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MASTER

**POST-IRRADIATION EXAMINATION OF
ZIRCALOY-2 AND INCOLOY-800 CLAD
FUEL RODS IRRADIATED TO 7000
MWd/TU IN THE
CONSUMERS BIG ROCK POINT REACTOR**

V. E. HAZEL

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT (04-3)-361

NUCLEAR FUELS DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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POST-IRRADIATION EXAMINATION OF
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V. E. Hazel

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SECTION I

INTRODUCTION

The objectives of this post-irradiation examination were to observe the condition of typical sound Consumers* BRP Developmental fuel rods and to establish the failure mechanisms encountered with Zircaloy-2- and Incoloy-800-clad powder fuel.

To ship the fuel rods from the Big Rock Point Reactor to the Vallecitos Radioactive

*Consumers Power Company, Big Rock Point (BRP) Plant, Charlevoix, Michigan.

Materials Laboratory (RML) hot cells, it was necessary to puncture and shear the rods into two sections each so they would be short enough to be handled at RML. The developmental fuel rods shipped to RML are listed, and the post-irradiation examination is summarized in Table 1. The fuel development work was performed under the High Power Density Program, U. S. AEC Contract AT(04-3)-361.

TABLE 1
CONSUMERS R AND D FUEL ROD SHIPMENT AND
HOT CELL EXAMINATION SUMMARY

<u>Rod⁽¹⁾</u>	<u>Gamma Scan</u>	<u>Dimensional Profiles</u>	<u>Metallography</u>	<u>Remarks</u>
CG-117 (I)	No	No	No	Sound rod.
CG-128 (P)	No	No	No	2- to 3-mil wear at one spacer, sound rod.
CG-143 (P)	Yes	Yes	Yes	Spotted cladding appearance, sound rod.
CG-251 (I)	No	No	No	Sound rod.
CK-240 (P)	Yes	Yes	No	Visually intact.
CK-360 (P)	No	No	No	Longitudinal crack in cladding.
CK-361 (P) and CK-537 (P)	No	No	No	Short sections of failed rods.
CR-123 (P)	No	No	No	Sound rod.
CR-125 (P)	No	Yes	Yes	Sound rod.
CR-132 (I)	No	No	No	Sound rod.
CR-163 (P)	Yes	Yes	Yes	Circumferential crack at top, bottom end plug missing.

Notes:

- (1) (P) = peripheral rod in bundle, (I) = interior rod. Peripheral rods generally operated at 10 to 15% higher power than interior rods. CG rods are from bundle D-2, CK from D-12, and CR from D-19.
- (2) See Table 2 for fuel design.
- (3) All fuel rods were visually examined.
- (4) The four CR rods were bubble leak checked at 20 psi. Only CR-163 emitted bubbles.
- (5) CR-125 and CR-163 were neutron radiographed. CR-163 showed a dark spot (cladding hydriding) at the top crack.

SECTION II

FINDINGS

- a. The observations on rods from bundle D-19, Zircaloy-2-clad, vipak powder, are consistent with a hydrogenous impurity explanation for the failures. The D-19 rod failures may have been accelerated by mechanical stresses imposed on the cladding by a Zircaloy disc at the top of the fuel. Additional work is required to verify and identify the responsible impurity or impurities.
- b. The Zircaloy-2-clad, pellet-fuel rods were sound after 7500 MWd/TU exposure. No detrimental effect from relatively heavy localized crud deposits was observable.
- c. Visual examination of Incoloy-800-clad powder fuel rods confirmed the failure severity and probable intergranular character of the cladding cracks.

SECTION III

FUEL ROD DESIGN

A partial review of the fuel rod design is listed in Table 2 and will be helpful in understanding some of the results and discussions in following sections, particularly in

relation to the Zircaloy-clad powder fuel rods. Additional features of the fuel design can be found in Reference (1), page 18.

TABLE 2
FUEL DESIGN SUMMARY

<u>Bundle Numbers</u>	<u>Rod Prefix</u>	<u>Cladding</u>	<u>Wall (inch)</u>	<u>Fuel</u>	<u>Remarks</u>
D 1, 2, 3	CG	Zircaloy-2	0.030	UO ₂ Pellet 94% TD	Cold diametral gap—7 mils.
D 10-15	CK	Incoloy-800	0.011	UO ₂ Powder 91% TD	Seam-welded cladding, cold worked.
D 18, 19, 20	CR	Zircaloy-2	0.030	UO ₂ Powder 84% TD	Disc at top of fuel column.

Notes:

- (1) Rod outside diameter is 0.425 inch, active fuel length is 69 to 70 inches.
- (2) % TD = percent of theoretical density.
- (3) The disc in the CR rods was 0.012-inch-thick Zircaloy-2, slightly cupped, and close fitting inside the cladding. Its purpose was to separate the fuel from the end plug to minimize UO₂ contamination of the end plug weld zone.

SECTION IV

IRRADIATION HISTORY OF FUEL RODS EXAMINED

The CG rods operated for 7500 MWd/TU, except for rod CG-117 which was out of the bundle one cycle and accumulated 3950 MWd/TU. The maximum rod heat flux was 355,000 Btu/h-ft² (11.6 kW/ft) early in life, and 314,000 Btu/h-ft² (10.2 kW/ft) near the time of removal.

The CK rods were irradiated to 7200 MWd/TU. The maximum heat flux was

430,000 Btu/h-ft² (14.0 kW/ft) early in life, and 316,000 Btu/h-ft² (10.3 kW/ft) close to the time of removal.

The exposure of the CR rods was 7300 MWd/TU. The maximum rod heat flux was 315,000 Btu/h-ft² (11.3 kW/ft). Near the time of discharge, the maximum heat flux was 300,000 Btu/h-ft² (9.8 kW/ft).

SECTION V

FISSION GAS RELEASE

During the puncturing operation, fission gases were collected in vacuum tanks. Radiation readings from these tanks were 2 to 8 mR/h. The expected radiation reading is about 200 mR/h for a tank containing 1% of the Kr-85 generated in one of the above fuel rods. Thus, measured dose rates indicate that only a small fraction of a percent of the generated fission gases were released and/or collected.

Centerline operating temperatures for the Consumers R and D fuel rods examined were calculated to be 2600 to 3200°F much

of the time. * equivalent to volumetric average temperatures of 1700 to 2000°F. Using these volumetric average temperature values, the fission gas release fraction should be on the order of 5%, based on Figure 1 of Reference (2). The low fission gas release in these rods is actually below the scatterband of the Reference (2) data for the appropriate volumetric average temperatures.

Gas from rod CR-125 was analyzed by gas chromatography with the results listed below.

*Reactor computer output.

CR-125 GAS TANK ANALYSIS

Gas	Oxygen	Nitrogen	Xenon	Krypton	Hydrogen	Helium
Volume, percent	19.0	79.9	0.22	Trace	0.12	0.33
Precision	1.0	2.0	0.02		0.02	0.01

Air in-leakage is obvious in this analysis, but the time and location of its entry is uncertain. The gas collection tanks were helium leak checked during construction, but a small leak may have developed, or a foreign particle may have lodged on the valve seat preventing full closing. An air leak of 10^{-6} cm³/sec would account for the quantity of oxygen and nitrogen observed. Any out-diffusion from the tank would preferentially reduce the quantities of the lighter gases,

making the above proportions incorrect. If, however, the above ratio of hydrogen to helium represents what was in the rod, it is evidence that CR-125 was unfailed.*

*Previous results at the Vallecitos Nuclear Center have shown that failed fuel rods typically contained much more hydrogen than helium, probably a result of water entry and chemical interactions which release hydrogen.

SECTION VI

NONDESTRUCTIVE EXAMINATION

The nondestructive examination consisted of a.) visual examination of all rods, b.) gamma scanning, c.) dimensional profiling, d.) leak testing, and e.) neutron radiographing of selected rods.

6.1 VISUAL EXAMINATION

The cladding surfaces had an irregular brownish-red to black appearance. Zircaloy-clad rod CG-143 had white oxide spots over much of the cladding surface. Localized deposits at spacers were observed on several rods (Figure 1). Cladding wear at the spacers was generally small. Shown in Figure 2 is the greatest amount of wear observed, estimated to be 2 to 3 mils maximum.

The lower end plug was missing from Zircaloy-2-clad powder fuel rod CR-163. This is shown in Figure 3a. It is estimated that 0.1 inch of the fuel column is missing, in addition to the end plug. Part of the lower end plug was subsequently found wedged in the lower spacer band of assembly D-19, which contained rod CR-163, Figure 3b. Apparently the cladding cracks were so fine or else covered with deposits that they could not be seen when this assembly was originally

1.9X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 1. LOCALIZED DEPOSIT BUILDUP AT A SPACER (PART OF THE DEPOSIT HAS CHIPPED AWAY) ZIRCALOY-2-CLAD POWDER FUEL ROD CR-163

visually examined after removal from the reactor.⁽³⁾ An intact end plug is shown in Figure 3c for comparison.

The powder fuel was well packed and remained in place both at the sheared

2X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 2. WEAR AT SPACER WIRE CONTACT POINT (NO SPRINGS IN SPACER) - ZIRCALOY-2-CLAD PELLETT FUEL ROD CG-128

locations and at the missing end plug. Little, if any, fuel fell out of the clad tubes during shipping and handling.

Shown in Figure 4 is the failed end of Incoloy-800-clad, swaged powder rod CK-537. A split in the Incoloy cladding of rod CK-360 is shown in Figure 5. In nearly all of the failure positions there were straight longitudinal cracks. These rods were clad with welded and drawn tubing, and the straight cracks may be at the tube weld seam. This explanation is suggested by results in Reference (3) and is speculative, since no new metallography was performed.

6.2 GAMMA SCAN

Rods CG-143, CK-240, and CR-163 were gamma scanned for determining their integrated axial power profile. Approximately 5% flux depression was noted at axial positions corresponding to spacer locations. The results are listed in Table 3.

1.9X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 3a. END REGION OF ZIRCALOY-2-CLAD ROD CR-163 SHOWING THAT THE LOWER END PLUG IS MISSING

0.7X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 3b. PART OF LOWER END OF ROD CR-163 WEDGED AT THE LOWER SPACER BAND OF ASSEMBLY D-19

2X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 3c. AN INTACT LOWER END PLUG OF A ZIRCALOY-2-CLAD POWDER FUEL ROD

1.9X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 4. FRACTURE OF INCOLOY-800-CLAD ROD CK-587—A STRAIGHT-LINE CRACK EXTENDS FROM THE ARROW DOWNWARD

1.8X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 5. SPLIT IN INCOLOY-800-CLAD ROD CK-360

TABLE 3

GAMMA SCAN RESULTS

Rod	Location of Peak	Peak/Average	Local/Average	
			At Top End of Rod	At Bottom End of Rod
CG-143	Upper one-fourth of rod	1.44	0.9	0.23
CK-240	Mid-rod	1.4	0.6	0.15
CR-163	Upper one-fourth of rod	1.33	0.75	0.2

6.3 DIMENSIONAL PROFILES

The rods that were gamma scanned were also dimensionally profiled at the RML. The objectives were to: a.) obtain independent results for comparison with previous in-pool profiles, ⁽⁴⁾ and b.) pin-point the axial and angular locations of dimensional variations which might be of interest for further examination [see References (1) and (4) for

significance and interpretation of profile characteristics]. The general pattern of the profiles agreed well with the in-pool profiles. The absolute values of the helical trace mean value generally agreed within 1 mil except for rod CR-163, where the in-pool and RML traces showed a 1.5-mil difference in absolute value. A 5-mil-high bulge was noted near the upper end plug of rod CR-163 corresponding to the upper failure location (see

Section VII). The profiles of rod CG-143 were used to select the location for a metallographic sample to evaluate surface deposits.

6.4 LEAK TESTING

All four CR rods (Zircaloy-clad powder fuel) were leak tested to determine if any of the other powder fuel rods besides CR-163 were failed, and to pinpoint the location of the penetration near the upper end plug of CR-163.* The deliberate puncture holes and lower end of CR-163 were sealed with epoxy resin. The rods were then pressurized with 20-psi argon and immersed in water. No bubbles were emitted from any of the rods except for the top end of CR-163. Shown in Figure 6 is the CR-163 circumferential crack located by the leak testing.

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 6. CIRCUMFERENTIAL CRACK AT TOP OF ZIRCALOY-2-CLAD ROD CR-163 AFTER INITIAL CUTTING OF METALLOGRAPHIC SECTION

*Bubbles were observed coming from the upper part of this rod during preparation for shipping.

6.5 NEUTRON RADIOGRAPHY

The ends of rods CR-163 and CR-125 were neutron radiographed to compare the appearances of end plug regions for a failed rod with an intact rod. The neutrograph is shown in Figure 7. Darker areas in the positive prints correspond to white areas on the negative which, in turn, are due to the attenuation and scattering of neutrons. Thus, the fuel and hydrogenous material appear dark and the cladding is light in the figure.

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 7. COMPARISON NEUTRON RADIOGRAPHS OF ZIRCALOY-2-CLAD FUEL RODS CR-163 AND CR-125, TOP END

The curved upper surface of the CR-125 fuel column was caused by the cupped surface of the separator disc (see Fuel Rod Design, Section III). The dark spots on the cladding surface are epoxy resin used to seal the puncture hole (see Introduction, Section I). The dark particles between the fuel column surface and end plug could be either fuel particles or pieces of the separator disc. The CR-125 end plug appears darker than the CR-163 end plug. It is uncertain whether this is a real indication of relative hydride content or merely from a residual epoxy (hydrogenous) film on CR-125.

Rod CR-163 does not have a well-defined upper fuel column surface, and the fuel has moved up against the end plug indicating failure

of the separator disc. The dark spot in the cladding is zirconium hydride at the crack (see Metallography, Section VII).

SECTION VII

METALLOGRAPHY

7.1 ZIRCALOY-2-CLAD VIPAK POWDER FUEL

Longitudinal sections were made of each end of rods CR-163 (failed) and CR-125 (sound). Several different planes of the upper end of CR-163 were made and polished. Much of the fuel and the separator disc were lost during preparation of the sample. The circumferential crack was present in each of the planes. The crack and the adjacent massive cladding hydriding are shown in Figures 8a, 8b, and 9. The cladding has locally thickened about 10% because of the volume increase on hydriding, and has also bulged outward. It was not clear whether the bulge was totally the result of the hydriding or was also influenced by radial loads from the separator disc which was at or near the crack. Most partial cracks initiated at the inner surface of the cladding. Some of the cracks had been exposed long enough to have the fracture surfaces oxidized. The cladding hydride content was significantly lower at regions away from the cracks.

The metallographic section of the CR-163 lower end is shown in Figures 10 and 11. As at the upper end, there is massive local cladding hydriding and thickening, with the partial cracks occurring on the inner surface. Approximately 1 inch above the cracks the hydride level diminishes to normal. The fuel particles appear to have a second phase at their surfaces, probably higher oxides.

The upper end plug section of rod CR-125 is shown in Figures 12, 13, and 14. The cladding and end plug have a slightly higher hydride content than regions away from the upper end, although they are still intact. The separator disc has deteriorated, apparently having become very brittle. The layered structure of the cracks is similar to Figure 8a and to Figure 4.3 of Reference (5), but analyses have not been made of the disc to verify the presence of hydride.

The lower end section of CR-125 appeared normal. There was little hydriding and no visual indication of overheating or mechanical damage. The macrograph is shown in Figure 15. Shown in Figure 16 are part of the end plug and the typical cladding condition in the area.

7.2 ZIRCALOY-2-CLAD PELLET FUEL

One metallographic cross section was made of the Zircaloy-2-clad, pellet fuel rod CG-143 to verify the profilometer measurements of deposits on the cladding and to observe cladding conditions under the deposits. This cross section is shown in Figure 17. The typical cladding condition is shown in Figure 18. The deposit has a very high density, is adherent, and extends around 180 degrees of circumference with a maximum thickness of 3.5 mils. The detailed deposit appearance is shown in Figure 19. Between the deposit

AS POLISHED

5X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 8a. FIRST METALLOGRAPHIC
PLANE OF CR-163 UPPER
FAILURE

AS POLISHED

5X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 8b. SECOND METALLOGRAPHIC
PLANE OF CR-163 UPPER
FAILURE

and cladding is an oxide layer 0.1 to 0.2 mil thick. This oxide layer extends completely around the circumference and locally thickens to 3 mils on the portion of the circumference with least deposit (see Figure 20). The thicker areas correspond to the white spots observed visually. The cladding was locally thinned about 2 mils (7%) at the oxide spots. There was no evidence of cladding overheating or deterioration at either the oxide or deposit region.

7.3 INCOLOY-800-CLAD SWAGED POWDER FUEL

No new metallography was prepared on the Incoloy-800-clad rods. A metallographic section of a piece of cladding from bundle D-10 prepared earlier is shown in Figure 21, indicating the intergranular nature of the cracking.⁽³⁾ The Incoloy-800 failures, coupled with generally good Zircaloy-2 performance, have substantially reduced interest in this material for cladding in Boiling Water Reactors.

ETCHED 75X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 9. CRACK AND CLADDING HYDRIDE
OF ZIRCALLOY-2-CLAD FUEL
ROD CR-163 UPPER FAILURE

AS GROUND 5X
(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 10. METALLOGRAPHIC PLANE
OF ZIRCALLOY-2-CLAD FUEL
ROD CR-163 LOWER FAILURE

ETCHED
(REDUCED TO 75% FOR REPRODUCTION) 75X

**FIGURE 11. CRACKS AND CLADDING
HYDRIDES OF ZIRCALOY-
2-CLAD FUEL ROD CR-163**

AS POLISHED 5X

(REDUCED TO 75% FOR REPRODUCTION)

**FIGURE 12. METALLOGRAPHIC PLANE OF
ZIRCALOY-2-CLAD FUEL ROD
CR-125 UPPER END**

AS POLISHED

100X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 13. FUEL ROD CR-125 SEPARATOR DISC

ETCHED

100X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 14. FUEL ROD CR-125 SEPARATOR DISC

AS POLISHED

5X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 15. METALLOGRAPHIC SECTION OF
FUEL ROD CR-125 LOWER END

ETCHED 75X
(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 16. LOWER END PLUG AND CLADDING
OF FUEL ROD CR-125

AS GROUND

10X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 17. FUEL AND CLADDING CROSS SECTION OF FUEL ROD CG-143

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 18. TYPICAL CLADDING OF FUEL ROD CG-143

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 20. OXIDE SPOT ON CG-143

AS POLISHED

500X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 19. DEPOSIT ON CG-143

10 PERCENT OXALIC ETCH

250X

(REDUCED TO 75% FOR REPRODUCTION)

FIGURE 21. INCOLOY-800 CLADDING INTERGRANULAR CRACKING IN SEAM WELD STARTING ON OUTSIDE DIAMETER

SECTION VIII

INTERPRETATION OF OBSERVATIONS

8.1 ZIRCALOY-2-CLAD POWDER FUEL

The examination revealed that one out of four rods (CR-163) returned had failed with a cladding crack near the upper end plug and the lower end plug broken off. The primary or first cause of failure cannot be unequivocally determined. There is some evidence to support internal hydriding from hydrogenous impurities in the rod as the failure mechanism. The final rod closure was effected by evacuating the rod to less than 100 microns at room temperature and back-filling with helium. Some high temperature out-gassing was applied to the fine particle UO_2 but, in retrospect, the total control over powder gas content was not sufficient to preclude hydrogenous contamination positively.

For this mechanism, the postulated failure sequence would be as follows: hydrogen released from the undetected contaminant preferentially reacted at the cladding disc region and massively hydrided both the cladding and the disc. The reaction was abetted by the mechanical contact between the cladding and disc which served to rupture their protective oxide films. The volume increase of the hydrided disc and/or fuel radial expansion stressed the hydride embrittled cladding, eventually resulting in cladding cracking. Fuel expansion loads on the disc ultimately fractured the disc and allowed the fuel to redistribute upward as seen in the neutron radiograph (Section VI). Water entering the rod at this upper crack would then account for the subsequent hydriding and fracture of the lower end plug and its fracture as the rod was removed. Lower end plug failure has been observed previously as a secondary failure after the rod failed elsewhere. ⁽⁶⁾

Alternatively, the lower end plug of rod CR-163 might have been the actual first point of initial water entry. This could have occurred from a poor weld, a crack induced by vibratory compaction, or from internal hydriding.

On balance, the hydrogenous impurity explanation is somewhat favored because of the CR-125 rod evidence, i.e., a disintegrated brittle disc in a sound rod, and because of the high frequency of failure, i.e., all three assemblies of this type indicated fission gas release. ⁽³⁾ This explanation is also consistent with the failure diagnosis at other laboratories where similar failure characteristics—local areas of massive hydriding—were encountered with Zircaloy-2-clad fuel. ⁽⁵⁾⁽⁷⁾

8.2 ZIRCALOY-2-CLAD PELLET FUEL

The main interest in the pellet-Zircaloy rods was the cladding performance in areas with relatively heavy deposits. The visual examination and the metallographic section both indicate satisfactory performance for up to 7500 MWd/T average exposure. However, if deposits continue to build up without spalling off, the cladding could still eventually over-heat. Profile measurements of rod CG-143 suggest that spalling is actually taking place. ⁽⁴⁾ If this is the case, the deposit thickness and resulting temperature increase are self-limiting. The fuel should be examined again after 15,000 to 20,000 MWd/T exposure to determine the deposit development completely.

One apparent beneficial effect of the deposits is the absence of localized heavy oxide spots under them (assuming that such oxide spots are potentially detrimental—for example, eventually thinning the cladding locally so that failure results).

It should be noted that all of the above discussion and observations on deposition are specific for the past BRP situation where the feedwater heaters contained Admiralty metal which contributed major percentages of copper and zinc to the deposition. The feedwater heaters have recently been changed to stainless steel, so future deposits will be different in composition and are expected to be much lower in magnitude.

8.3 INCOLOY-800-CLAD SWAGED-POWDER FUEL

Visual examination of the failed Incoloy-800 fuel rods indicated gross failure with many straight-line cracks, which probably initiated at the tube weld seam. The slight irregularities and branches at the fracture surfaces indicate that they are probably intergranular, similar to results obtained previously with pieces of irradiated cladding from the same fuel bundles.⁽³⁾

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