
11.2 ATOM % BURNUP

11×10^{22} n/cm^2 FAST FLUENCE

Figure 8.

HEDL-P-23C-12A

CORNER PIN 13.7 ATOM % BURNUP
2 DAYS OF POST BREACH OPERATION



HEDL 8010-049.3

Figure 9.

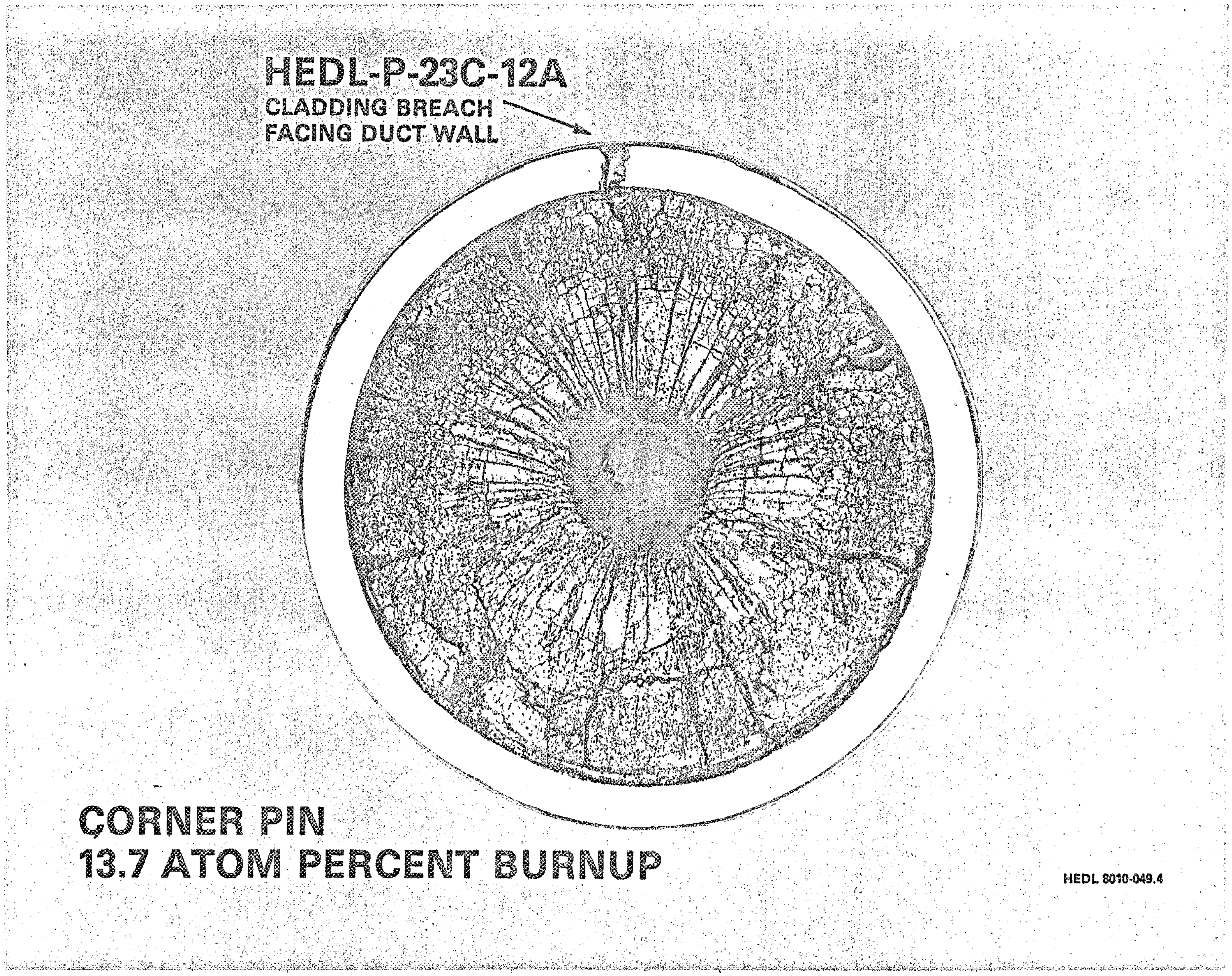

HEDL-P-23C-12A
CLADDING BREACH
FACING DUCT WALL
CORNER PIN
13.7 ATOM PERCENT BURNUP
HEDL 8010-049.4

Figure 10.

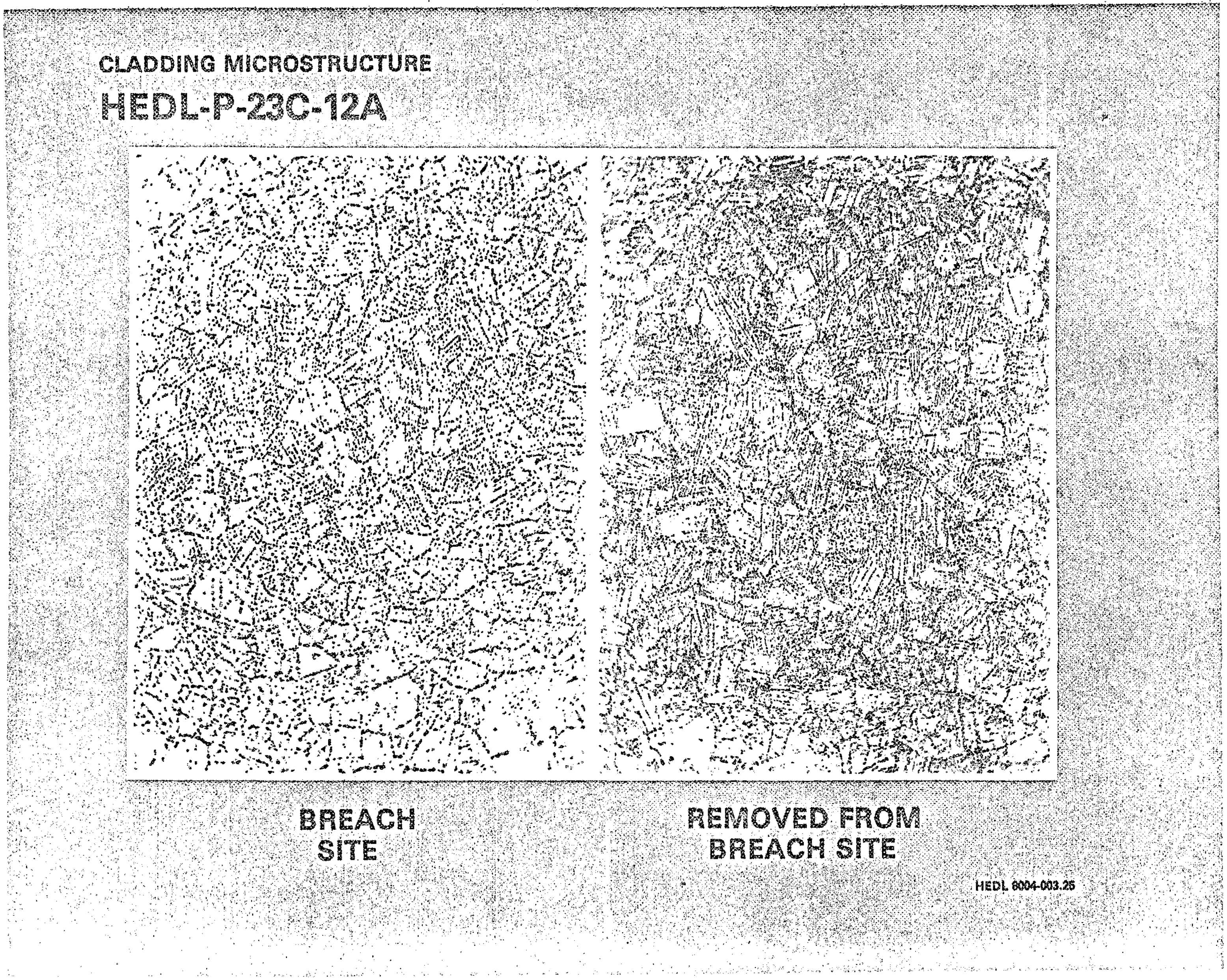
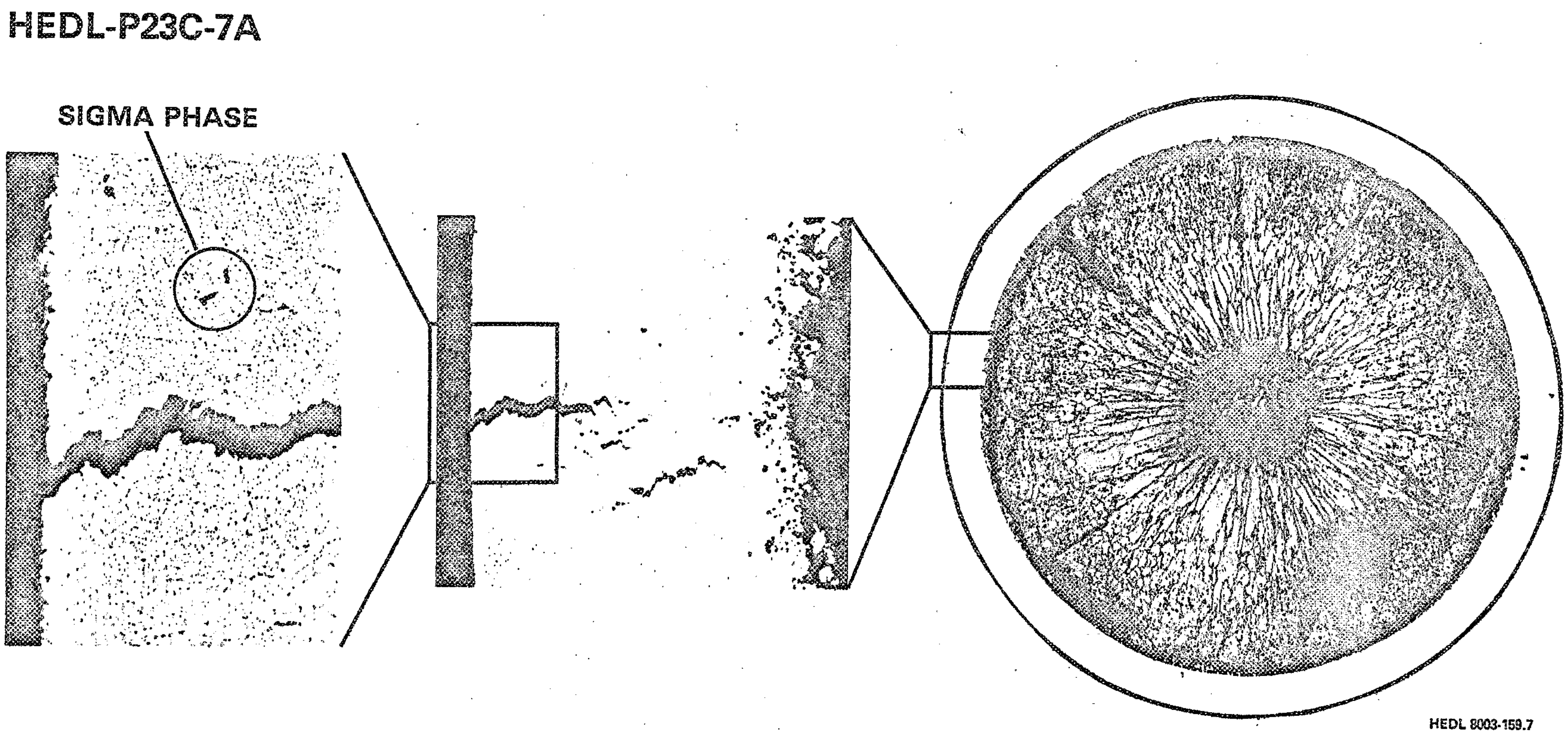

CLADDING MICROSTRUCTURE
HEDL-P-23C-12A
BREACH SITE
REMOVED FROM BREACH SITE
HEDL 8004-003.25

Figure 11.

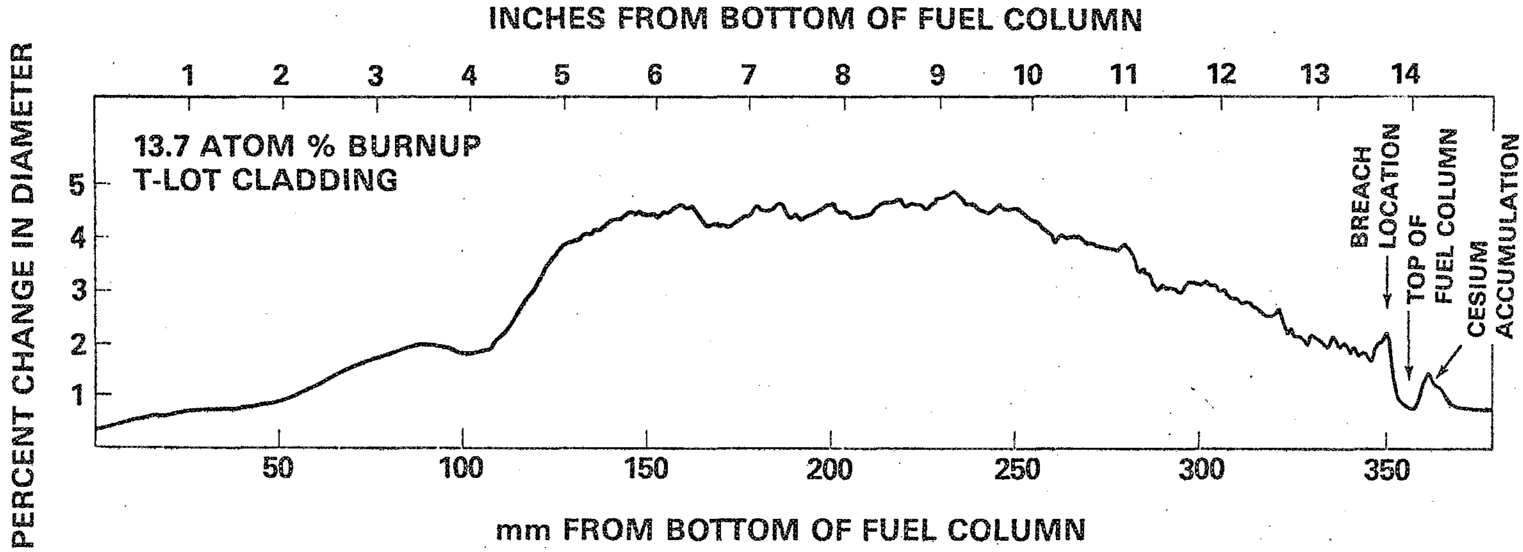


13.7 ATOM % BURNUP

12×10^{22} n/cm^2 FAST FLUENCE

FIGURE 12.

DIAMETER MEASUREMENTS
HEDL-P-23C-7A



HEDL 8010-049.9

Figure 13.