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FINAL REPORT: WARP FAILURE OF A THIRTY-SIX INCH LONG URANIUM-2 WT. % ZIRCONIUM ALLOY TUBULAR FUEL ELEMENT, PT-IP-250-A, (RM-568)

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URANIUM - 2 WT. % ZIRCONIUM ALLOY TUBULAR FUEL ELEMENT,
PT-IP-250-A, (RM-568)

L. E. Kuhlken

January 25, 1963

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INTRODUCTION

The N-Reactor will be charged with tubular fuel elements consisting of two components. Both components, an outer tube with a concentric inner tube, have a uranium core, coextruded with a Zircaloy-2 cladding. The testing in support of N-Reactor fuels has been conducted in the experimental loops in the K-East Reactor. Although the process tubes in the KER loops are smaller than the proposed N-Reactor process tubes, the test loops operate at the water temperatures and pressures that will exist in the N-Reactor. To obtain the desired heat fluxes and core temperatures in KER loop test elements, enriched uranium fuel was used. The cladding surface temperatures and fuel temperatures were near anticipated N-Reactor values.

SUMMARY

A KER tube-in-tube fuel element with a 1.6% enriched uranium-2 wt.% zirconium core was irradiated to 1250 MWD/T before failure on April 23, 1960. The inner tube warped during irradiation and made contact with the inner surface of the outer element causing two hot spots. Oxidation and hydriding then caused the cladding to fail--thus exposing the uranium alloy to the coolant. Corrosion of the alloy core was much less

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than would have been expected in a fuel element with a uranium core and a similar cladding defect. The failed inner tube was found to have decreased 0.025 inch in length during irradiation and to have increased 2% in outside diameter at the upstream end.

FABRICATION

The outer and inner fuel elements discussed in this report was made from coextrusions No's. 21132 and 21073, respectively, by Nuclear Metals, Inc. (1) The fuel core material of 1.6% enriched uranium alloyed with 2 wt.% zirconium was fabricated by double vacuum induction melting. The rough castings were machined to final billet size before coextrusion with Zircaloy-2 cladding components made from Allegheny-Ludlum Steel Corporation, Heat No. 8YG050. At Hanford, the extrusions were chemically stripped of copper and cut to length. The cut pieces were beta-heat-treated in a salt bath at 730 C and air-cooled. The inner tube was bowed after heat treatment and was straightened by rolling on an asbestos plate on the floor. The remaining bow was 0.075 inch, single throw, and was uniform in one plane. The uranium was etched from the ends of the inner and outer pieces to a depth of 0.250 inch in an HCl solution, and the resulting recess was cleaned in an HF-HNO₃ solution. End rings were welded into place by the electron beam welding process; and the cladding surface was vapor blasted, pickled in the HF-HNO₃ solution, and examined for defects. After the fuel element supports were spot-welded into place, the outer and inner tubes were autoclaved in 400 C steam. The completed fuel element components are shown in Figure 1.

A reject inner piece from the extrusion was cut for metallography as shown in Figures 2a and 2b. The micrographs in Figure 2a show the

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uniformity in the cladding thickness and extrusion bond. Figure 2b shows the uranium grain structure at the center and edge of the fuel element.

IRRADIATION HISTORY

The fuel element was charged in KER Loop 4 on February 21, 1960^(3,4,5). The reactor operating conditions for this are given by Kratzer⁽²⁾. The maximum core temperature for this element was 415 C.

The reactor shut down on April 23, 1960, after a five-minute rise in the neutron activity for Loop 4.^(6,7) The element had received 1250 MWD/T exposure to this date. Examination in KE basin after discharge showed the inner tube had made contact within the outer tube due to warp.

POSTIRRADIATION EXAMINATION

Figure 3 shows the inner tube before and after disassembly from the outer tube in the Radiometallurgy facilities.⁽⁸⁾ The inner tube had made contact in two places on the inside of the outer tube as shown in the end views. The inner element was also 0.25 inch shorter than the outer tube after irradiation, and the warp was so great that the inner tube could not be removed without cutting of the assembled element.

Metallographic sections were made through the upstream and downstream hot spots. The downstream hot spot location shown in Figure 4a and 4b, revealed fuel core was exposed to the coolant. There occurred no undercutting or fragmentation of fuel core due to coolant attack in the uranium-zirconium alloy. The pronounced boundary between massive hydride and metallic Zircaloy-2 can be seen in the micrographs of the edges of the hot spot. This hydride formation is shown in more detail in Figure 5 where the hydride needles extending below the massive zirconium hydride have ob-

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scured the Zircaloy-2 grain structure. The upper micrograph is taken near the center of the hot spot, where the cladding began to spall. The two lower pictures are taken of the same field near the edge of the hot spot.

A comparison of Figure 6 with Figure 2b shows the effect of temperature and irradiation on the grain structure of uranium-2 wt.% zirconium alloy.

The reaction of the upstream hot spot with the coolant was not as damaging to the fuel element, but there is similar evidences of coolant attack. The change in thickness of the zirconium hydride layer near the upstream hot spot was uniform as the center of the hot spot was approached. Dendritic cracks occurred through the hydride layer, shown in Figure 7, and ended at the hydride-metallic Zircaloy-2 interface. At the center of this hot spot the hydride layer extended through the clad to the fuel core. At the terminus of the crack, there was a micropit where the fuel core had been attacked (Figure 8).

Figure 9 and 10a show longitudinal and transverse sections of the upstream end of the inner fuel tube. Excessive swelling and cracking (Figure 10c), occurred in the element during irradiation. The inclusions found in the fuel and clad in this fuel section (Figure 10b) were unexpected and their presence is unexplained. Table I shows the dimensional changes that occurred in the inner element.

Damage to the inside cladding of the outer tube was not as severe as the damage to the inner tube. Figures 11, 12a, 12b, and 13, show the extent to which the hydride had decomposed to oxide near the center and at the edge of the downstream hot spot. The same type of structure existed

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at the upstream hot spot, with more spalling of the cladding (Figures 14 and 15). The hydride layer was very extensive at the location of maximum temperature in the hot spot.

CONCLUSIONS

Failure is attributed to excessive warp of the inner tube within the outer tube causing restriction of flow and formation of hot spots. The inner element had a preirradiation warp of 0.075 inch which may have been a contributing factor to the failure or may have been an indication of asymmetric conditions which would induce working during irradiation. However, the exact cause of the excessive in-reactor warp was not established.

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TABLE I

OUTER DIAMETERS BEFORE AND AFTER IRRADIATION

	<u>Inner Tube</u>		
	<u>Before</u>	<u>After</u>	<u>Change</u>
0° Numbered end	1.048	1.051	+0.003
Center	1.047	1.051	+0.004
Unnumbered end	1.046	1.075	+0.027
90° Numbered end	1.047	1.051	+0.004
Center	1.045	1.053	+0.008
Unnumbered end	1.045	1.061	+0.016
	<u>Outer Tube</u>		
	<u>Before</u>	<u>After</u>	<u>Change</u>
0° Numbered end	1.819	1.832	+0.013
Center	1.820	1.837	+0.017
Unnumbered end	1.820	1.826	+0.006
90° Numbered end	1.817	1.827	+0.010
Center	1.820	1.823	+0.003
Unnumbered end	1.818	1.816	-0.002

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FIGURE 1 - DISASSEMBLED ELEMENTS AFTER AUTOCLAVE TESTING

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FIGURE 2a. TRANSVERSE SECTION THROUGH A REJECT PIECE
SHOWING EXTRUSION BOND.

URANIUM - 2 wt. % ZIRCONIUM CORE TO
ZIRCALOY-2 CLADDING BOND AREA - AS
POLISHED - BRIGHT FIELD -
100X

Zr-2

U - 2 wt. % Zr

TRANSVERSE SECTION OF INNER
ELEMENT - AS POLISHED -
4X

HW-76356

URANIUM - 2 wt.% ZIRCONIUM CORE EDGE
POLARIZED LIGHT - 100X

URANIUM - 2 wt.% ZIRCONIUM CORE CENTER
POLARIZED LIGHT - 100X

FIGURE 2b. GRAIN STRUCTURE OF URANIUM - 2 wt.% ZIRCONIUM
BEFORE IRRADIATION.

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DOWNSTREAM HOT SPOT SHOWING
BARE URANIUM IN THE CENTER,
1/2X

END VIEW AT DOWNSTREAM,
NUMBERED END

BOTTOM VIEW OF
INNER FUEL ELEMENT
AFTER IRRADIATION,
1/2 X

END VIEW AT UPSTREAM
UNNUMBERED END

UPSTREAM HOT SPOT, 1/2X

FIGURE 3. WARPED INNER FUEL ELEMENT AFTER IRRADIATION, SHOWING HOT SPOTS AND FIT IN
OUTER ELEMENT.

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SECTION THROUGH DOWNSTREAM
HOT SPOT, AS ETCHED, 1.2X

DOWNSTREAM HOT SPOT, AS ETCHED, BRIGHT FIELD, 50X

RIGHT EDGE OF DOWNSTREAM HOT SPOT, SHOWING ZIRCONIUM
HYDRIDE IN ZIRCALOY-2 CLADDING, BRIGHT FIELD, 50X

FIGURE 4a. DAMAGE TO FUEL CORE AT DOWNSTREAM HOT SPOT WHERE HYDRIDED
CLADDING SPALLED.

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SECTION THROUGH DOWNSTREAM
HOT SPOT, AS POLISHED, 1.7X

DOWNSTREAM HOT SPOT, AS POLISHED,
POLARIZED LIGHT, 50X.

LEFT EDGE

RIGHT EDGE

OUTSIDE EDGES OF DOWNSTREAM HOT SPOT SHOWING ZIRCONIUM
HYDRIDE IN ZIRCALOY-2 CLADDING, AS POLISHED, POLARIZED
LIGHT, 50X.

FIGURE 4b. DAMAGE TO FUEL CORE AT DOWNSTREAM HOT SPOT.

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POLARIZED LIGHT, 250X

BRIGHT FIELD, 250X

POLARIZED LIGHT, 250X

FIGURE 5. ZIRCALOY-2 CLADDING ON INNER ELEMENT NEAR DOWNSTREAM HOT SPOT SHOWING MASSIVE ZIRCONIUM HYDRIDE FORMATION.

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FIGURE 6. CENTER OF URANIUM - 2 wt.% ZIRCONIUM CORE AFTER IRRADIATION.

POLARIZED LIGHT, 250X

BRIGHT FIELD, 250X

EDGE OF URANIUM - 2 wt.% ZIRCONIUM CORE AFTER IRRADIATION.

POLARIZED LIGHT, 250X

BRIGHT FIELD, 250X

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FIGURE 7. ZIRCALOY-2 CLADDING ON INNER FUEL ELEMENT NEAR UPSTREAM HOT SPOT SHOWING CRACKS
EXTENDING THROUGH MASSIVE ZIRCONIUM HYDRIDE LAYER TO METALLIC ZIRCALOY-2 CLADDING,
BRIGHT FIELD, 250X.

FIGURE 8. MICRO PIT THROUGH ZIRCALOY-2 CLADDING
ON INNER ELEMENT EXTENDING TO URANIUM-2
WT.% ZIRCONIUM CORE AT UPSTREAM HOT SPOT,
AS POLISHED, BRIGHT FIELD, 250X

FIGURE 9. SECTION THROUGH UPSTREAM, NUMBERED END CAP,
SHOWING NON-SYMMETRICAL SWELLING OF URANIUM -
2 WT.% ZIRCONIUM CORE DURING IRRADIATION, 1.7X.

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FIGURE 10a. SECTION THROUGH INNER FUEL ELEMENT, 1-1/2 INCH
FROM UPSTREAM, UNNUMBERED END, 1.7X.

FIGURE 10b. INCLUSIONS IN ZIRCALOY-2 CLADDING - URANIUM -
2 WT. % ZIRCONIUM CORE INTERFACE, 1-1/2 INCH
FROM UPSTREAM END OF INNER FUEL TUBE,
BRIGHT FIELD, 250X.

ZIRCALOY-2 CLADDING

URANIUM - 2 WT.% ZIRCONIUM CORE

FIGURE 10c. CRACKS IN URANIUM - 2 WT.% ZIRCONIUM CORE, 1-1/2 INCH
FROM UPSTREAM, UNNUMBERED END OF INNER FUEL TUBE,
BRIGHT FIELD, 250X.

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FIGURE 11. SEGMENT CUT FROM INSIDE OF OUTER TUBE AT
DOWNSTREAM HOT SPOT, 1/3X.

FIGURE 12a. ZIRCONIUM DIOXIDE AND ZIRCONIUM HYDRIDE FORMATION ON
ZIRCALOY-2 INNER CLADDING OF OUTER TUBE AT EDGES OF
DOWNSTREAM HOT SPOT, POLARIZED LIGHT, 50X.

BRIGHT FIELD, 250X

POLARIZED LIGHT, 250X

FIGURE 12b. ZIRCONIUM DIOXIDE FORMATION ABOVE ZIRCONIUM HYDRIDE
ON ZIRCALOY-2 INNER CLADDING NEAR DOWNSTREAM HOT
SPOT ON OUTER FUEL ELEMENT.

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ADJACENT TO HOT SPOT POLARIZED
LIGHT, 50X.

AT HOT SPOT, POLARIZED
LIGHT, 50X.

ADJACENT TO HOT SPOT, WITH
CRACKS THROUGH ZIRCONIUM
HYDRIDE LAYER, BRIGHT FIELD,
250X.

AT HOT SPOT, BRIGHT FIELD
250 X.

FIGURE 13. INNER ZIRCALOY-2 CLADDING OF OUTER TUBE ADJACENT AND AT THE
DOWNSTREAM HOT SPOT SHOWING ZIRCONIUM DIOXIDE AND ZIRCONIUM
HYDRIDE FORMATION.

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BRIGHT FIELD, 50X .

BRIGHT FIELD, 250X.

FIGURE 14. ZIRCONIUM DIOXIDE AND ZIRCONIUM HYDRIDE FORMATION AT SPALLED AREA OF UPSTREAM HOT SPOT ON INNER ZIRCALOY-2 CLADDING OF OUTER FUEL ELEMENT.

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BRIGHT FIELD, 250X

POLARIZED LIGHT, 250X

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FIGURE 15. EXTENT OF ZIRCONIUM HYDRIDE FORMATION TO URANIUM
2 WT. % ZIRCONIUM CORE AT UPSTREAM HOT SPOT ON INNER
ZIRCALOY-2 CLADDING OF OUTER FUEL ELEMENT.

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