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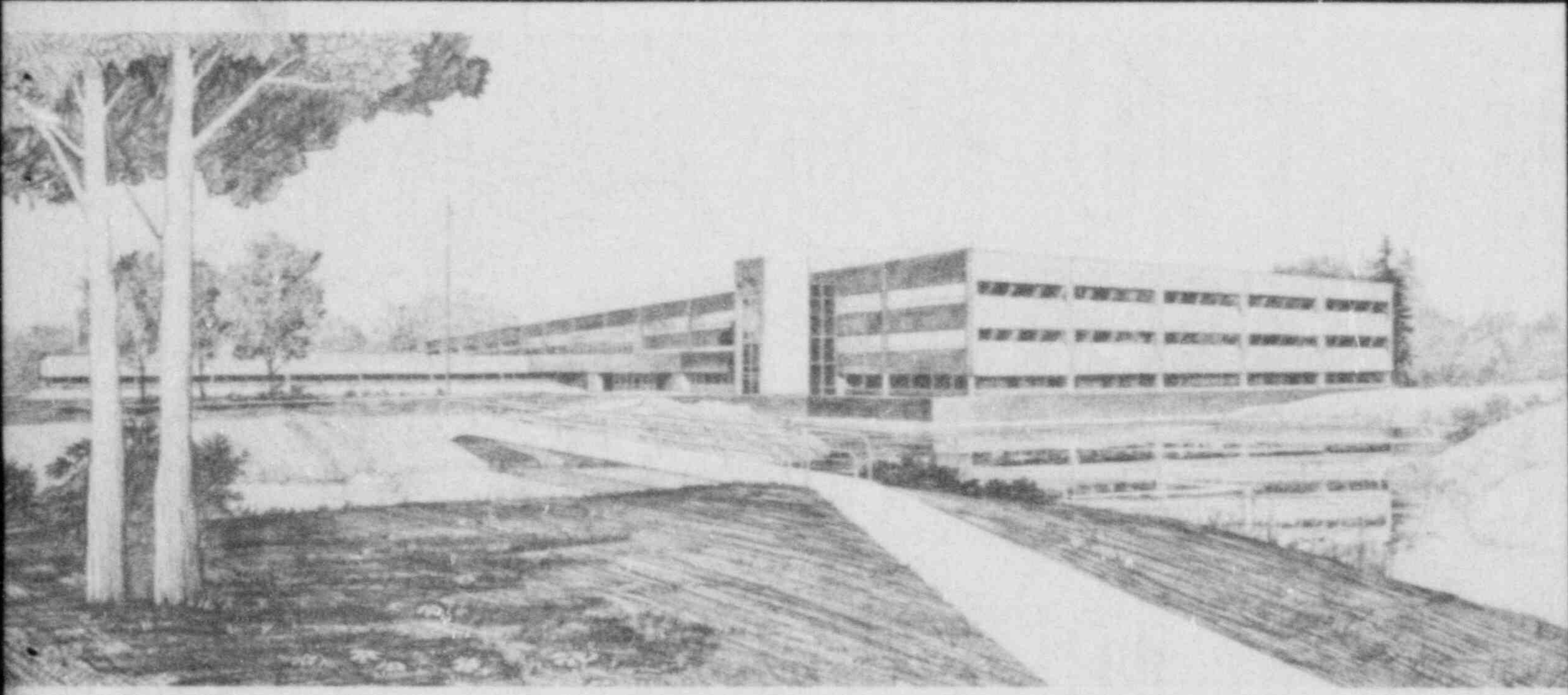

Idaho National Engineering Laboratory
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The Performance of Defected Spent LWR Fuel Rods in Inert Gas and Dry Air Storage Atmospheres

Charles S. Olsen

January 1985

Prepared for the
U.S. Nuclear Regulatory Commission
Under DOE Contract No. DE-AC07-76IDO1570

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THE PERFORMANCE OF DEFECTED SPENT LWR FUEL RODS IN INERT GAS AND DRY AIR STORAGE ATMOSPHERES

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ABSTRACT

A testing program using eight commercial pressurized water reactor and boiling water reactor spent fuel rods was conducted to investigate their long-term stability under a variety of possible dry storage conditions. The objective of this project was to provide the Nuclear Regulatory Commission with information to confirm or establish dry spent fuel storage licensing positions for long-term, low-temperature (<250°C) spent fuel rod behavior during dry storage and radioactive contamination arising from spallation of cladding crud. The results of a nondestructive examination of eight fuel rods, which included color closed-circuit television visual examinations, color photography, dimensional measurements, and neutron radiography, are presented.

A6309—Dry Spent Fuel Storage Studies

SUMMARY

A testing program using eight commercial pressurized water reactor (PWR) and boiling water reactor (BWR) spent fuel rods was conducted to investigate their long-term stability under a variety of possible dry storage conditions. The objective of this project is to provide the Nuclear Regulatory Commission with information to confirm or establish spent fuel dry storage licensing positions for long-term, low-temperature (<250°C) spent fuel rod behavior during dry storage and for radioactive contamination arising from spallation of cladding crud. Thus far, the testing program has included three interim nondestructive examinations and one destructive examination. This report presents the results of the third nondestructive examination, conducted to find any degradation in eight fuel rods after being subjected to 13,168 h at temperature. During this examination, visual observations, diametrical measurements, and neutron radiography were used to assess the fuel rod behavior.

The BWR fuel showed no measurable change from the pretest condition. The artificial defects had not changed and no diametrical growth in the cladding occurred. A BWR fuel rod replaced one that breached after the second interim examination, and a 1.9-cm crack developed in this rod at the bottom defect. About 17% cladding deformation was observed at the defect. For the other defected BWR fuel rods, the diametrical measurements indicated no fuel rod strain.

Some of the BWR fuel rods have failed at some of the defects but not at all of the defects. However, none of the PWR fuel rods have failed. The BWR results may not be applicable to PWR fuel because of the wide differences observed between PWR and BWR fuel rod behavior. The PWR fuel rods now are being destructively examined to determine the extent of oxidation, but additional effort is required to determine oxidation mechanisms and identify the causes of the differences in behavior between PWR and BWR fuel.

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THE PERFORMANCE OF DEFECTED SPENT LWR FUEL RODS IN INERT GAS AND DRY AIR STORAGE ATMOSPHERES

INTRODUCTION

A long-term, eight-rod, fuel rod test (using commercial fuel) was initiated at 229°C covering a wide range of storage atmospheres, rod types, and cladding conditions. These tests were part of a long-range project to evaluate the behavior of spent fuel during dry fuel storage conditions. Results from this project will provide the Nuclear Regulatory Commission with the information to confirm or establish spent-fuel, dry storage licensing positions regarding long-term, low-temperature (<250°C) spent fuel rod behavior during dry storage and radioactive contamination arising from spallation of cladding crud.

In an unlimited air atmosphere, oxidation of UO_2 may occur with a concurrent volume expansion and rupture of the cladding. The contamination potential may be enhanced by (a) oxidation of the fuel along the grain boundaries, which would release fission gases trapped in the grain boundaries, (b) fallout of fuel particulate from the rupture, and (c) spallation of the crud from stresses imposed on the cladding by fuel expansion. Similar behavior, although at different rates, may occur with other atmospheres containing impurities such as an inert atmosphere with moisture or some other oxidant. Estimates have been made of maximum storage temperatures expected,[1] but information is needed to assess a satisfactory storage temperature with regard to defected rods in an oxidizing environment.

Four intact and four defected rods were tested. The four defected rods were examined during the first and second nondestructive interim examinations.[2,3] The first interim examination was conducted after 2235-h exposure at temperature, and a second interim examination was conducted after a total of 5962 h at temperature. A breached rod from the second interim examination, which was replaced with another fuel rod, was destructively examined. The third and final nondestructive examination was conducted after 13,168 h.

The contamination potential of spent fuel during long-term, low-temperature (<523 K) dry storage depends on the fuel rod performance in the atmosphere selected for storage. Because perforated rods that occur in-reactor are not routinely isolated, some rods with cladding perforations may be stored in dry environments and develop cladding breaches. Contamination may result from release of fuel particulate, spallation of the crud coating from stresses imposed on the cladding, or fission gas release.

This report presents the results of the third interim nondestructive examination. The results from the first and second nondestructive examinations have been previously published.[2,3]

EXPERIMENTAL PROCEDURE

Four pressurized water reactor (PWR) fuel rods from the H. B. Robinson reactor and four boiling water reactor (BWR) rods from the Peach Bottom reactor were heated in a furnace to simulate temperatures occurring during dry storage conditions. These fuel rods were described previously.[4,5] Four rods (two PWR and two BWR) each contained artificial defects in the form of 0.76-mm-diameter holes placed at different orientations and axial positions (Table 1). Stainless steel capsules with a 1.75-cm inside diameter were used to contain the fuel rods with each one in its own atmosphere (Table 2). One defective rod of each type was placed in a sealed capsule containing 0.1 MPa of an argon/1% helium mixture. The other two defected rods were placed in capsules that terminated at each end with a series of 2-μm and 15-μm in-line filters open to the cell atmosphere. These filter sizes were based on fuel particle sizes expected from ruptured fuel rods.[6] The intact rods were handled in a similar fashion. One intact rod of each type was placed in a sealed capsule containing 0.1 MPa of an argon/1% helium mixture. Also one intact rod of each type was placed in a capsule containing air/1% helium mixture. The leak rate on the sealed capsules was a maximum of 2.5×10^{-7} cm^3/s.

The fuel rods were heated in a shielded 14-zone, 12.8-m-long clamshell furnace capable of holding the 8 encapsulated, unmodified LWR fuel rods (Figure 1). The fuel rod capsules were placed around an instrument train, which contained 10 axially located thermocouples (Figure 2). Furnace-control thermocouples indicated a ± 3-K radial temperature gradient, with the center of the furnace being the hottest.

The furnace temperatures were read and printed on paper tape once an hour with a Fluke data logger. During the last 10 weeks before shutting the furnace down for the final nondestructive examination, the Fluke data logger was connected to an Apple II + personal computer for storing the temperature data on floppy diskettes for subsequent data reduction.

For each furnace campaign, the furnace was brought to temperature over a 12-h period and, other than for power outages, ran continuously until the interim examinations (Figure 3). The furnace was allowed to cool by natural means at a rate of less than 5 K/h. The furnace was operated at 229°C for 5932 h, and then gradually decreased to 217°C during the next 7206 h.

Peach Bottom rod PH462-E3 was removed from the furnace after 5962 h at 229°C. This rod was replaced with PH462-C5, which was heated for 7206 h at temperatures decreasing from 229°C to 217°C. The remaining seven rods were heated for 13,168 h, 5962 at 229°C, and 7206 h from 229°C to 217°C.

Table 1. Defect locations

Fuel Rod	Defect Location[a] (in cm)	Orientation (in degrees)	Defect Location[a] (in cm)	Orientation (in degrees)	Defect Location[a] (in cm)	Orientation (in degrees)
BO5-E7	36.8	90	179.1	240	—	—
BO5-G7	27.9	200	205.7	0	—	—
PH462-D6	52.1	90	224.8	270	—	—
PH462-C5	66.8	0	236.2	0	401.3	0

a. Measured from the top of the fuel rod.

Table 2. Fuel rod storage conditions

Reactor Type	Assembly and Rod Number	Capsule Atmosphere	Capsule Pressure (MPa)	Fuel Rod Condition
PWR	BO5-G7	Ar/1%-He	0.1	Defected (2 holes)
PWR	BO5-E7	Air	0.1	Defected (2 holes)
PWR	BO5-08	Ar/1%-He	0.1	Intact
PWR	BO5-B8	Air/1%-He	0.1	Intact
BWR	PH462-D6	Ar/1%-He	0.1	Defected (2 holes)
BWR	PH462-E4	Air/1%-He	0.1	Intact
BWR	PH462-E5	Ar/1%-He	0.1	Intact
BWR	PH462-C5[a]	Air	0.1	Defected (3 holes)

a. After the second furnace campaign, this rod replaced PH462-E3.

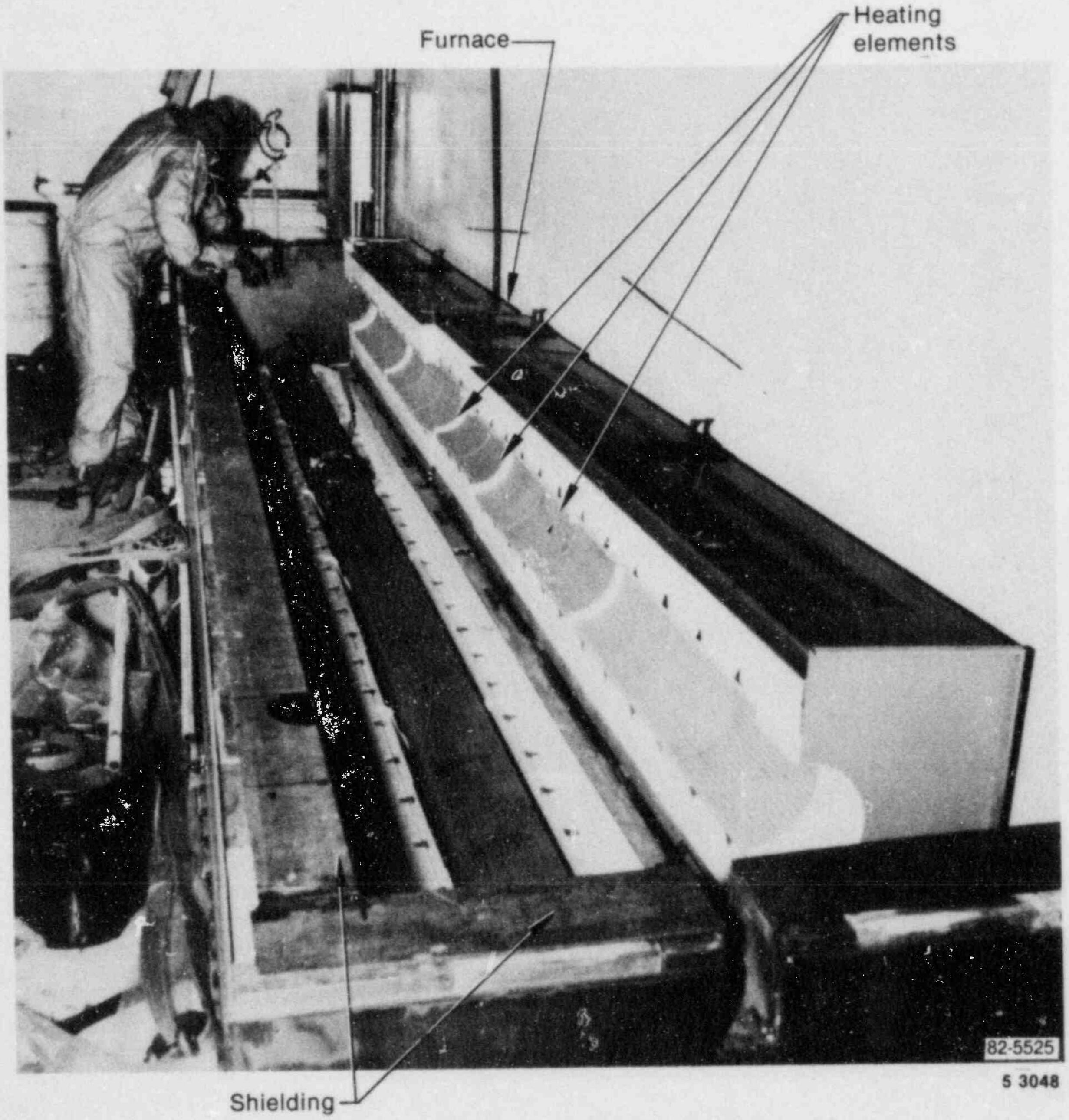

Figure 1. Dry fuel storage furnace.

The fuel rod capsules were removed from the furnace on July 13, 1984. After the fuel rods were removed from the capsules, each rod was placed in an inspection fixture and visually examined. The visual examination was recorded with a color closed-circuit television camera attached to a Kollmorgen periscope. In addition, selected areas on the fuel rods were photographed in color with a 35-mm camera attached to the Kollmorgen periscope. A data back was attached to this camera in order to record a photograph number directly on the film.

The diameters of the fuel rods were measured with a vernier caliper with a resolution of 0.025 mm. The measurements were made at three fuel rod orientations of 0, 120, and 240 degrees. The defect sizes were measured from the photographs and a scale in the photograph.

After the visual examination, the fuel rods were cut into lengths approximately 140 cm long for neutron radiography. The nine sections containing the defects and the center section from the undefected fuel rod PH462-E4 were neutron radiographed at the Test Reactor Area neutron radiograph facility. Each section was radiographed at 0 degrees (direction of the defect) and at a direction 90 degrees to the defect.

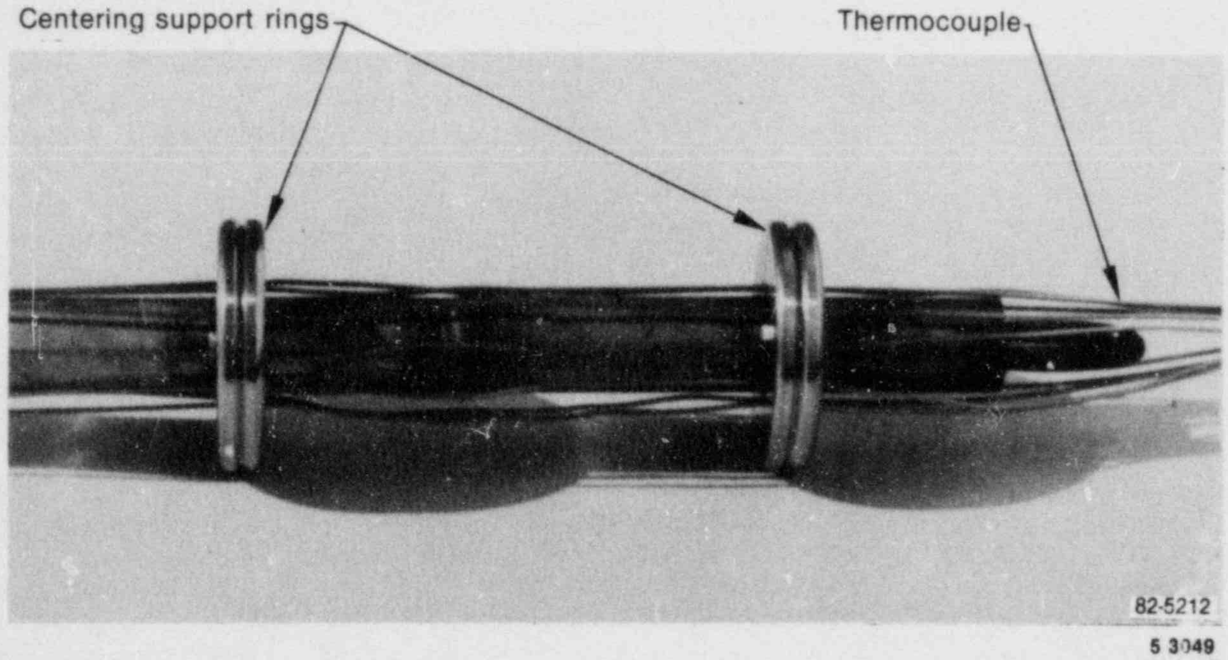

Figure 2. Thermocouple train.

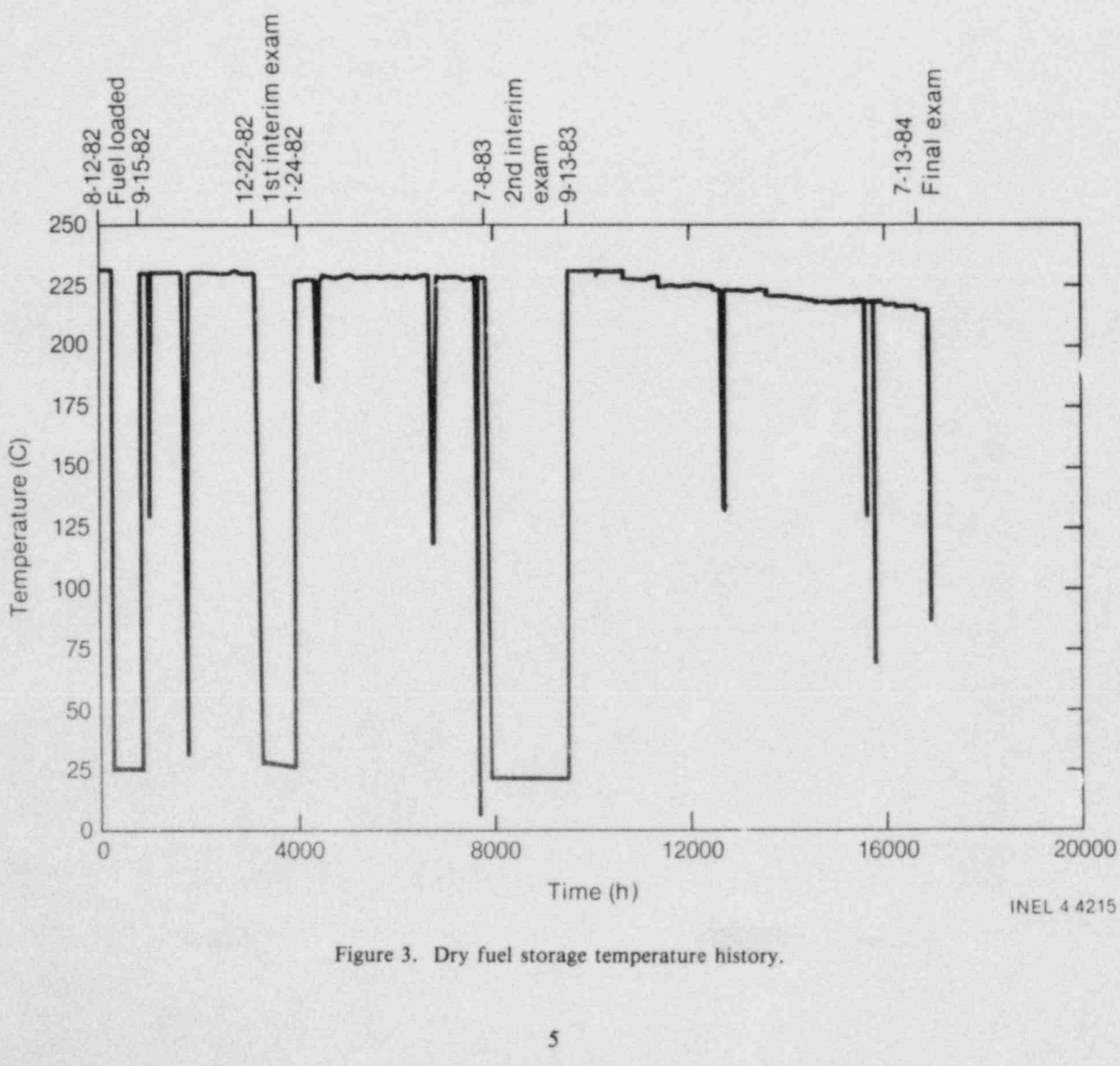

Figure 3. Dry fuel storage temperature history.

EXPERIMENTAL RESULTS

Visual Examination

All eight rods were visually examined. The general surface condition of the H. B. Robinson fuel rods appeared to be unchanged. The fuel rods heated in air (both intact and defected) were similar in appearance to those heated in argon (Figures 4 and 5). There is little crud deposition on the fuel rods exhibiting a smooth oxide on the surface.

The general surface appearance of the four BWR fuel rods also appeared to have not changed. The artificial defect at the top of rod PH462-C5 did not appear to be fully open. When this hole was drilled into the cladding, indications were that the drill bit had penetrated through the wall. The defect located at the bottom showed significant enlargement and developed an axial crack emanating from both sides of the original hole (Figure 6). Also the top defect in rod PH462-D6 did not appear to be fully open to the atmosphere.

The BWR rods similarly to the PWR fuel rods did not exhibit much crud deposition on the surface of the cladding. An atypical crud deposition is shown in Figure 7.

This discussion has been limited to typical results of the visual examination. Photographs of each of the defects after the third furnace cycle are shown in Appendix A.

Fuel Rod Strain

The fuel rod diameter measurements are listed in Table 3, and the defect sizes are listed in Table 4. Significant fuel rod strain was measured in the BWR PH462-C5 fuel rod. The crack size in PH462-C5 was asymmetrical, extending 8.6 mm up the rod and 10.2 mm down the rod from the defect. Its width at the widest point was 1.3 mm. The original defect, which was 0.76 mm, increased by 0.25 mm neglecting the initial crack opening. The fuel rod expanded 17% at 90 degrees from the crack and 7% at 30 degrees almost parallel to the crack. The deformation of the failed BWR fuel rods was apparently constrained by the fuel rod capsule. The maximum deformation of the fuel rod is 1.73 cm, compared with 1.75 cm inside diameter of the capsule. The fuel rod was stuck inside the capsule when the capsule was being unloaded. There is no apparent fuel rod strain in the other three BWR fuel rods, based on the fuel rod diameter measurements.

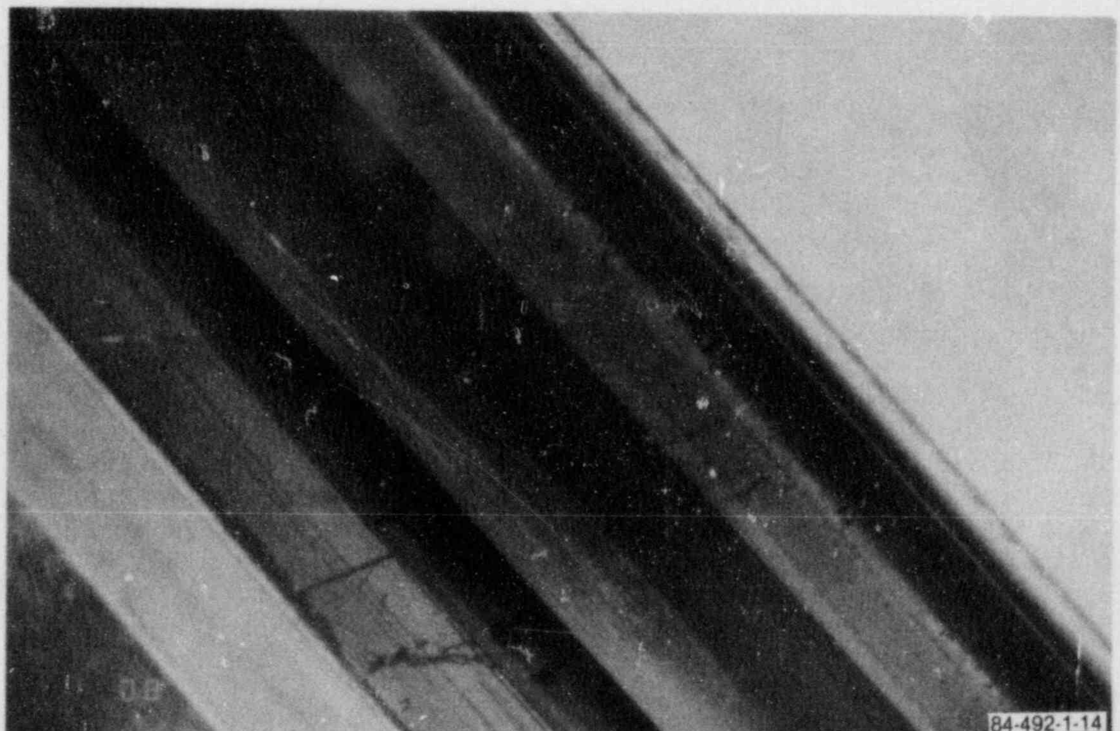

Figure 4. Top defect in fuel rod BO5-G7 heated in argon.

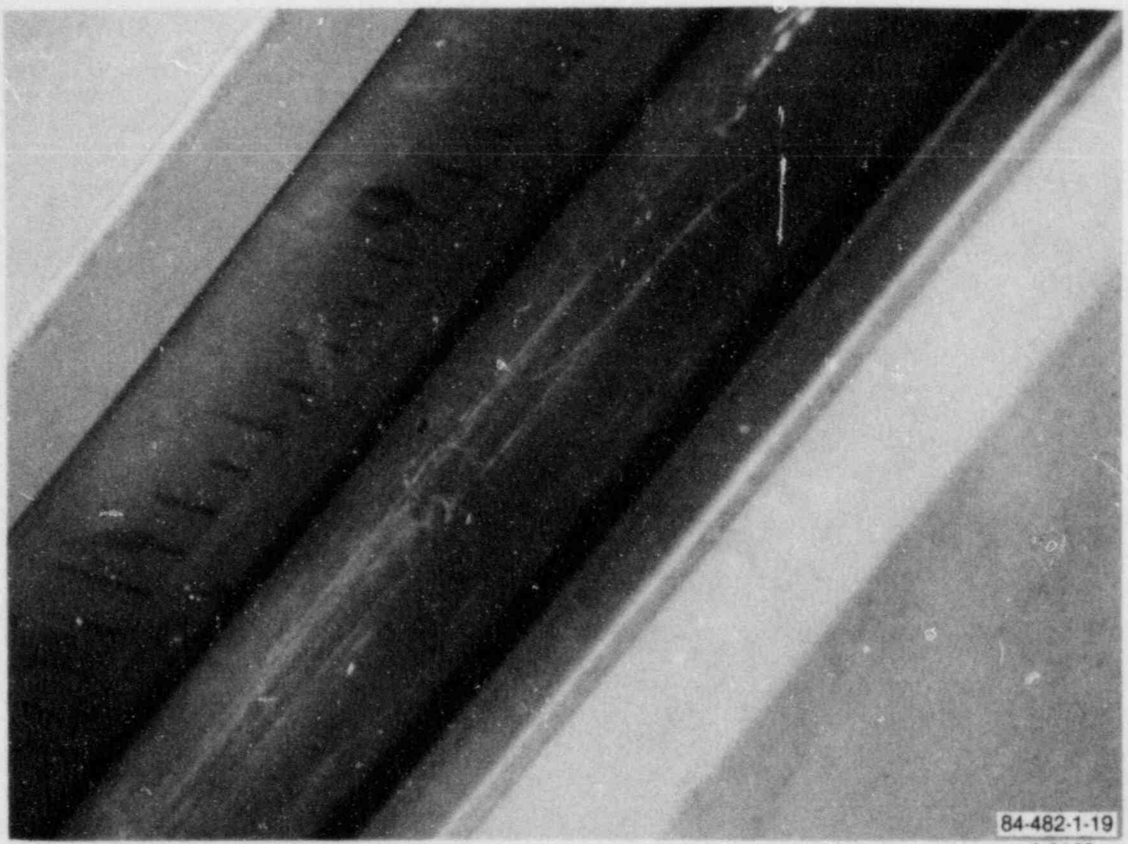

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Figure 5. Top defect in fuel rod BO5-E7 heated in air.

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Figure 6. Crack in fuel rod PH462-C5, 401 cm from the top (bottom defect).

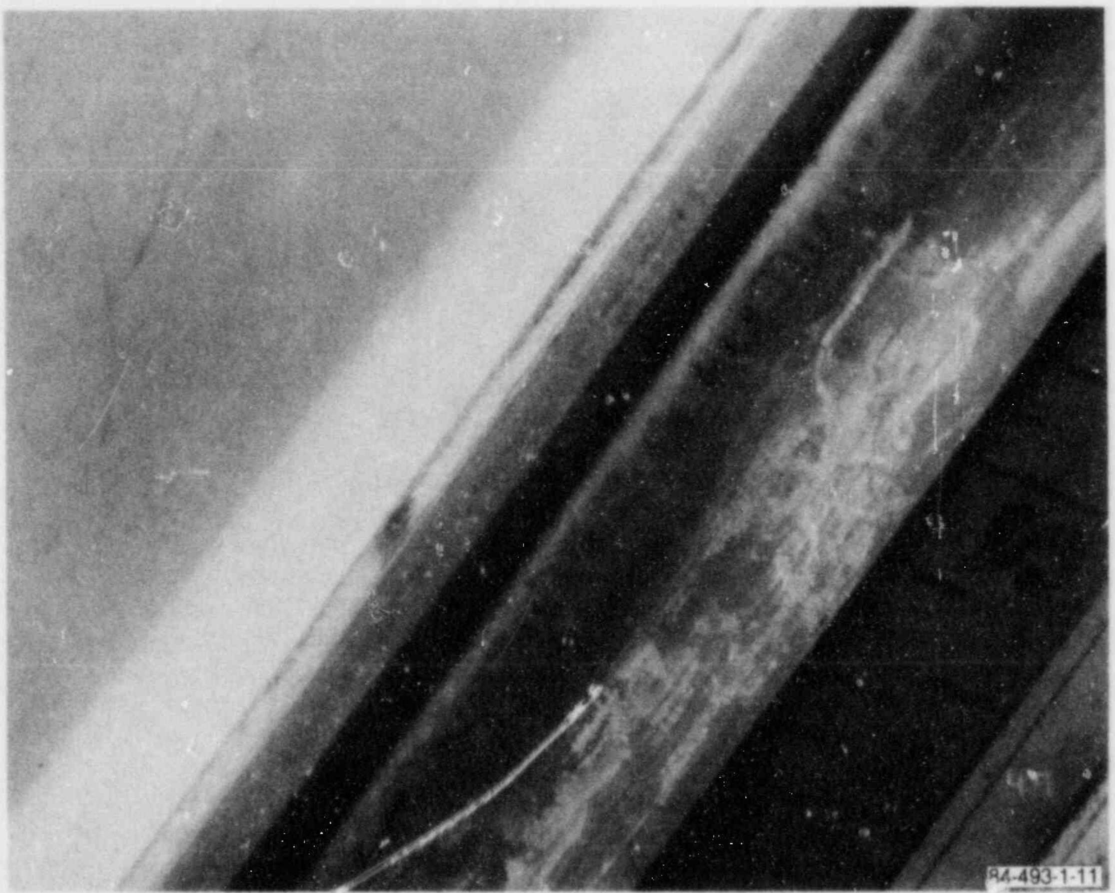


Figure 7. Typical crud deposits on a BWR fuel rod.

Although the fuel rod diameter indicated no strain, the middle defect in PH462-D6 increased in diameter by 0.13 mm from 0.88 mm measured during the second interim examination to 1.01 mm measured during the third interim examination. The top defect was apparently closed, and measurements indicated nominal defect size.

The fuel rod diameters for the PWR fuel rods did not change much from the nominal dimensions. The fuel rod diameters varied from 10.46 to 10.67 mm, slightly less than the nominal 10.72 mm. The smaller diameter may be attributed to cladding creep during steady-state irradiation in the reactor. These values are comparable to the values measured previously.[2,3] The defects did not increase in size in the PWR fuel rods.

Neutron Radiography

The neutron radiographs for the defected BWR fuel rods are shown in Figures 8 through 10. In addition, the neutron radiograph of the undefected center section of PH462-E4 is shown in Figure 8. The fuel pellets in PH462-C5 bottom section have distinct pellet/pellet interfaces except in the area of the 1.9-cm crack. At the crack, the pellet/pellet interfaces are not distinct, and the fuel has expanded in this area. About 13 cm of the fuel has apparently oxidized in this area. In contrast, the pellet/pellet interfaces in PH462-E4 are distinct with very little fuel pellet cracking.

In the area of the defects of the top section of PH462-C5 (Figure 10) and of the top section of PH462-D6 (Figure 9), the fuel pellets are essentially intact with distinct pellet/pellet interfaces. The fuel does not appear to be oxidized. On the other hand, the fuel in the areas of the defects in the center section of PH462-D6 (Figure 9) and in the center of PH462-C5 (Figure 10) is heavily cracked with a large gap at the defect location. The pellet/pellet interfaces are not very distinct at the defect locations. The fuel appears to be oxidized in the immediate area of the defect.

Table 3. Fuel rod diametrical measurements

Fuel Rod	Diameter (mm)	Direction (degree)	Location
PH462-C5	16.71	0	401-cm
	15.57	120	Defect
	15.33	240	
	14.15	0	236-cm
	14.20	120	Defect
	14.33	240	
	14.15	0	67-cm
	14.12	120	Defect
	14.12	240	
BO5-E7	10.54	0	37-cm
	10.67	120	Defect
	10.62	240	
	10.52	120	179-cm
	10.57	240	Defect
	10.52	0	
BO5-B8	10.59	120	350-cm Defect
PH462-D6	14.20	0	52-cm
	14.20	120	Defect
	14.22	240	
	14.17	0	225-cm
	14.30	120	Defect
	14.27	240	
BO5-G7	10.52	0	206-cm
	10.59	120	Defect
	10.57	240	
	10.59	0	28-cm
	10.54	120	Defect
	10.67	240	
PH462-E4	14.25	0	51-cm
	14.25	120	Location
	14.25	240	
	14.25	0	224-cm
	14.27	120	Location
	14.27	240	
BO5-08	10.64	0	36-cm
	10.46	120	Location
	10.52	240	
	10.49	0	224-cm
	10.44	120	Location
	10.59	240	
PH462-E5	14.30	0	51-cm
	14.27	120	Location
	14.22	240	

Table 4. Defect diametrical measurement

Fuel Rod	Diameter (mm)	Direction[a] (degree)	Location
PH462-C5	3.71	0	401-cm
	3.51	90	Defect
	0.91	0	236-cm
	0.36	90	Defect
	0.36	0	67-cm
	0.25	90	Defect
BO5-E7	0.99	0	37-cm
	0.79	90	Defect
	0.79	0	179-cm
	0.79	90	Defect
PH462-D6	0.79	0	52-cm
	0.71	90	Defect
	0.99	0	225-cm
	1.02	90	Defect
BO5-G7	0.88	0	206-cm
	0.80	90	Defect
	0.81	0	28-cm
	0.92	90	Defect

a. Direction relative to rod; 0 is longitudinal and 90 is transverse.

The neutron radiographs for the defected PWR fuel rods are shown in Figures 11 and 12. The radiographs for the sections from the BO5-E7 fuel rod (Figures 11 and 12) and the center section from BO5-G7 (Figure 11) indicate that the fuel is not oxidized. The fuel shows distinct pellet/pellet interfaces with a small amount of pellet cracking in BO5-E7 top section. Some fuel appears oxidized at the defect in the BO5-G7 top section.

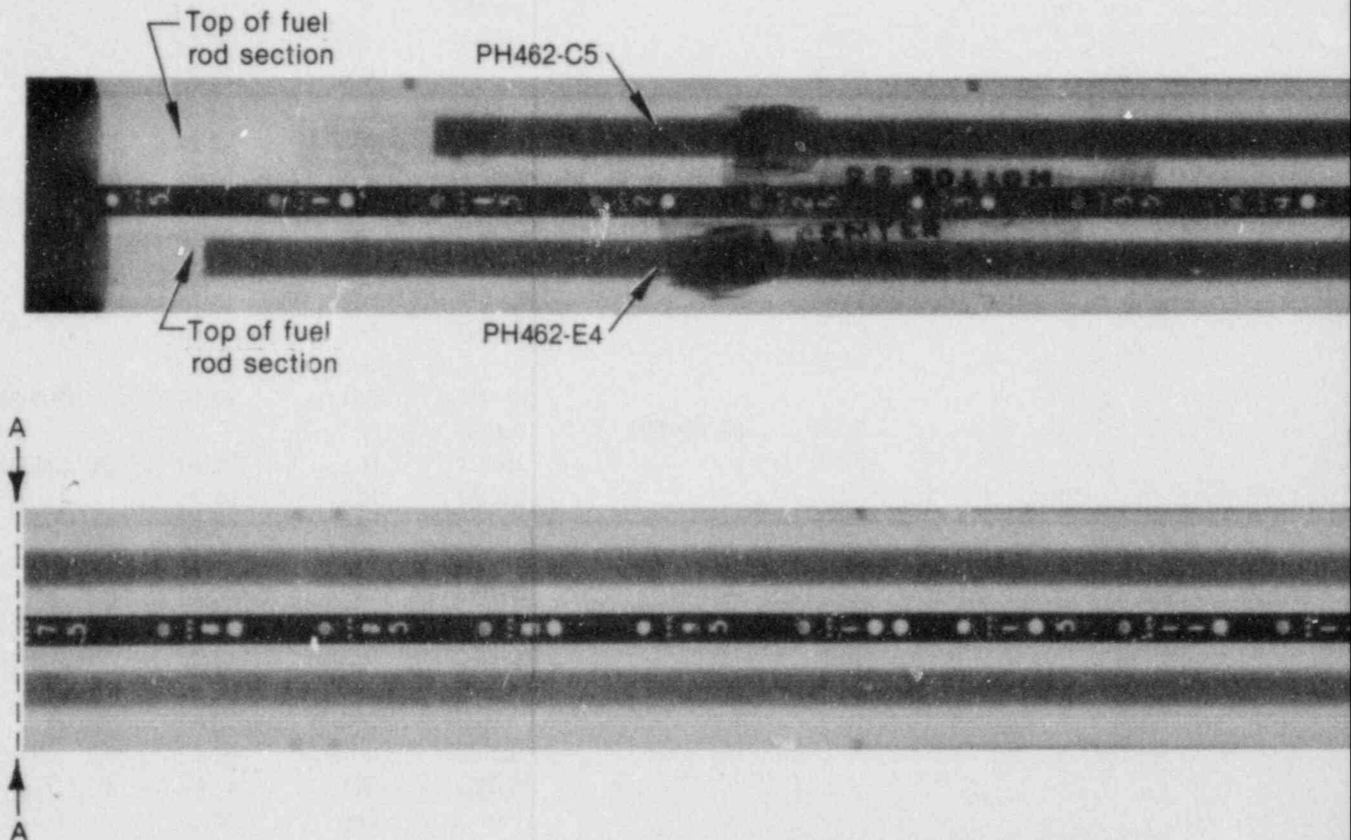
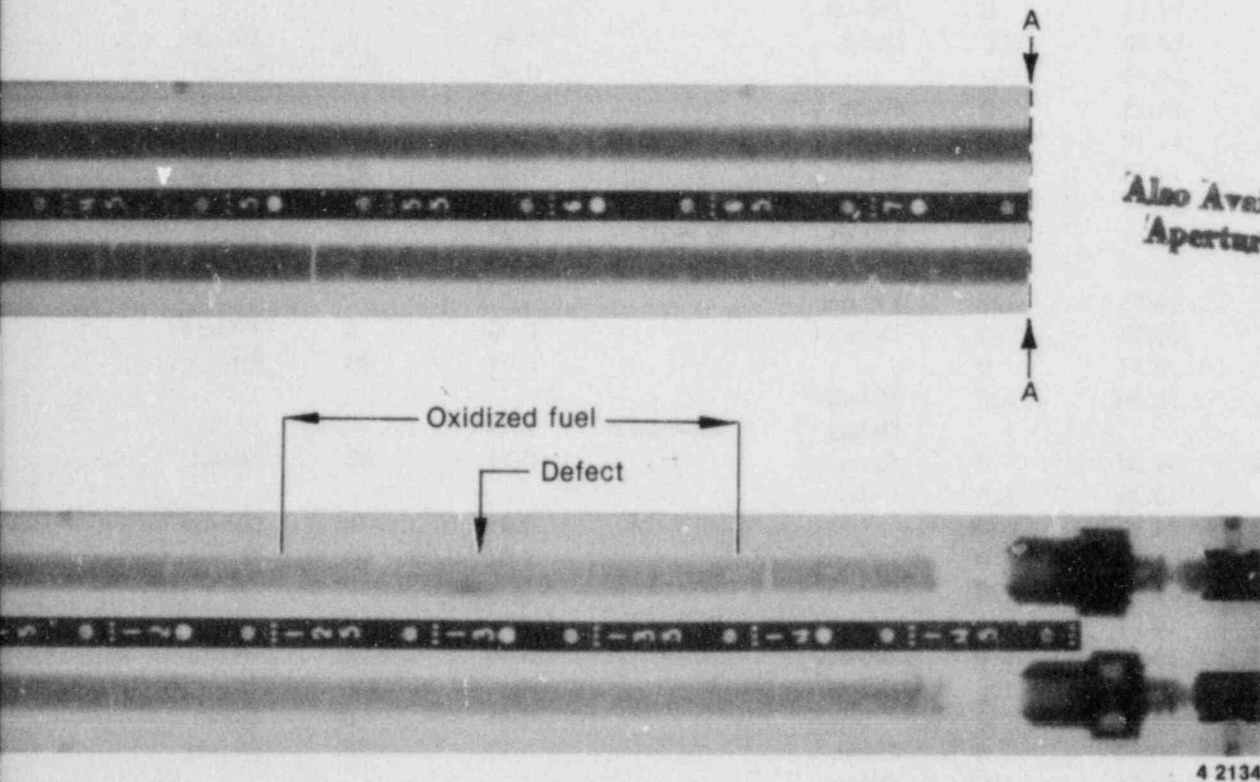


Figure 8. Neutron radiographs of PH462-C5



bottom and PH462-E4 center sections.

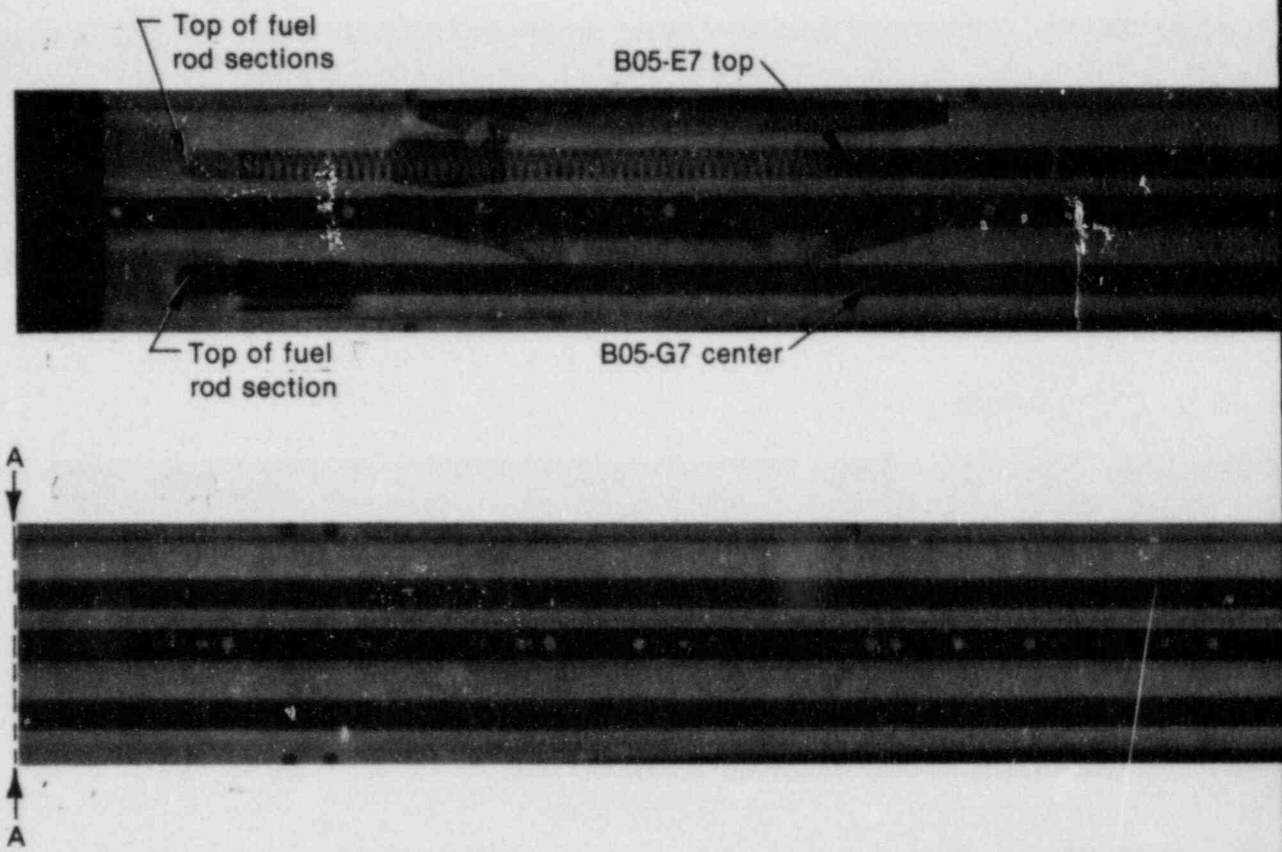
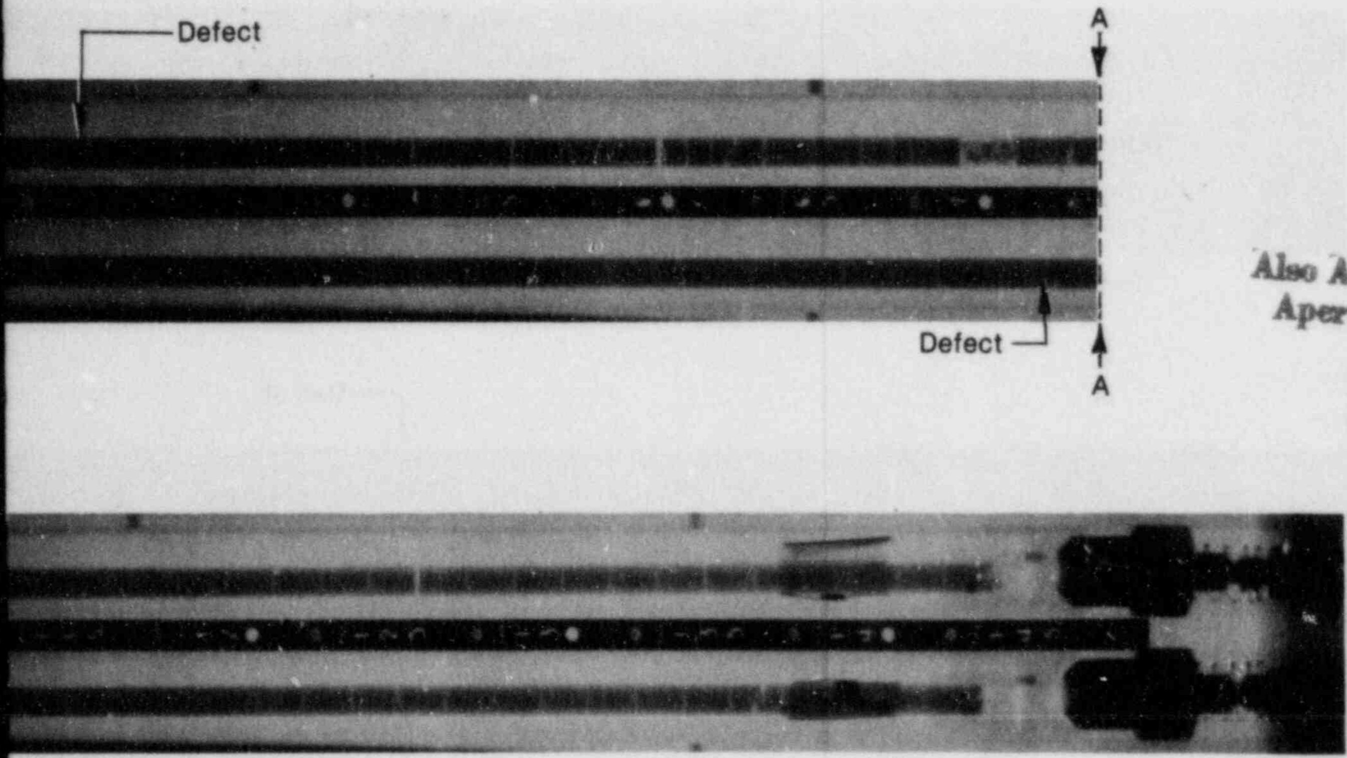


Figure 11. Neutron radiographs



Bottom of fuel rod sections

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of BO5-G7 center and BO5-E7 top sections.

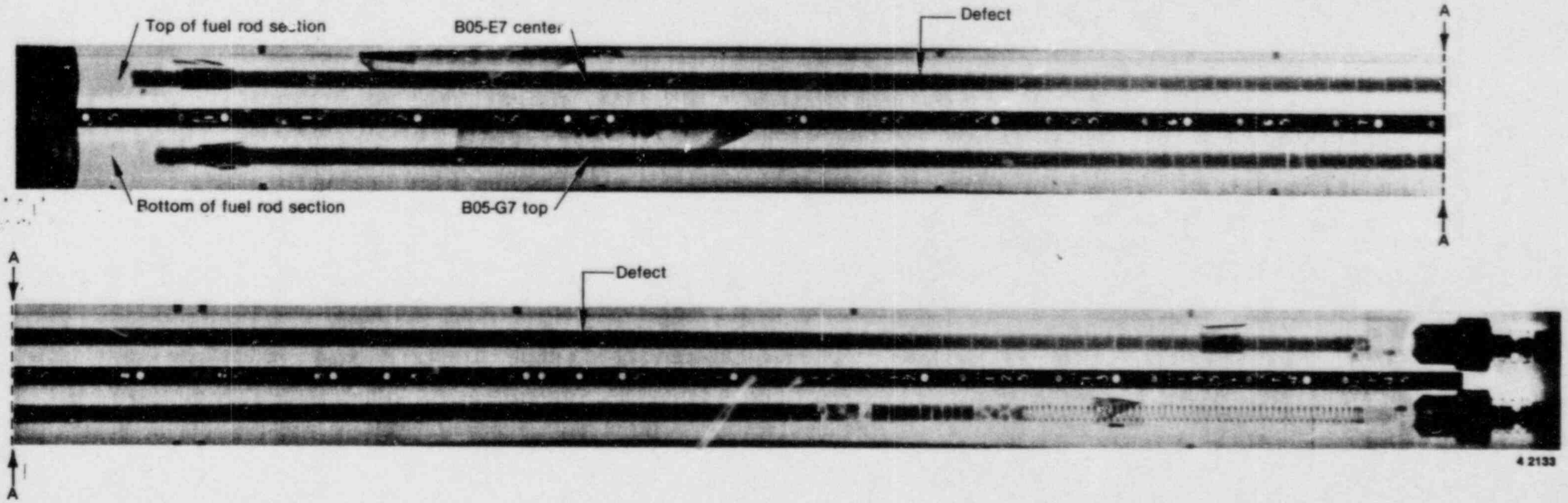

Figure 12. Neutron radiographs of BO5-E7 center and BO5-G7 top sections.

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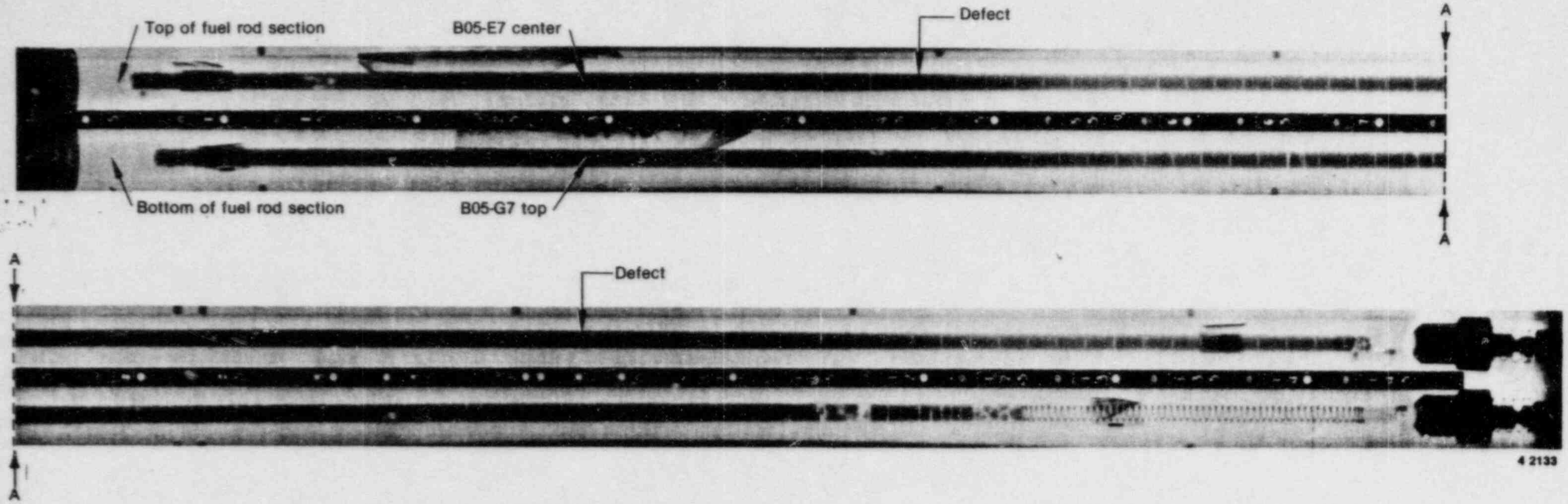

Figure 12. Neutron radiographs of BO5-E7 center and BO5-G7 top sections.

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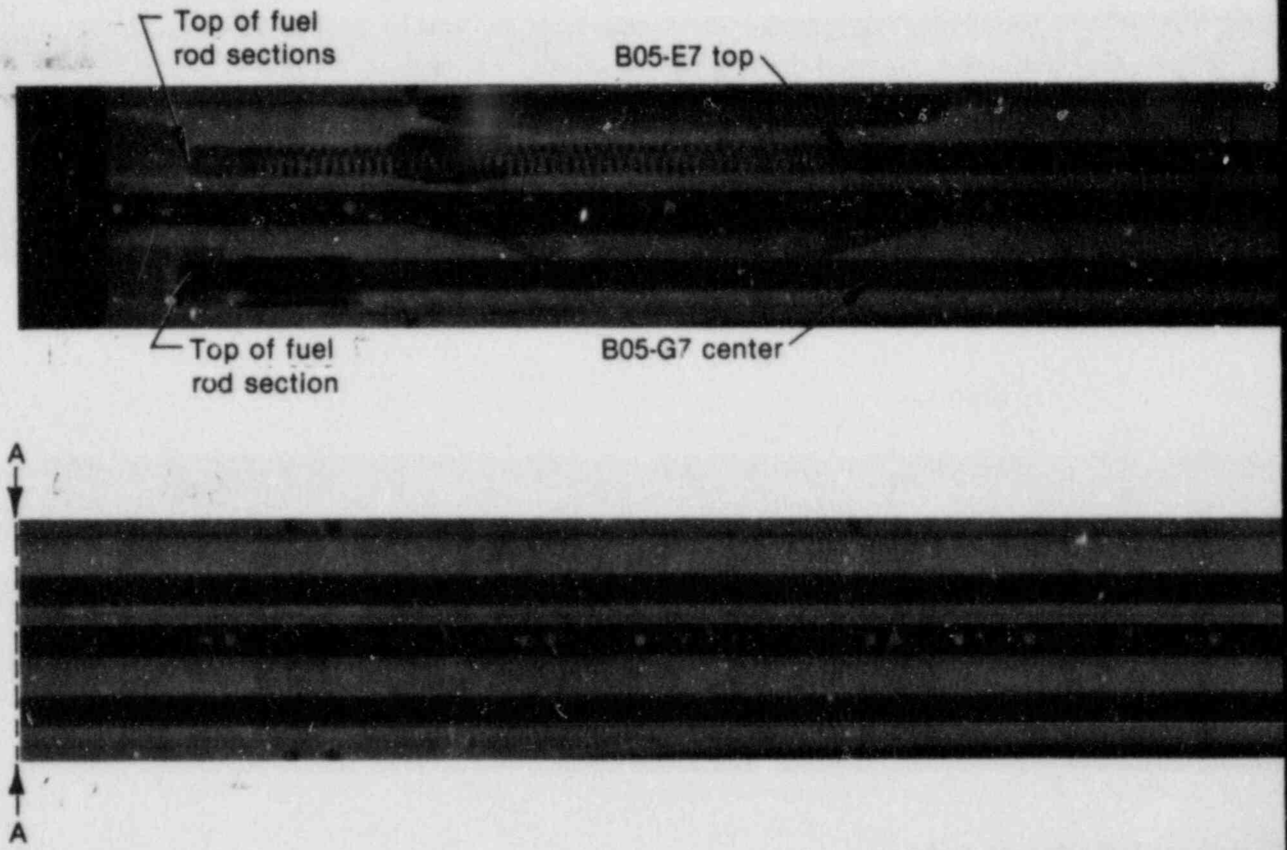
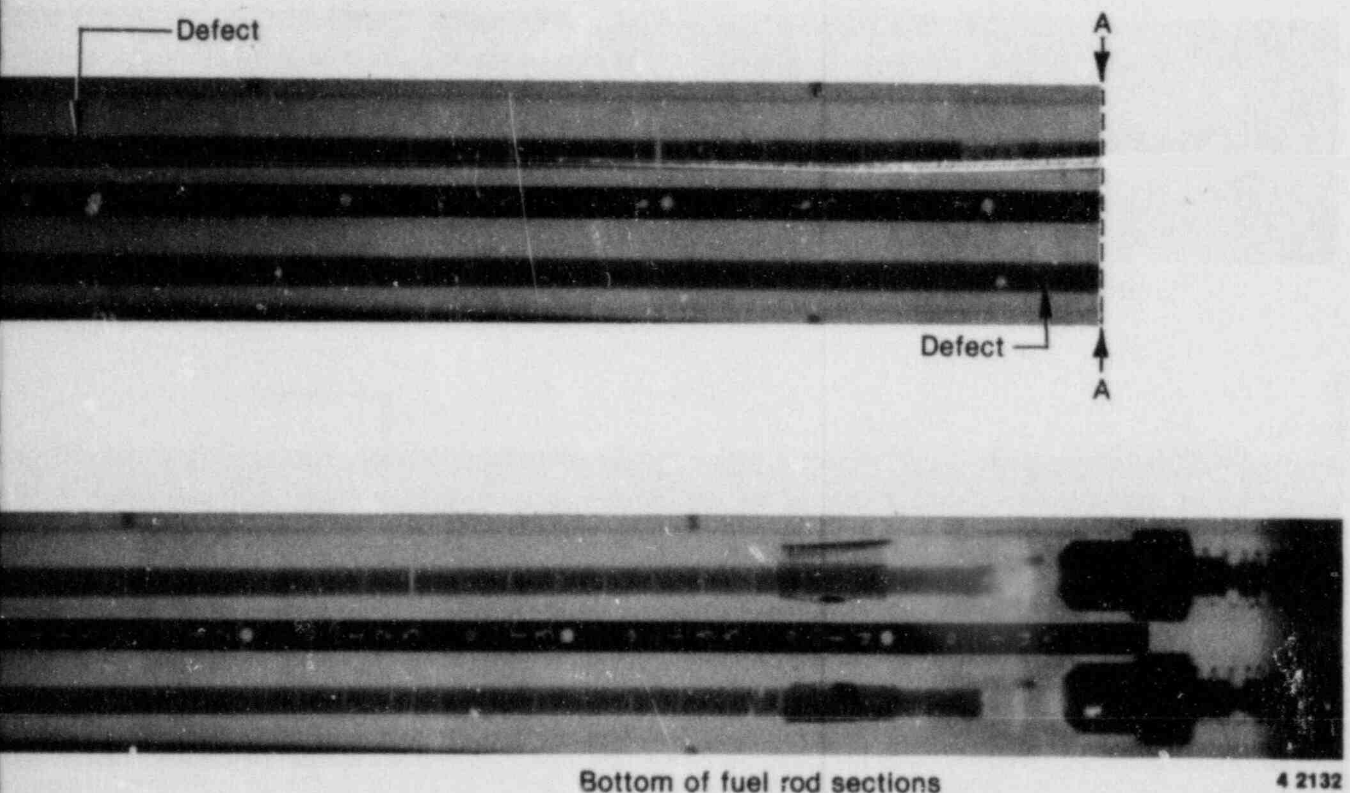


Figure 11. Neutron radiographs



of BO5-G7 center and BO5-E7 top sections.

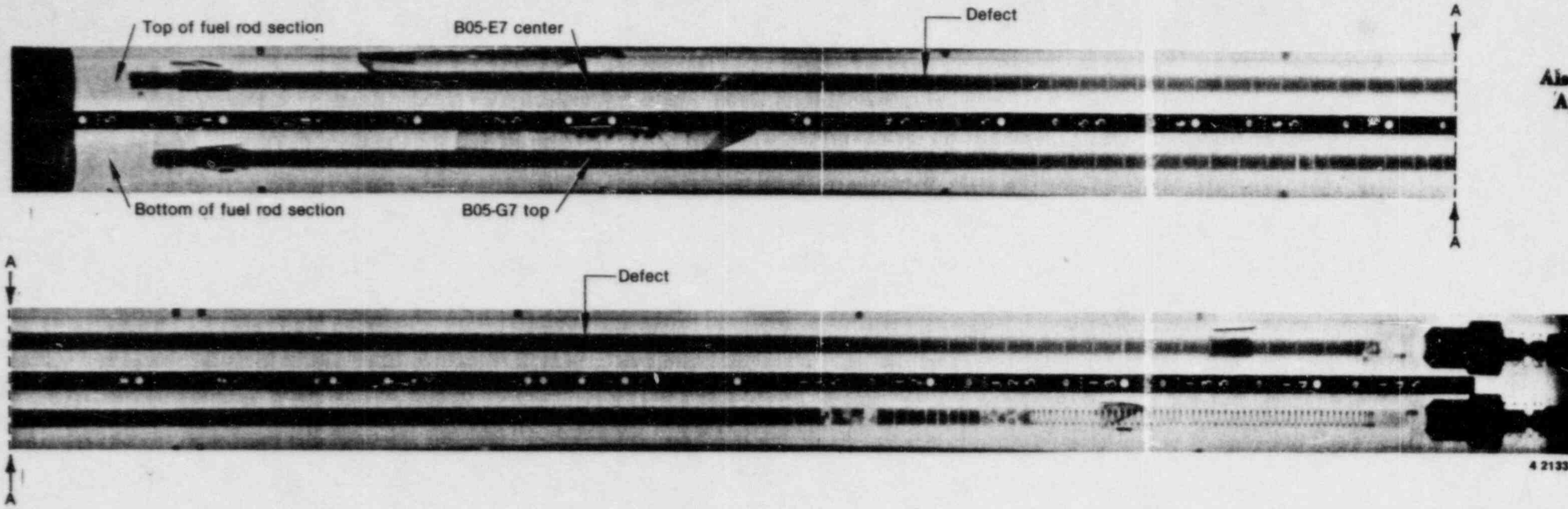


Figure 12. Neutron radiographs of BO5-E7 center and BO5-G7 top sections.

DISCUSSION

In unlimited air, a crack was initiated from the artificial defect located at the bottom of the BWR fuel rod PH462-C5. The neutron radiograph of this area indicates that about 13 cm of the fuel may be oxidized. The defect at the top of PH462-C5 did not enlarge because the defect may be blocked. The neutron radiograph also does not indicate fuel oxidation in the defect area, but some oxidation may be present at the center defect of PH462-C5. A fuel rod destructive examination will show the condition of the defects as well as that of the defects in other fuel rods. Cracks did not start at all defects in the BWR fuel rods.

The PWR fuel rod heated in unlimited air has not deformed. Assuming that all the artificial defects have penetrated through the wall of the cladding, this behavior may be attributed to the smaller gas gap resulting from cladding creepdown during reactor operation. Because the cladding diameter decreased from 10.72 mm to 10.57 mm, the cold diametrical gas gap decreased from 0.2 mm to 0.05 mm. With the smaller gap volume, a correspondingly smaller volume of air could enter the fuel rod and oxidize the fuel. Equally as well, the PWR oxidation behavior may result from the defects not being located at pellet/pellet interfaces. The interfaces with chamfered pellets provide an additional gas volume and surface area for oxidation of the pellets. If the defects are not located at the pellet interfaces, then the oxidation may be restricted to the gap volume described above.

The neutron radiographs indicate fuel oxidation at the defect of the top section of BO5-G7. The other defects may not have penetrated the cladding.

The visual examination indicates that the crud deposition on both the PWR and BWR fuel rods is very small. As a result, these rods may not be typical of heavier crud deposits that may be found on other fuel rods from other plants.

CONCLUSIONS

BWR fuel rods have developed cladding cracks at some artificial defects, but not at all defects, during heating in an unlimited air atmosphere at temperatures between 217°C and 229°C.

The storage of PWR fuel rods in unlimited air at 229°C has not shown any effect on the PWR fuel rods. A destructive examination is planned for the PWR rods as well as the BWR rods to learn more about the extent of the fuel oxidation.

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6. R. A. Lorenz et al., *Fission Product Release from Highly Irradiated LWR Fuel*, ORNL/NUREG/TM-287, February 1980.

APPENDIX A
PHOTOGRAPHS OF FUEL ROD DEFECTS

Figure A-1. Defect at 206 cm in B05-G7.

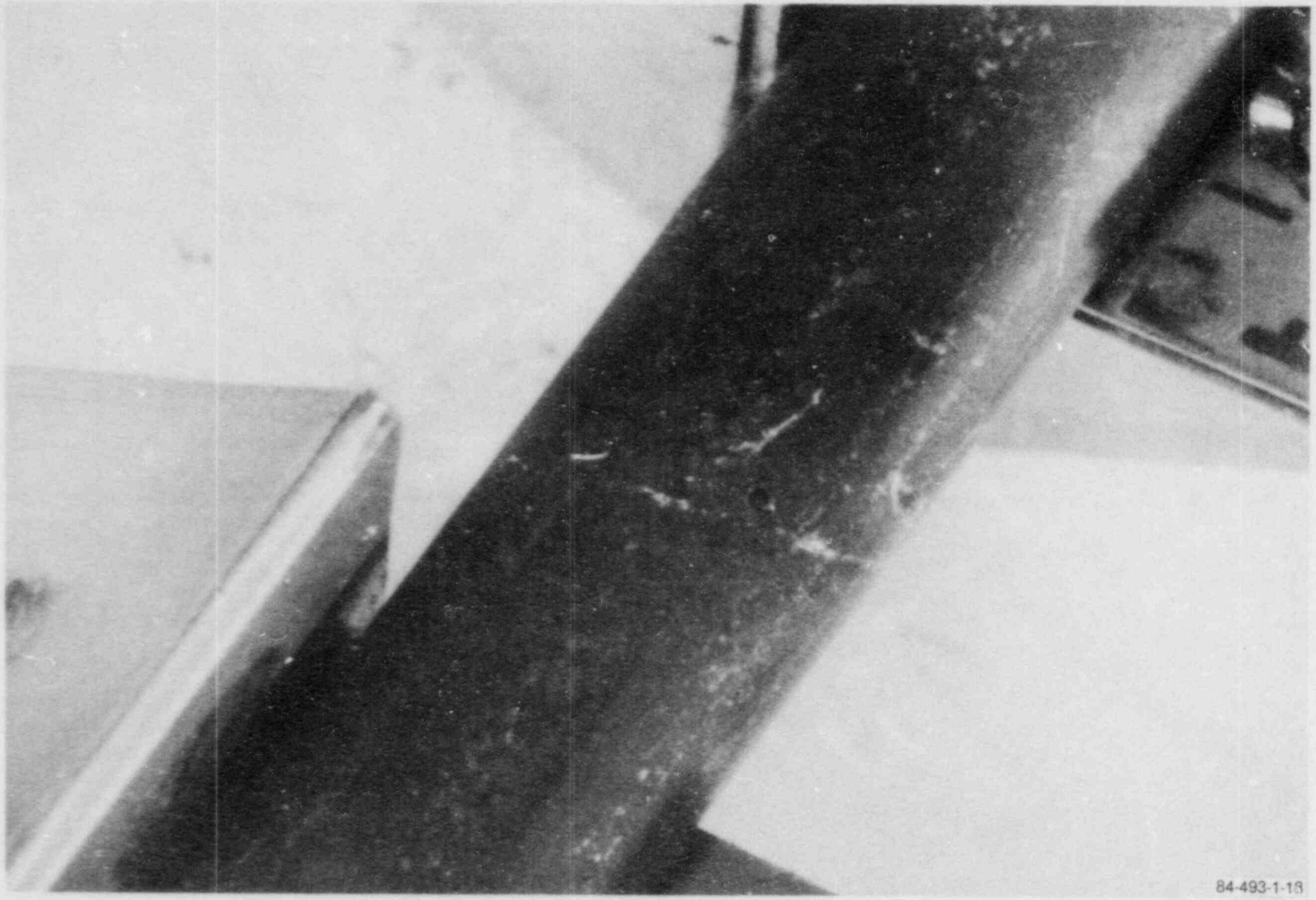

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Figure A-2. Defect at 225 cm in PH462-D6.

Figure A-3. Defect at 52 cm in PH462-D6.

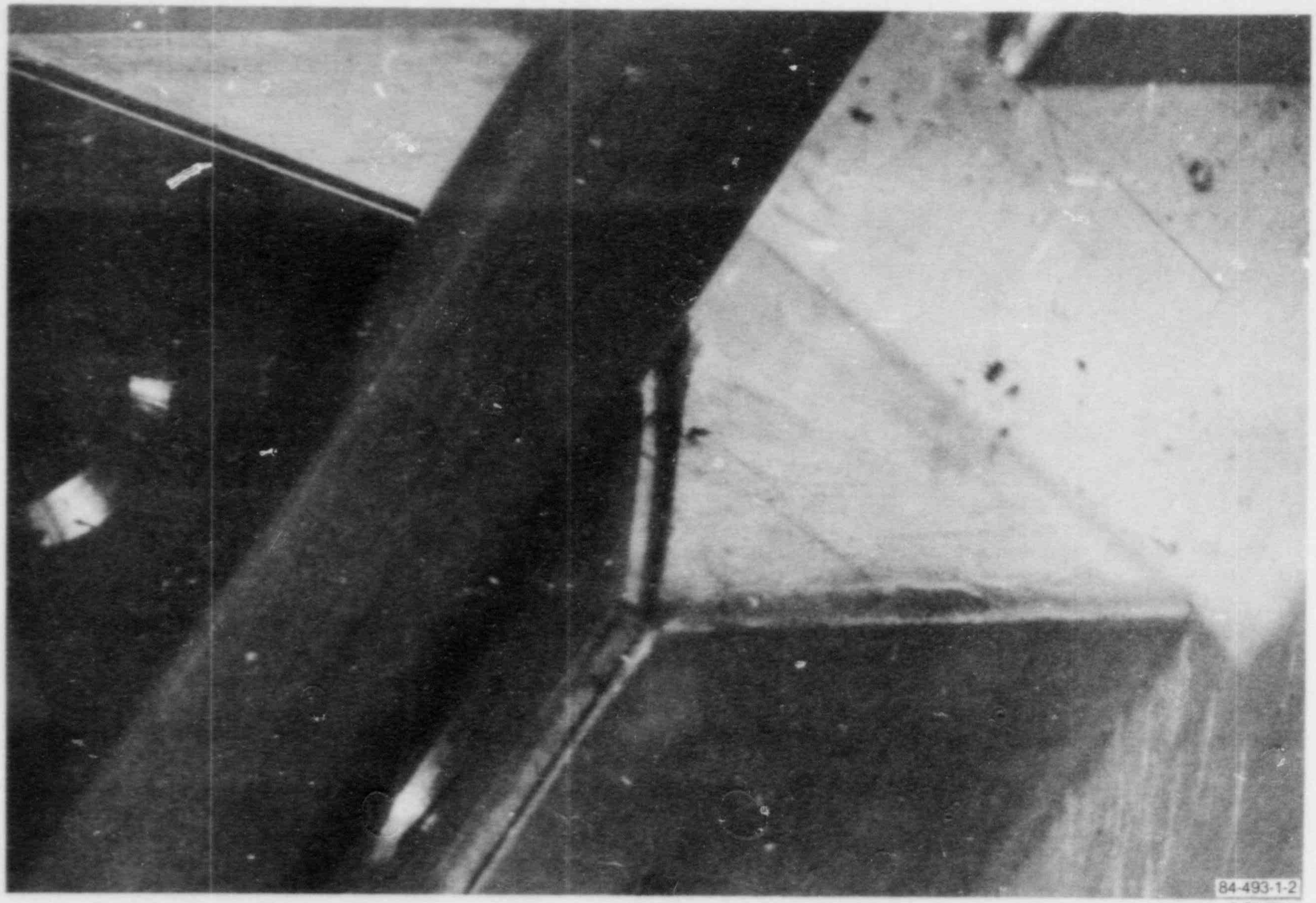

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Figure A-4. Defect at 206 cm in BO5-E7.

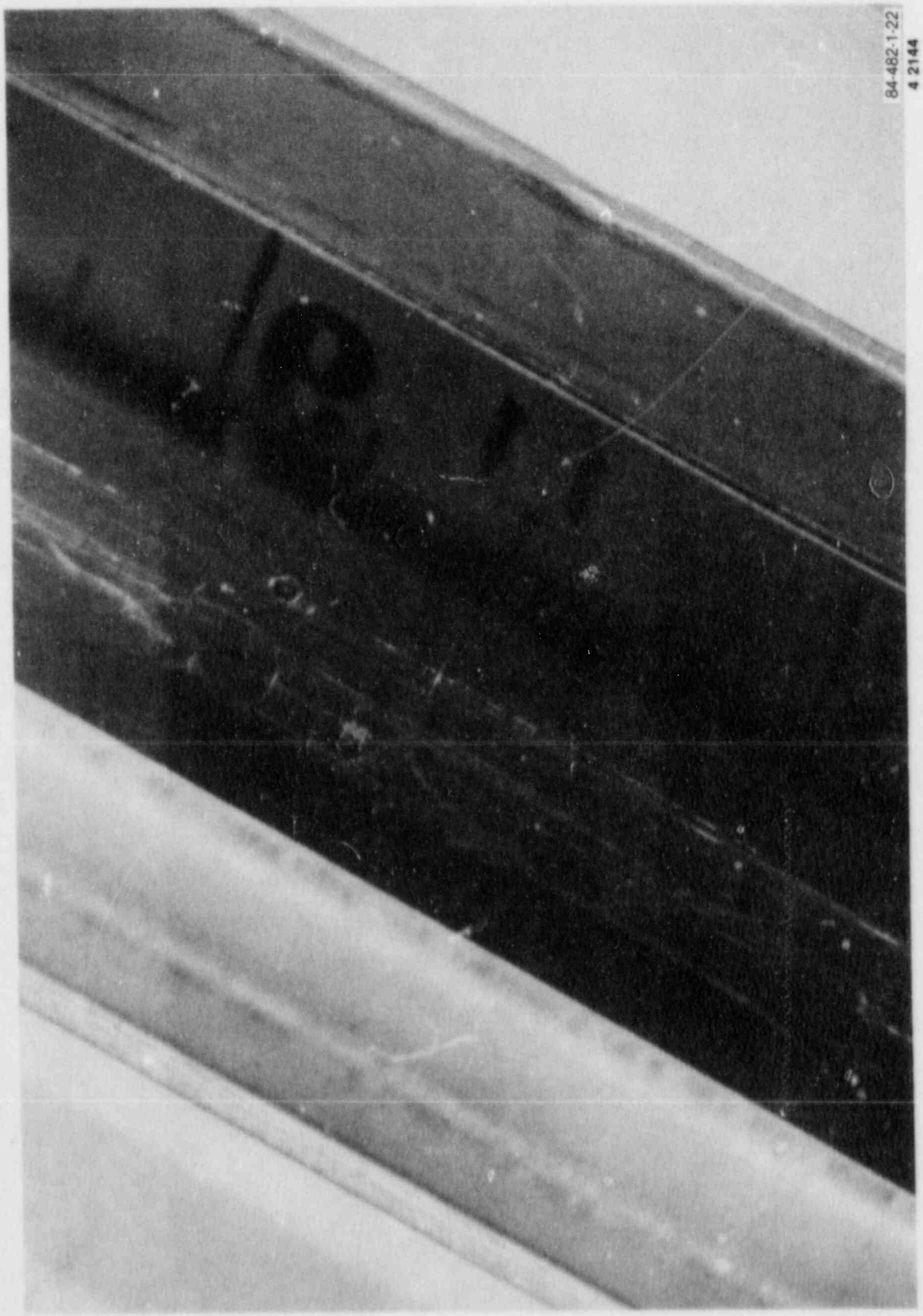


Figure A-5. Defect at 37 cm in BO5-E7.

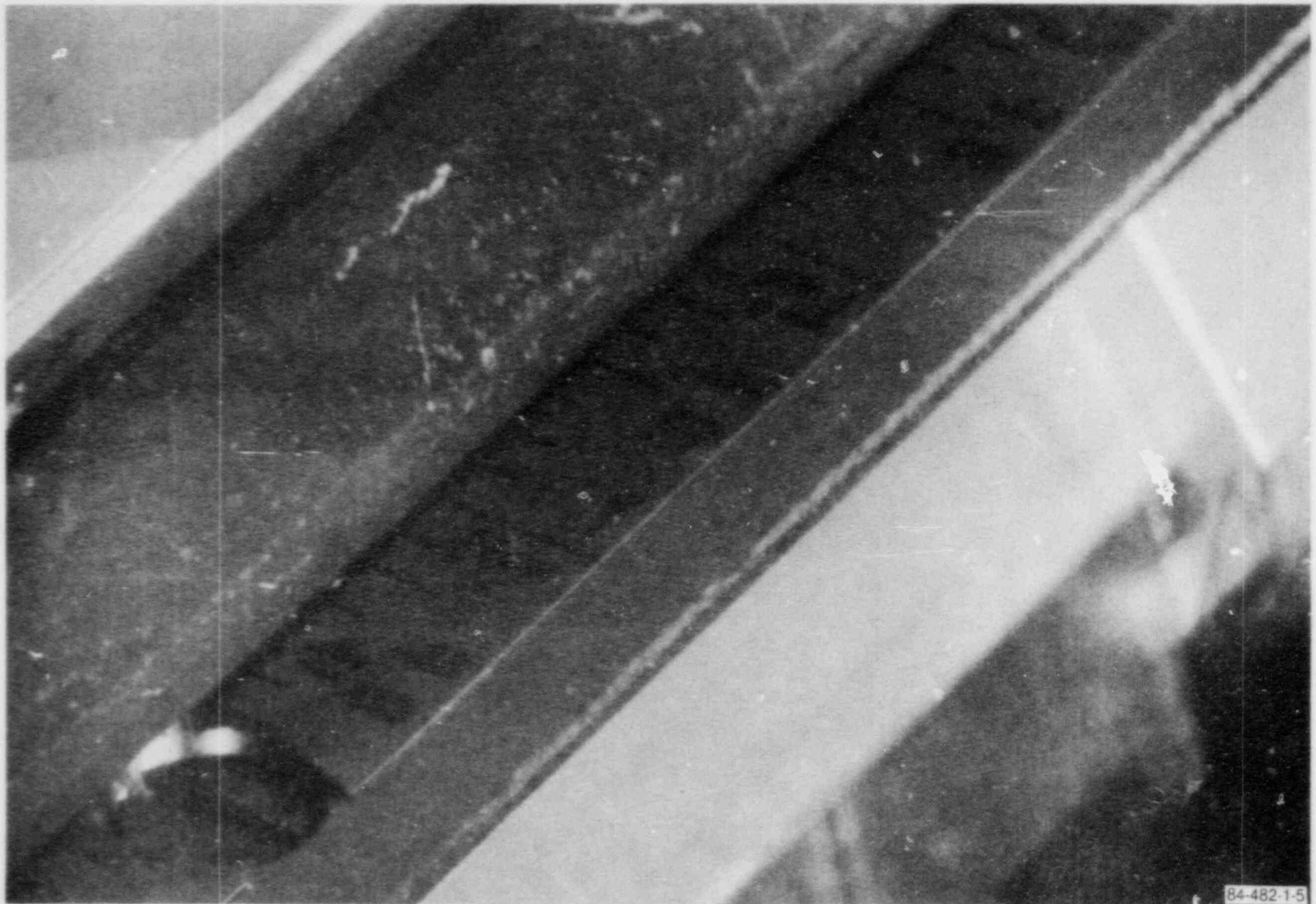
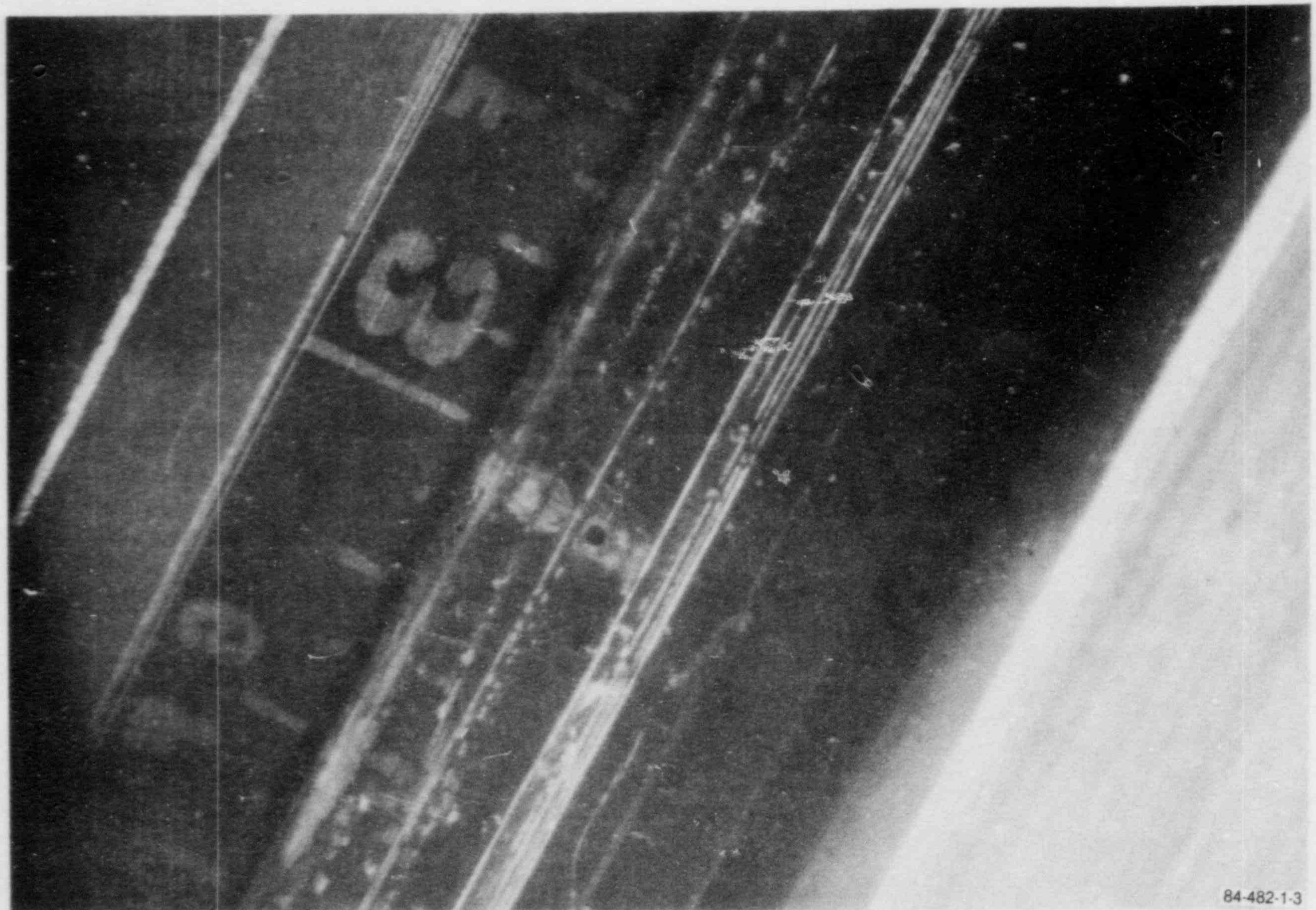


Figure A-6. Defect at 66 cm location in PH462-C5.



84-482-1-3
4 2142

Figure A-7. Defect at 236 cm location in PH462-C5.

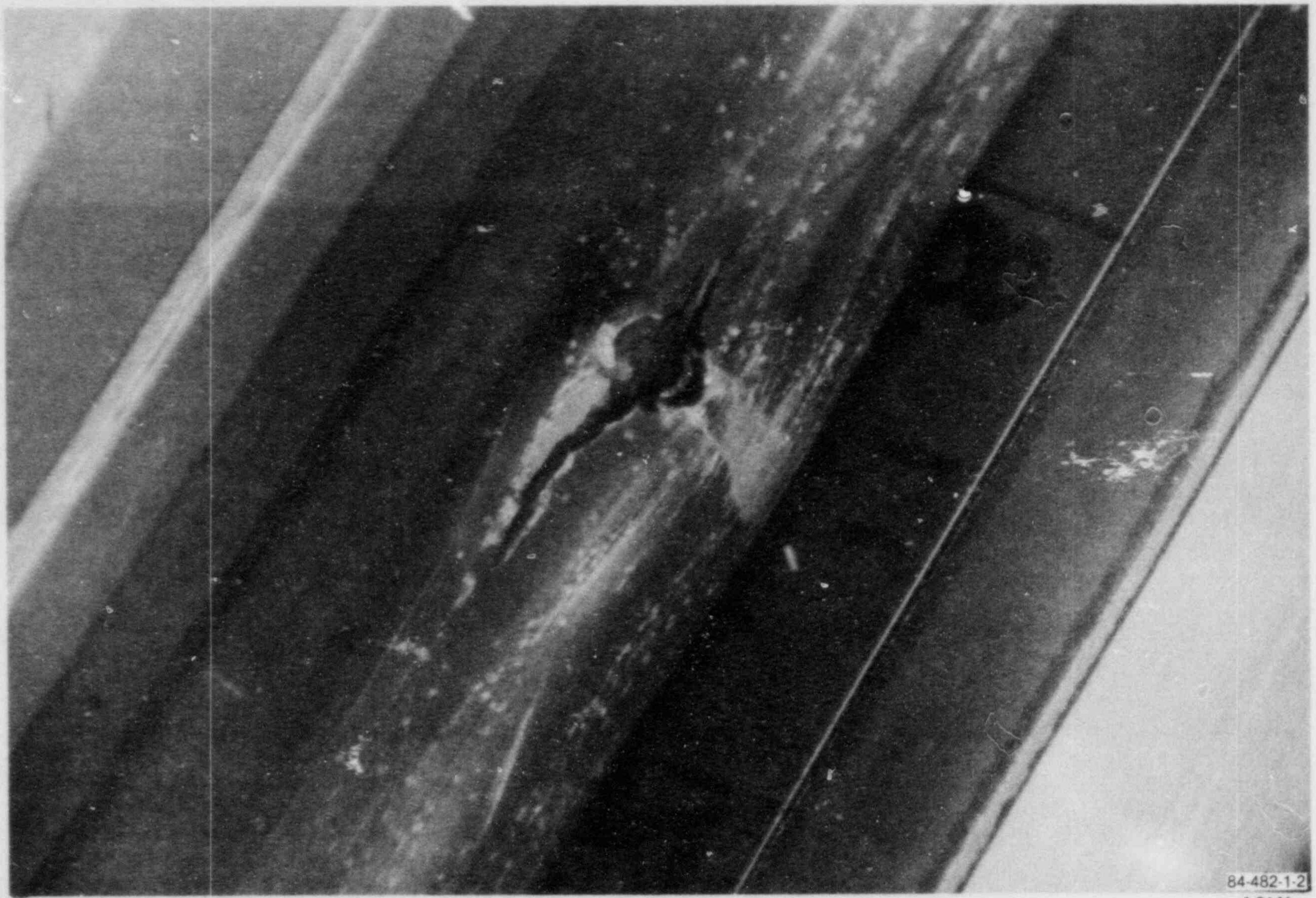


Figure A-8. Crack from bottom defect of PH462-C5.

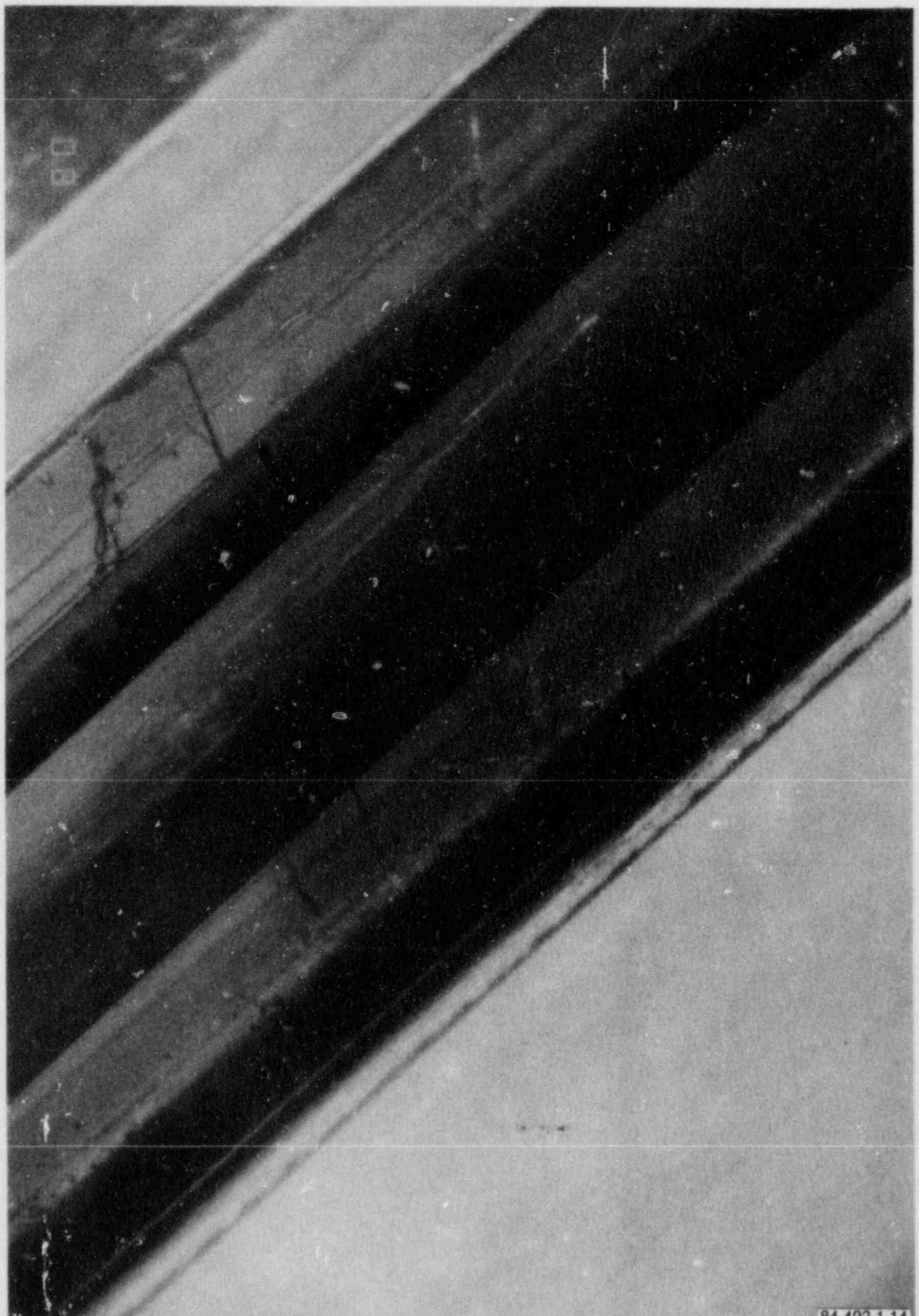


Figure A-9. Defect at 28 cm in BO5-G7.

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