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AEC RESEARCH AND DEVELOPMENT REPORT

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**IRRADIATION TESTING
OF TUBULAR FUEL ELEMENTS:
FINAL REPORT: PT-IP 292A**

G. T. GEERING

APRIL, 1961

HANFORD LABORATORIES

**HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON**

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G. T. Geering
Fuels Development
Reactor and Fuels Research and Development Operation
Hanford Laboratories

April, 1961

HANFORD ATOMIC PRODUCTS OPERATION
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ABSTRACT

Zircaloy-2 clad uranium and uranium-2 weight percent zirconium fuel tubes were irradiated to 3200 MWD/T in a high temperature water cooled loop. The outer clad of one tube split due to swelling of the uranium. Postirradiation examination of the fuel cores included metallography, electron microscopy, density determinations, dimensional measurements, and radiochemical burn-up analysis.

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IRRADIATION TESTING OF TUBULAR FUEL ELEMENTS:
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INTRODUCTION

The Hanford "N" Reactor, now under construction will use fuel of uranium metal clad with Zircaloy-2. The uranium will be coextruded with Zircaloy-2 into long tubes of two diameters. The long tubes will be cut to shorter sections, then processed and assembled into fuel elements. Each fuel element will consist of two tubes concentrically mounted. Flexible spacers attached to the outer tubes will center the fuel element in the reactor pressure tube.

Early tests of full-scale "N" Reactor fuel elements have not been possible because the available high-temperature test loops did not have pressure tubes with sufficiently large diameters. But a test program using scaled-down elements in high-temperature, water-cooled loops has been in progress since 1958.

SUMMARY

Four tubular fuel elements were tested in a high-temperature loop until failure occurred. The exposure at the time of failure was 3200 MWD/T. Each of the elements consisted of two coextruded tubes clad with Zircaloy-2. Two elements had uranium cores and two had uranium-2 w/o zirconium cores.

The failure occurred on the outer clad of an inner tube having a uranium core. As the uranium expanded during irradiation, the clad was locally strained until a lengthwise split resulted. The reaction of cooling water with the uranium caused some fragmentation of the tube.

The clad performed very well in the high-temperature water environment. An adherent black oxide coating was produced on the clad during autoclave testing of the fuel tubes and this coating remained intact during irradiation. Some white oxide corrosion occurred on the end rings of two elements, but the penetration was not serious.

Irradiation produced surface roughening of the uranium tubes, but the surfaces of the U-2 wt % Zr tubes appeared to be unchanged by irradiation.

Metallography revealed crack networks in the uranium tubes but not in the U-2 wt % Zr tubes. The cracks did not penetrate into the Zircaloy-2 clad.

The density decreases and dimensional changes of four tubes were measured, and the volume increases of the same tubes were computed from these measurements. The density of the U-2 wt % Zr tubes decreased 6.15 and 4.65 percent respectively for the inner and outer tubes. The density of the uranium tubes decreased 2.96 and 4.56 percent respectively for the outer and inner tubes. The outer diameters of all tubes increased. One outer tube developed ovality up to 3 percent. The inner diameters of three tubes decreased uniformly, but the inner diameter of the failed tube increased in an irregular manner. The length of the tubes did not change significantly.

FABRICATION

The fuel tubes for testing were coextruded by Nuclear Metals, Inc. (1) under Contract No. AT(30-1)-1565, Sponsor Agreement No. S-55, Modification No. 2. The Zircaloy-2 used as fuel clad was vacuum melted and forged by Allegheny Ludlum Steel Corporation. The chemical analysis of a typical heat is given in Table I.

TABLE I

CHEMICAL ANALYSIS OF ZIRCALOY-2

Allegheny Ludlum Heat No. 5YH-037

Blend No. Z-5 - Melted 4-25-57

<u>Element</u>	<u>Ingot Top wt %</u>	<u>Ingot Bottom wt %</u>
Tin	1.24	1.20
Iron	0.11	0.11
Chromium	0.11	0.12
Nickel	0.05	0.05
Nitrogen	0.006	0.006
Hydrogen	0.001	0.002

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Billet Preparation

The Zircaloy-2 billet components were formed by pre-extruding forged bar. The details of the pre-extrusion work are given on pages 39-43 of Reference 1.

Uranium Billet Components

The uranium was obtained as castings from National Lead Company's Fernald Plant. (Table II)

The castings were triple-beta-quenched and machined to 7-inch diameter. The 7-inch diameter finished stock was then extruded to approximately 4.5-inches diameter to yield billet components for the outer tubes and to approximately 4-inch diameter to yield components for the inner tubes.

TABLE II

CHEMICAL ANALYSIS OF URANIUM Fernald Production Order No. A-259

<u>Ingot</u>	<u>Density</u>	<u>Impurity Content (ppm)</u>						
		<u>Carbon</u>	<u>Nitrogen</u>	<u>Boron</u>	<u>Iron</u>	<u>Manganese</u>	<u>Nickel</u>	<u>SiO₂</u>
31931	18.97	355	13	0.2	10	7	13	10
39132	18.97	386	21	0.2	13	8	16	18
31933	18.94	402	31	0.2	15	8	10	30

Uranium-2 Wt % Zirconium Billet Components

The U-2 wt % Zr alloy was made by Nuclear Metals, Inc. The zirconium and uranium was melted in a vacuum-induction furnace and cast into "donuts". The "donuts" were remelted and cast directly to billet component size. See Table III for the zirconium analyses of the U-Zr alloy castings.

TABLE III
ANALYSIS OF U-2 WT % ZIRCONIUM ALLOY

	<u>Casting No.</u>	<u>Zr. Analysis (wt %)</u>	
		<u>Top</u>	<u>Bottom</u>
Outer Tube	UX 183	1.81	1.76
Inner Tube	UX 211	2.17	2.13

Billet Assembly

The billets used in the coextrusions were assembled and processed in the following sequence:

1. Outgas copper components.
2. Assemble Zircaloy-2 over uranium or U-2 wt % Zr core.
3. Clad the billet with copper components.
4. Evacuate and seal billet.
5. Leak test with helium.

Coextrusion

The sequence of operations followed by Nuclear Metals, Inc. in the coextrusion process was as follows:

1. Paint billets with Aqua Dag.
2. Heat to extrusion temperature in graphite container.
3. Paint extrusion tools with mixture of three parts Aqua Dag to one part molybdenum disulphide powder.
4. Heat extrusion tools to 900 F.
5. Lubricate liner, die and mandrel with Dag No. 170, (a dispersion of semi-colloidal graphite in petroleum oil).
6. Load and extrude (extrusion variables given in Reference 1, pp. 47-80).

Processing and Assembly

After the tubes were received at Hanford they were given a salt-bath beta heat treatment to randomize the grain structure of both the

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uranium and the U-2 wt % Zr extrusions. The tubes were heat treated after they had been cut to length, but before the copper was removed. (Tubes were held vertically during heat treatment and cooling.) After copper removal, the tubes were chemically milled with hydrochloric acid to produce recesses at each end. Zircaloy-2 end rings were fitted into the recesses and electron-beam welded to the Zircaloy-2 cladding. (Figure 1A) The spacers (Figure 1B) were spot-welded onto the tubes and sized to the correct height and then the tubes were autoclaved and inspected. After tests, the tubes were assembled into four fuel elements, each composed of two concentric tubes (Figures 2 and 3). The dimensions of the finished elements are given in Table IV.

The processing and assembly sequence was as follows:

1. Cut to 18-inch length.
2. Salt-bath heat treat vertically at 730 C for 6 minutes.
3. Air cool vertically.
4. Machine to length.
5. Vapor blast.
6. Pickle in nitric acid to remove copper.
7. Vapor blast.
8. Pickle in nitric acid to remove residual copper.
9. Chemically mill end recesses to a depth of 0.250 inch with hydrochloric acid.
10. Pickle tube ends with HNO_3 -HF solution.
11. Insert end rings and weld to the Zircaloy-2 clad in vacuum electron beam apparatus.
12. Perform ultrasonic bond and clad thickness tests.
13. Perform fluorescent dye penetrant tests.
14. Pickle all surfaces with HNO_3 -HF.
15. Spotweld spacers onto the clad, size to the correct height.
16. Pickle all surfaces with HNO_3 -HF.
17. Hold in a steam autoclave for 72 hours at 400 C, 1500 psi.

FIGURE 1(A)
End Closure

FIGURE 1 (B)
Fuel Spacer

FIGURE 2

As-Fabricated Tubes Prior to Assembly Into Tube/Tube Fuel Elements

1/2 X

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FIGURE 3
Schematic Drawing of Element

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18. Inspect visually.
19. Measure outer diameters, inner diameters, length and warp.
20. Assemble inner tubes into outer tubes.

TABLE IV

DESCRIPTION AND NOMINAL DIMENSIONS OF THE

TEST ELEMENTS

	<u>Diameters</u>	<u>Dimensions in Inches</u>
Inner Tube	OD	1.050
Inner Tube	ID	0.500
Outer Tube	OD	1.820
Outer Tube	ID	1.450
Clad Thickness (All Surfaces)		0.020
End Ring Depth		0.25
Length of Fuel Core		17.50
Overall Element Length		18.00
Weight Per Linear Inch For Uranium Tubes		<u>Gram/Inch</u>
Inner Tube		163
Outer Tube		214

OPERATING CONDITIONS

The four fuel elements were charged into a 2.028-inch ID Zircaloy-2 pressure tube in a Hanford reactor. (2, 3, 4) The elements were charged next to each other in the following sequence: uranium, U-2 wt % Zr, U-2 wt % Zr and uranium (Figure 4.)

During the periods when the loop was operated at full power and on recirculating flow the loop cooling water was maintained at high temperature and pressure. (5, 6) Maximum calculated fuel temperature was 440 C

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A-2	—	B-2	—	Outer Tubes
A-1	C-1	B-1	D-1	Inner Tubes

FIGURE 4

Test Charge Order and Numbering System

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for an outer tube and 370 C for an inner tube. A temperature summary is given in Table V. The irradiation was stopped when a delayed neutron monitor on the test loop signaled that a failure had occurred; the reactor was shut down two minutes after the signal began.

TABLE V
MAXIMUM FUEL TEMPERATURES (C)

<u>Fuel Element Number</u>	<u>Temperature</u>
A-1	410
B-1	430
A-2	330
B-2	350

POSTIRRADIATION EXAMINATION

After the failure, the elements were discharged and examined under water in the reactor storage basin. A clad split was found on one of the uranium core inner tubes.

Two complete elements, one uranium and one U-2 wt % Zr were moved to a Hanford radiometallurgy cell for detailed examination. At a later date, the two remaining inner tubes were also moved in for examination. The numbering system used to identify the fuel elements during postirradiation examination is given in Figure 4.

Fuel Element A-1: Uranium Core Inner Tube

The clad split was located on the downstream end of tube A-1. It was about 1/2 inch long, its center 2.50 inches from the downstream end of the element. A longitudinal striation in the Zircaloy-2 clad extended from both ends of split. A photograph of the split is shown in Figure 5A. When the tube was rotated 180 degrees some deep diagonal grooves were

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(A)

45°

(B)

225°

Clad Split and Associated Longitudinal Striation 2X

Diagonal Grooves in the Clad 180° from the Split 2X

FIGURE 5

Details of the Clad Split Failure

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visible. (Figure 5B) The photographs in Figure 5 were made before the fuel elements were shipped to the radiometallurgy cell. During shipment the tube broke into two pieces. The line of fracture was along one of the diagonal grooves shown in Figure 5B. The broken tube is shown in Figures 6, 7, and 8. Three transverse metallographic specimens were taken from the tube (See Figure 6). An axial cut was made through the blister formed by the clad spit. The position of this cut is shown in Figure 9.

Metallographic Section A-A

Section A-A was cut from the tube 3 inches from the downstream end. (Figure 6) Numerous cracks appeared in the uranium core of Section A-A. The larger cracks tended to be radial and some were filled with uranium oxide. One uranium oxide-filled crack propagated from the uranium into the clad, causing a groove which later became a tear. The tear resulted from postirradiation handling and was not directly related to the clad spit which caused failure. No uranium cracks were associated with the clad spit which caused failure.

The grooves which are shown in Figure 5B were caused by the propagation of internal cracks which filled with uranium oxide during failure. Area 1 of Section A-A includes an oxide filled crack (Figure 10). Figure 11 (Section AA, area 3) reveals uranium oxide filled cracks which propagated into the inner clad. The metallographic details of the outer clad tear are shown in Figure 12.

The uranium-Zircaloy-2 bond remained intact during irradiation. Even fragmentation of the uranium did not disrupt the bond (Figures 13 and 14).

Section A-A also intercepts a striation extending from the clad split. In the metallographic examination (Figures 16 and 17) the striation appeared as a local plastically deformed section in the clad. Apparently, the uranium behaved as though it had low-strength or "fluid" properties

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during irradiation. As the uranium volume increased due to fission product buildup, the clad was subjected to a "hoop" stress. The clad then strained plastically to form a locally reduced section which appeared as an external striation.

Since some cracks in Section A-A were oxide filled and some were not, many of the cracks did not propagate from the uranium into the clad. Some cracks near the inner bore are shown in Figure 17.

The grain structure of the uranium was highly distorted as is commonly observed in irradiated uranium. The postirradiation microstructure of the uranium in Section A-A is shown in Figure 18.

Section B-B

Section B-B was located 1.25 inches from the downstream end of the tube (See Figure 6). The same large crack which appeared in Section A-A also appeared in Section B-B. (It spiraled down the length of the tube.) The angular orientations of the crack at the two sections were about 90 degrees apart (Figures 19 and 20).

It will be noted that Section B-B intersected the spot welds which attached the spacers to the fuel clad. All of the spot welds contained a metallic second phase, possibly the uranium-zirconium intermetallic compound. Evidently uranium was dissolved in the weld nugget during the spot welding operation. A cross-section of one of the spot welds is shown in Figure 21. This cross section shows a second phase in the weld nugget, but no evidence of uranium melting.

A cross-section of another spot weld is shown in Figure 22; the weld nugget it reveals contains no uranium. The cross-section's distance from the central fusion zone is the likely reason.

One of the spot welds caused melting of the underlying uranium. (Figure 23) The fusion zone in this instance penetrated into the uranium, and uranium was carried up into the weld nugget. Micrographs of the uranium-zirconium compound in the weld nugget are shown in Figures 24 and 25.

B-B

2X

6

A-A

C-C

FIGURE 6

Location of Transverse Metallographic Sections

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FIGURE 7

Profiles of the Fuel Tube Long Fragment (the 0° View is Shown in Figure 6)

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FIGURE 8

Details of the Fragments

Flow →

0°

0.8 X

D-D

2 X

FIGURE 9

Location of Axial Metallographic Section D-D

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Details of a Crack Network in Section A-A

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Section A-A Area 3
FIGURE 11
Micrographs of Cracks in Section A-A Areas 2 and 3
50 X

Section A-A Area 2
50 X

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Area 4 Polarized Light 250 X

Area 5 Polarized Light 250 X

FIGURE 12
Details of Clad Tear in Section A-A

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Section A-A Area 6

250 X

FIGURE 13

Details of the Propagation of Uranium Oxide Filled Cracks

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Section A-A Area 7

1000 X

FIGURE 14

Details of Bond Near Crack in Section A-A

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0°
↓

2X

Section A-A

Section A-A Area 8

50X

FIGURE 15

Cross-Section of Longitudinal Clad Striation Which Caused Failure

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Section A-A Area 9 Polarized Light 250 X

FIGURE 16

Plastic Flow in Longitudinal Clad Striation
Section A-A

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Section A-A Area 10

50 X

Section A-A Area 10

250 X

FIGURE 17

Internal Cracks Arrested by the Clad

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Near Center Area 1

250 X

Adjacent to Large Crack in Area 1

250 X

FIGURE 18

Postirradiation Uranium Microstructure in Section A-A

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Section B-B 1.8 X

Section B-B Area 1

50 X

FIGURE 19

Details of Clad Crack in Section B-B

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Section B-B Area 2 Bright Field Illumination 250 X

Section B-B Area 2 Polarized Light 250 X

FIGURE 20

Micrographs of Clad Crack in Section B-B

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FIGURE 21

Section Through Spot Weld at 90° Section B-B

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Weld Cross-Section

50 X

Condition of the Bond

250 X

FIGURE 22

Section Through Spot Weld at 270° Section B-B

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1-2-2000-1

FIGURE 23
Section of Spot Weld at 0° Section B-B

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Section B-B Area 3

250 X

Section B-B Area 4

250 X

FIGURE 24

Alloying in Spot Weld

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Section B-B Area 6 1000X

Area 5

FIGURE 25

Details of Alloying in Spot Weld

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Section C-C

Section C-C was made near the mid-length of the tube (see Figure 6). A deep clad striation was found in this section. It appears in the outer clad the top of Figure 26 and is shown magnified in Figure 27. This striation is apparently not a continuation of the longitudinal clad split which caused failure, but it could have caused a failure had the irradiation continued.

Figure 27 reveals that the clad has been reduced to about 1/3 of its original thickness. Some cracks were found in the uranium of Section C-C, but they were not related to the clad striation. Furthermore, these internal cracks did not propagate into the clad, but ended at the clad-core bond. Some typical cracks in the uranium are shown in Figure 28.

Fuel Element A-2: Uranium Core Outer Tube

The uranium core outer tube A-2 from the failed fuel element was not damaged (Figure 29). Its surface was roughened slightly more than that of the inner tube. Two transverse cuts sectioned A-2 at mid-length. The ring so formed was examined on both cut surfaces. One side of the ring is shown in Figure 30, and the opposite side in Figure 31.

During the cutting procedure, the uranium was overheated--possibly into the beta-phase--so that recrystallization occurred. The dark areas in the uranium shown in Figures 30 and 31 are recrystallized. The changes accompanying recrystallization resulted in cracking of the uranium. In Figure 31, a resultant crack in the uranium can be seen next to the fuel clad. In most cases, the recrystallized areas have separated from the clad adjacent to them. The separation is in the uranium and not in the uranium-Zircaloy-2 bond. A cut was made parallel to the axis of the fuel tube and normal to the recrystallized patches in Figures 30 and 31. The etched surface of this cut is shown in Figure 32. (Recrystallized area at the bottom). It can be seen that the recrystallized area extends away from the transverse surface and conforms to the heat pattern generated during cutting.

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Section C-C

3.8 X

FIGURE 26

Cross-Section Near the Mid-Length of Tube A-1

Section C-C Area 1

FIGURE 27
Incipient Clad Failure

FIGURE 28
Cracks in Section C-C

Cracks in Uranium Outer Tube and Recrystallization
Area Formed During Cutting Operation

FIGURE 30

A-2 Section A-A

Inert Ion Etched 1.25X

As-Polished 1.25X

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0.54 Percent Burnup

FIGURE 29
Uranium Outer Tube A-2

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As-Polished

A-2 Section B-B

Inert Ion Etched

A-2 Section B-B

FIGURE 31

Cracks in Uranium Outer Tube and Recrystallized
Areas Caused During Cutting Operation

Inert Ion Etched

FIGURE 32

Recrystallized Uranium in Core Formed During Cutting Operation

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A void space was left at the end of the fuel core to provide space for expansion of the uranium. During irradiation this void became partially filled with expanding uranium. In addition, the pressure of the water coolant caused the uranium to flow plastically into the void in a longitudinal direction. The resulting redistribution of uranium caused the clad to bow inward near the ends of the tube (Figure 33).

Fuel Element B-1: Uranium-2 Wt % Zirconium Core Inner Tube

The elements with U-2 wt % Zr cores were free of surface roughening. Inner tube B-1 is shown in Figure 34 (scratches were caused by handling tools). Its surface appeared to be unchanged by irradiation. The end of inner tube B-1 showed some white oxide corrosion. The protective black zirconium-oxide coating which was formed during autoclave testing was intact elsewhere on the tube. White oxide corrosion occurred on the end-closure welds (Figure 35); some of this had formed during autoclaving, implying that a little oxygen and nitrogen contamination had occurred during welding. The fuel element spacers on all the fuel tubes in the test developed white oxide coatings, indicating surface contamination of the Zircaloy-2 sheet from which the spacers were made. Neither the fuel element end-closure welds nor the spacers were seriously damaged by the white oxide formation.

A cross-section at the mid-length of tube B-1 is shown in Figure 36A. This cross-section was searched for cracks. None were found although in fuel element A-1 (the uranium tube) cracks had been found in every metallographic section. The microstructure of the U-2 wt % Zr core is shown in Figure 36B.

Fuel Element B-2: Uranium-2 Wt % Zirconium Core Outer Tube

The outer tube B-2 is shown in Figure 37. Its surface, like that of inner tube B-1, was scratched by handling tools but unchanged by irradiation. End views of B-2 are shown in Figure 38. These ends of the tube reveal some deterioration of the black oxide film, but less than that

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observed on B-1. Tube B-2 is free of internal cracks (Figure 39). The microstructure of the U-2 wt % Zr core is shown in Figure 39. Photomicrographs of the inner and outer bonds are shown in Figure 40. The core-clad bond of tube B-2 remained in good condition during irradiation.

Electron Microscopy

The fission gases generated in the fuel during irradiation agglomerate to form pores. At the operating temperatures of this test the pores should be less than 1 micron in diameter. Thus they could not be studied with an optical microscope. Replicas of metallographic cross-sections were made in a hot cell, then studied with an electron microscope.

The metallographic cross-sections were made adjacent to the density specimens, one each for tubes A-1, A-2, B-1, and B-2. The polished surfaces were prepared by cathodic ion bombardment. A Faxfilm replica was made in the hot cell. Carbon was then deposited on the Faxfilm and UO_2 used to produce shadows. Electron micrographs obtained from the replicas are shown in Figure 41-46.

Fission gas pores were observed in all of the replicas. (On an electron micrograph they appear as raised areas with white shadows.) The amount of porosity is roughly proportional to the observed density decreases. The porosity of tube B-2, for example, is the greatest observed in any of the electron micrographs. Tube B-2 also has the greatest density decrease.

Tube B-1 has much less porosity than B-2 and also has less density decrease than B-2. It would be expected that the inner fuel tubes should decrease in density more than the outer tubes, since the temperatures of the inner tubes are higher during irradiation. But although the uranium tubes behaved this way, the U-2 wt % Zr tubes behaved just the opposite. The outer tube of U-2 wt % Zr decreased in density more than the inner tube. Three independent observations confirmed this--porosity observed in the electron microscope, density decrease, and diameter measurements.

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Preirradiation

Postirradiation

FIGURE 33

Section Through the End Closure of A-2
Showing Flow of Uranium During Irradiation

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FIGURE 34
Uranium-2 wt % Zirconium Inner Tube B-1

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1.36 X

1.36 X

FIGURE 35

End Views of Uranium-2 wt % Zirconium
Inner Tube B-1

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A

Inert Ion Etched

2.2 X

B

Inert Ion Etched

1000 X

FIGURE 36

Metallographic Section of Uranium-2wt % Zirconium
Tube B-1

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0.45 Percent Burnup

FIGURE 37

Uranium - 2 wt % Zirconium Outer Tube B - 2

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Downstream End

1.5 X

Upstream End

1.5 X

FIGURE 38

End Views of Uranium-2 wt % Zirconium
Outer Tube B-2

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Surface
Strain at
Lower Left

A

Inert Ion Etch

1.25 X

B

Inert Ion Etch Near Center

500 X

FIGURE 39

Metallographic Section of Uranium-2 wt % Zirconium
Tube B-2

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FIGURE 40

Core-Clad Bond Uranium-2 wt % Zirconium Tube B-2

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Tube A-1
Burnup, 0.42 Percent
Operating Temperature, 410 C
Density Decrease, 5.8 Percent

FIGURE 41

Fission Gas Pores in Irradiated Uranium Inner Tube Fuel Element

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Tube B-1
Burnup, 0.38 Percent
Operating Temperature, 430 C
Density Decrease, 4.7 Percent

FIGURE 42

Fission Gas Pores in Irradiated Uranium-2 wt % Zirconium
Alloy Inner Tube Fuel Element

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Tube A-2
Burnup, 0.54 Percent
Operating Temperature, 330 C
Density Decrease, 3.5 Percent

FIGURE 43

Fission Gas Pores in Irradiated Uranium Outer-Tube Fuel Element

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Tube B-2
Burnup, 0.45 Percent
Operating Temperature, 350 C
Density Decrease, 6.1 Percent

FIGURE 44

Fission Gas Pores in Irradiated Uranium-2 wt % Zirconium
Alloy Outer-Tube Fuel Element

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Tube A-2
Burnup, 0.54 Percent

FIGURE 45

Spherical Pores in the Grain Boundaries of
Irradiated, Recrystallized Uranium

Burnup 0.00 Percent

15,000 X

Burnup 0.38 Percent

23,000 X

FIGURE 46

Effect of Irradiation on the Epsilon Phase in Uranium-2 wt % Zirconium

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The only metallographic specimens in which grain boundaries could be discerned came from the region of tube A-2 which had been overheated during cutting. The heating was sufficient to cause alpha phase recrystallization of the uranium and well defined grain boundaries. A portion of one such boundary is shown in Figure 45.

The distribution of pores within the grains did not appear to be changed by recrystallization, but numerous spherical pores of about 500 A diameter appeared in the resulting grain boundaries. These smaller pores are apparent in the grain boundary at the left of Figure 45. A crack seems to have formed adjacent to the pores at the upper portion of the grain boundary. Some of the recrystallized grains were entirely separated from the matrix by grain boundary cracking.

The uranium-zirconium intermetallic compound appeared in the unirradiated U-2 wt % Zr as eutectoid platelets when viewed in the electron microscope. After irradiation the platelets were almost non-existent. The structures of the unirradiated and irradiated U-2 wt % Zr are shown in Figure 46A and B.

Dimensional Measurements

Before irradiation, all of the fuel tubes were measured. The diameters were measured 2 inches from the ends and at the tube midlengths. Tube lengths were measured at two places 90 degrees apart. Warp was measured by dial indicators at four stations along the length of the tube.

After irradiation, the outer diameters were measured with a micrometer and the inner diameters with an optical cathetometer. The wall thicknesses of the outer tubes were measured optically from photographs of the postirradiation cross-sections. See Tables VI and VII.

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TABLE VI
DIAMETER MEASUREMENTS, INCHES

		OUTER TUBES (Outside Diameter)									
		A-2					B-2				
		1 822	1 825	1 823	1 818	1 820	1 819	1 818	1 818	1 818	1 817
Preirradiation	0°	1 822	1 825	1 823	1 818	1 820	1 819				
	90°	1 824	1 824	1 825	1 818	1 818	1 817				
Change During Irradiation	0°	-0.003	+0.001	+0.000	+0.011	+0.011	+0.006				
	90°	-0.003	-0.002	-0.002	+0.003	+0.007	+0.009				
		INNER TUBES (Outside Diameter)									
		A-1					B-1				
		1 047	1 046	1 045	1 045	1 046	1 048	1 045	1 047	1 047	1 046
Preirradiation	0°	1 047	1 046	1 045	1 045	1 046	1 048	1 046	1 043	1 045	1 045
	90°	1 045	1 046	1 048	1 048	1 046	1 046	1 045	1 044	1 045	1 046
Change During Irradiation	0°	+0.042	+0.029	+0.015	+0.010	+0.011	+0.011	+0.014	+0.016	+0.003	+0.007
	90°	+0.039	+0.019	+0.012	+0.009	+0.009	+0.010	+0.015	+0.015	+0.001	+0.000
		(Inside Diameter)									
		A-1					B-1				
		0.501	0.501	0.501	0.501	0.502	0.503	0.501	0.502	0.504	0.501
Preirradiation	0°	0.501	0.501	0.501	0.501	0.502 <td>0.503</td> <td>0.501</td> <td></td> <td></td> <td></td>	0.503	0.501			
	90°	0.501	0.502	0.502	0.502	0.502	0.504	0.501			
Change During Irradiation	0°	-	+0.015	-	-	-	-0.003	-			
	90°	-	+0.013	-	-	-	-0.003	-			

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TABLE VII
POSTIRRADIATION WALL THICKNESS MEASUREMENTS
AT MIDLENGTH OF TUBES, INCHES

Position (From Arbitrary Index Degrees)	Tube Number	
	A-2	B-2
0	0.1970	0.1875
45	0.2020	0.1898
90	0.1902	0.1962
135	0.1798	0.1923
180	0.1760	0.1956
225	0.1780	0.1875
270	0.1855	0.1841
315	0.1897	0.1881
Mean Postirradiation Wall Thickness	0.1872	0.1901
Mean Preirradiation Wall Thickness	0.182	0.181

Postirradiation length measurements were accurate to ± 0.030 inch. No significant changes in length occurred due to irradiation. All of the tubes had preirradiation warp, confined generally to one plane. The total indicator readings varied from 0.020 to 0.040 inch prior to irradiation. After irradiation only tube D-1 had a measureable increase in warp. Tube D-1 had a maximum total indicator reading of 0.050 inch after irradiation, but the plane of maximum warp had shifted about 200 degrees. The other tubes also exhibited a shift in the plane of warp.

Density Measurements

A density specimen was taken from the midlength of tubes A-1, A-2, B-1, and B-2. The specimens taken from the outer tubes were cut into four ring segments. The Zircalov-2 clad was removed from the density specimens by dissolution in HF-HNO₃ solution before density measurements were made. All of the specimens decreased in density due to irradiation (Table VIII).

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TABLE VIII
DENSITY MEASUREMENTS

<u>Tube No.</u>		<u>Postirradiation (g/cm³)</u>	<u>Preirradiation (g/cm³)</u>
A-1		17.92	19.02
A-2	0°	18.33	
	90°	18.37	19.02
	180°	18.36	
	270°	18.39	
B-1		17.42	18.26 ± 0.02
B-2	0°	17.54	
	90°	17.19	18.26 ± 0.02
	180°	16.73	
	270°	17.14	

The preirradiation values were determined with the same apparatus as the postirradiation values.

DISCUSSION

The Clad Failure

The failure of the clad of tube A-1 was not unexpected because similar clad failures had occurred in rod-cluster fuel elements. (7) A possible failure mechanism can be stated with these assumptions:

1. the uranium core of the fuel element has low-strength or "viscous fluid" properties during irradiation,
2. the uranium swells during irradiation, and
3. the Zircaloy-2 clad suffers radiation damage and loses its ability to work harden, thereby becoming plastically unstable.

As the uranium swells during irradiation, the outer clad of the fuel tube is subjected to a "hoop" stress. Simultaneously, the inner clad is subjected to a compressive load tending to collapse it. The hoop stress acting on the outer clad increases with fuel element exposure because of increases in the swelling of uranium with exposure. This in turn imposes a creep condition with increasing load. As the load is increased localized

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plastic deformation of the clad forms a longitudinal striation. Plastic deformation proceeds along this striation until the clad splits. The clad strain at failure is thus distributed very non-uniformly around the circumference of the fuel tube and most of the clad strain is associated with the striation or failure. Locally the clad is highly plastic but it appears that very little work hardening occurs.

Comments on Fuel Volume Changes

The fuel temperatures reported in this study are accurate to ± 10 percent. However, the temperature differences between fuel elements are much more accurately known because of the small variation of neutron flux in the test facility. The most important variables affecting volume in this test are fuel temperature and fuel burnup.

The inner tubes operated with higher core temperatures than the outer tubes because of their relatively larger wall thickness. The two elements which were examined were located at positions one (upstream) and three. The maximum fuel temperatures in these two elements varied from 330 to 430 C.

The volume increases were determined for each tube and correlated with maximum core temperatures and burnups. Volume increase was determined by density and diameter measurements. The density specimens were taken from the midlength of the tubes. The diameter measurements were made at the same place place on the tubes. Clad thickness was determined optically, and the volume increases were computed from the diameters. In Table IX the results of both methods are compared and the burn-up values, operating temperatures, and dimensions are given for each tube. Volume increases for the inner tubes are plotted in Figure 47 as a function of temperature. Methods (1) and (2) agree within 20 percent for the inner tubes. In Figure 48 the volume increases for the outer tubes are plotted as a function of temperature; density and diameter measurement approaches again agree within 20 percent. The rate of volume increase

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		<u>Burnup</u>	<u>% $\frac{\Delta \rho}{\rho}$</u>	<u>% $\frac{\Delta V}{V}$</u>	<u>Max. Core Temp. (C)</u>	<u>Tube Dimensions (Inch)</u>
A-1	Uranium	0.2	-5.8	5.0	410	18.0 Length 1.050 OD
B-1	U-2 Wt % Zr	0.30	-4.7	3.5	430	0.500 ID 0.020 Clad Thickness
A-2	Uranium	0.54	-3.5 $\pm$ 0.14	2.7	330	18.0 Length 1.820 OD
B-2	U-2 Wt % Zr	0.45	-6.1 $\pm$ 2	4.9	350	1.450 ID 0.020 Clad Thickness

FIGURE 47

Density Decrease and Volume Increase as a Function of Maximum Core Temperature for KER Inner Tubes

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FIGURE 48

Density Decrease and Volume Increase as a Function of Maximum Core Temperature for KER Outer Tubes

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FIGURE 49
Density Decrease/Burnup as a Function of Maximum Fuel Temperature

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FIGURE 50

Density Decrease/Burnup as a Function of Maximum Fuel Temperature

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