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**ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM
QUARTERLY PROGRESS REPORT NO. 10
FEBRUARY - APRIL 1970**

COMPILED BY
F. H. MEGERTH

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AEC Research and
Development Report
May 1970

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**Quarterly Progress Report No. 10
February--April 1970**

Compiled by
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1. INTRODUCTION

At the time of the final shutdown of the Vallecitos Boiling Water Reactor (VBWR) and the termination of the AEC Fuel Cycle Program (Contract AT(04-3)-189, Project Agreement 11), the leading Zircaloy-2-clad UO_2 fuel rods of the program's Type J basic assemblies had attained rod average exposures as high as 3×10^{20} fissions/cm³ (10,000 MWd/t U).

To demonstrate at the earliest possible time the capability of Zircaloy-clad fuel to achieve average burnups of at least 6×10^{20} fissions/cm³ (20,000 MWd/t U) and to take advantage of the available lead time in achieving these burnup targets, 98 of the higher exposure Fuel Cycle Program rods were incorporated in a special assembly designated as SA-1 and inserted in the Dresden reactor for additional irradiation. The assembly consisted of two 7-by-7 subassemblies, stacked one on top of the other in a channel of standard dimensions for the Dresden reactor.

Assembly SA-1 was operated continuously from June 1964 to September 1969, with the exception of reactor shut-downs for refueling and maintenance.

To investigate in detail the performance of the SA-1 fuel rods and to determine the isotopic composition of the highly exposed fuel, a two-phase program of destructive examination and analysis was drawn up. For the initial phase of the program, ten rods were removed from the assembly in January 1967, after 1200 days of VBWR and Dresden operation, and were shipped to the Vallecitos Nuclear Center. The remaining rods operated a total of 1850 days. The two 44-rod subassemblies now have been shipped to VNC, where the final phase of the program is in progress.

Prior reports to the Atomic Energy Commission under Project Agreement 41 comprise the following:

- a. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 1, November 1967–January 1968," March 1968 (GEAP-5598).
- b. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 2, February 1968–April 1968," May 1968 (GEAP-5624).
- c. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 3, May 1968–July 1968," August 1968 (GEAP-5667).
- d. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 4, August 1968–October 1968," November 1968 (GEAP-5702).
- e. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 5, November 1968–January 1969," February 1969 (GEAP-5746).
- f. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report Nos. 6 and 7, February–July 1969," August 1969 (GEAP-10079).
- g. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 8, August–October 1969," November 1969 (GEAP-10121).
- h. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 9, November 1969–January 1970," February 1970 (GEAP-10160).

2. SUMMARY

The two SA-1 subassemblies, which were received at Vallecitos Nuclear Center (VNC) in March were visually examined in the hot cells and found to be in generally good condition. All rods were removed from the subassembly structures and individually inspected.

In general, the appearance of these more highly exposed fuel rods was similar to that observed after the first two cycles of Dresden operation, both in pool examinations at Dresden and in examinations of the ten removed rods conducted in the hot cells at VNC.

The corrosion product, or crud, film that was deposited on the rods during operation generally gave most of the surface area a coloration best described as bluish-gray with varied amounts of reddish-brown. The reddish-brown portion of the film frequently was distributed in the form of speckles, and in such cases the surface usually appeared somewhat rough in texture. Metallographic examinations of fuel rod sections performed during the initial phase of the program indicates that this surface roughness is probably a consequence of an uneven, pitting type ZrO_2 corrosion layer.

There were noticeable differences in the degree and extent of surface roughness among different rods, and along the length and around the circumference of a given individual rod. The axial variation in roughness tended to correspond with the axial power profile, but there were exceptions to this relationship.

An increased deposition of brownish crud was observed on most rods at the three spacer locations along the fuel column. Spalling or cracking of the crud had occurred in several instances at these locations.

A few rods showed spalling or cracking of the crud layer between the spacer locations. A corner rod that operated in the top subassembly and positioned at a wide-narrow water gap throughout its Dresden irradiation exhibited the greatest amount of crud spalling.

Many of the rods were marked with fine longitudinal lines. These lines appeared to result from handling, but it is remotely possible that some of them might be hairline cracks.

In addition to those rods with hairline markings, a few rods exhibited small pitlike penetrations, short jagged cracks, small blisters, or discolored areas. The depths of penetration and exact natures of these anomalies could not be determined solely by visual inspection of the external surfaces, and additional investigations with neutron radiography and possibly pressure testing are planned.

Several thin slivers of irradiated UO_2 were examined by transmission electron microscopy with both the 100-keV and 650-keV machines. The slivers were extracted from a metallography specimen with an average burnup of 8.1×10^{20} fissions/cm³ (29,700 MWd/t U), which was obtained from one of the initial ten rods removed from SA-1.

Several small pores were visible at the edge of one of the slivers. Samples taken from regions relatively near the pellet periphery showed numerous defects. Rod or plate shaped inclusions were visible in a sliver from a peripheral location. Only a few defects were visible in two thin fuel chips taken from near the pellet center when examined in bright field. In the dark field image, on the other hand, the structure of one of the chips looked severely disrupted.

3. FUEL EXAMINATIONS

3.1 VISUAL EXAMINATIONS OF SUBASSEMBLIES AND INDIVIDUAL FUEL RODS (G. P. Ferguson, F. H. Megerth)

The two SA-1 subassemblies each contained 44 fuel rods, arranged as shown in Figure 1, during the last two of their four cycles of Dresden operation. The assembly operated approximately 650 days (hours of turbine-generator operation $\div$ 24) during these two cycles. The rods thus accumulated a total exposure time of approximately 1850 days in the VBWR and Dresden. The final assembly average burnup, including VBWR and Dresden irradiation, is estimated to be 8×10^{20} fissions/cm³ (30,000 MWd/tU). Information on the average and local peak burnups for individual rods, as well as a more precise estimate of assembly average burnup, will be provided later by chemical burnup analyses combined with gamma scanning.

The four sides of each subassembly were examined with a Kollmorgen periscope in the hot cells at Vallecitos in order to determine the external surface appearance of some of the rods before they were removed from the subassembly structures and thus subjected to an unavoidable scraping of the surfaces by the spacer springs and bands. The conditions of the spacers and other parts of the subassembly structures also were of interest from the standpoint of the possible effects on fuel rod operation. Upon completing a subassembly examination, each rod was removed and examined. (Some of the design and fabrication characteristics of the SA-1 fuel rods are given in Table 1.)

The two subassemblies appeared to be in generally good condition. The spacing between visible outside rods was uniform.

An overall view of subassembly B-1, which was in the top position during operation, is shown in Figure 2. The four corner rods in each subassembly are completely hidden from view, and the rods next to the corner rods are partially hidden by the stainless steel corner angles.

In general, the appearance of the rods was similar to that observed after the first two cycles of Dresden operation, both in pool examinations at Dresden and in examinations of the ten removed rods conducted in the hot cells at VNC.¹

The corrosion product, or crud, film that was deposited on the rods during operation generally gave most of the surface area a coloration best described as bluish-gray with varied amounts of reddish-brown. The reddish-brown portion of the film frequently was distributed in the form of speckles, and in such cases the surface usually appeared somewhat rough in texture. Metallographic examinations of fuel rod sections performed during the initial phase of the program indicates that this surface roughness is probably a consequence of an uneven, pitting type ZrO_2 corrosion layer.² An example of this type of surface is shown in Figure 3. As this figure shows, the degree of speckling and roughness varied from rod to rod at a given elevation.

Figure 1. Arrangement of Fuel Rods in SA-1 during Dresden Unit No. 1 Operating Cycles 5 and 6

Figure 2. Subassembly B-1 at End of Irradiation

Figure 3. Surface Appearance of SA-1 Fuel Rods at Midlength (Rods A8, A15, A22 and A29 in Subassembly A-1)

Figure 4. Rough Surfaces on Rods B64, B78 and B85 at Bottom Spacer of Subassembly B-1

Table 1
CHARACTERISTICS OF SA-1 FUEL RODS

Cladding Material	Zircaloy-2
Condition of Cladding Material, as received	Annealed
Cladding Thickness, nominal, cm (inch)	0.056 (0.022)
Cladding i.d., nominal, cm (inch)	0.965 (0.380)
Cladding o.d., nominal, cm (inch)	1.077 (0.424)
Pellet Diameter, cm (inch)	0.947 (0.373) to 0.955 (0.376)
Pellet Density, average, percent of theoretical	95
Active Fuel Length, cm (inch)	94 (37)
Initial Uranium Enrichment, percent U-235	2.76-3.5

Practically all rods showed some roughness between the short end plugs, located at the middle of the assembly, and a location near the distant edge of the closest spacer, i.e., 5 cm to 8 cm (2 in. to 3 in.) away from the plugs (Figure 4).^{*} The roughness at this axial location generally extended completely around the rod. About three-fourths of the rods showed some roughness elsewhere along their lengths, and in somewhat over half of these cases the degree of roughness decreased in going from the center of the full assembly to the upper and lower extremities, i.e., from relatively high- to low-power locations. Somewhat less than one-fourth of these rough rods showed rough-smooth axial patterns that varied from the one just described, and for a few within this group the relationship between roughness and power appeared to be reversed. For the rest of the rods, little if any axial variation in surface roughness could be detected over the fuel columns. Some variation around the peripheries was apparent on about three-fourths of those rods that exhibited any significant amount of roughness.

A bandlike pattern in the surface roughness and speckling was observed over 10 to 15 cm (4 to 6 in.) lengths of three "A" rods (Figure 5). This pattern occurred over the fuel column between the plenum and a point about 23 cm (9 in.) from the plenum, and the smooth, unspeckled rings occurred at pellet-length intervals in each case.

Several rods exhibited groups of smooth rings in which the rings were relatively closely spaced, as shown in Figure 6. These ring groupings typically extended about 1 cm (1/2 in.) along the rod and usually were located either between 47 and 50 cm (18-1/2 and 19-3/4 in.) from the short end plug or between 55 and 59 cm (21-1/2 and 23-1/4 in.) from it. In general, only one such group of rings was observed on a given rod.

In contrast to the above phenomenon, blisterlike protusions that were grouped in the form of circumferential rings were noted on approximately one-fifth of the fuel rods. The typical length of these "rough ring" groupings was essentially the same as that of the smooth rings described in the preceding paragraph, and the usual locations were similar. The rough rings were observed most frequently either between 43 and 48 cm (17 and 19 in.) from the short end plug or between 53 and 58 cm (21 and 23 in.) from it. In only one instance, however, were both kinds of rings observed on the same fuel rod. Rings of blisters also were observed during the initial phase of the program and appeared in sectional view as areas of greater than normal corrosion.³ The smooth rings very likely represent areas of unusually low corrosion, but the reasons for these variable patterns in ZrO_2 formation are uncertain.

The long end plugs and plenum regions of the cladding generally were coated with a smooth reddish-brown film of crud (Figure 7).

Approximately ten rods showed spalling or cracking of the crud layer at locations between the subassembly spacers. In most cases, the spalling occurred as isolated, singular spots on the order of 0.3 cm (1/8 in.) across its largest dimension. Rod B53 showed intermittent, longitudinal cracks in the crud between 85.5 and 94.5 cm (33-3/4 and 37-1/4 in.) from the short end plug (Figure 8).

* The SA-1 rods are sealed with a 0.952 cm (0.375 in.) long plug at one end and a 3.492 cm (1.375 in.) long plug at the other. A 4.42 cm (1.74 in.) long plenum is adjacent to the longer plug, while a standard pellet lies next to the shorter plug. The longer plugs and plenums were pointed upward in the top subassembly (B-1) and downward in the bottom subassembly (A-1). Unless indicated otherwise, the axial positions of points of interest on the surface of either an "A" rod or a "B" rod are defined in terms of distance from the shoulder of the shorter end plug.

Figure 5. Bandlike Surface Pattern on Rod A15

Figure 6. "Smooth Rings" on Rod B55 at 48 cm (18-3/4 in.) from Short End Plug (Subassembly B-1)

Figure 7. Long End Plug and Plenum Regions of Rods B57, B64, B71, B78 and B85

Figure 8. Cracks in Crud Layer on Fuel Rod B53

Corner rod B56, which operated in the top subassembly and was positioned at a wide-narrow water gap throughout its Dresden irradiation exhibited the greatest amount of crud spalling. The crud had spalled away down to a white ZrO_2 surface in five separate locations from $\sim 2\frac{1}{2}$ to 40 cm (~ 1 to 16 in.) above the bottom of the subassembly (Figure 9). Most of the spalled areas were $\frac{1}{2}$ cm wide by $\frac{1}{2}$ to 1 cm long, and some were larger. Their locations appeared to be associated, but not necessarily directly aligned, with spacers and corner angle recesses. It is quite possible, of course, that a significant amount of crud spalling took place during removal of the rod from the subassembly. On the other hand, the other seven corner rods showed relatively little or no spalling.

A relative increase in crud deposition generally was observed on a rod at one or more of the subassembly spring type spacer locations. The deposits at these locations typically were reddish-brown in color and extended a centimeter or so ($\sim \frac{1}{2}$ in.) on either side of the apparent spring-rod contact point. An example of these deposits is shown in Figure 10, in which the area of increased deposition shows up as a relatively darker region in the black and white photography. The deposition was comparatively somewhat less at the topmost and bottommost spacers in the full assembly, which were located over the fuel rod plenums instead of over the fuel columns. A more localized and flaky appearing buildup of crud occasionally was observed on the rod surface at a spacer location. These localized buildups, examples of which are shown in Figure 11, were as large as approximately 0.3 cm ($\frac{1}{8}$ in.) in diameter and were located 0.3 to 0.6 cm ($\frac{1}{8}$ to $\frac{1}{4}$ in.) below the apparent spring-rod contact point.

Flakes of crud were observed clinging to the bottom edges of a few of the bottom subassembly spacer bands (Figure 12). The flakes were present on two sides of the second spacer from the top and on one side of the third spacer.

Spalling or cracking of the crud near spacer locations was noted on about ten rods. In most cases the spalling or cracking was limited to one spacer contact area per rod. Most of the spalled areas were 0.5 cm ($\sim \frac{3}{16}$ in.) in diameter or less. An example of spalled crud at a spacer band location is shown in Figure 13. Some cracks of uncertain depth up to about 0.6 cm ($\frac{1}{4}$ in.) long were noted at other spacer locations (Figure 14).

In addition to the above crud spalling, apparent scrape marks were visible on about one-half of the outside noncorner rods in subassembly A-1 in the vicinity of either the first or second spacers from the top. A few such marks also were noted on the subassembly B-1 rods. The marks were located either at the top edges of the bands or at the bottom of the oval openings in the bands (see Figure 12). Most of these marks were shiny and may have been caused by recent handling.

Orange material, sometimes in combination with a bright red material, was noted on 15 rods near spacer spring contact points (Figure 15). It was present at various spacer locations, but in general it was found at only one contact point on a given rod. Similar appearing material also was seen on one "A" rod at the bottom edge of the top spacer band and at the bottom edge of the 0.6 cm ($\frac{1}{4}$ in.) wide horizontal band at the top of the subassembly structure (Figure 16).

Nearly all rods in subassembly A-1 showed rather uneven, light gray rings that were centered about 6 cm ($2\frac{1}{2}$ in.) from the short end plugs and usually extended 0.9 to 1.0 cm ($\sim \frac{3}{8}$ in.) The rings appeared to have been formed in conjunction with an eroding of the crud layer (Figure 17). None of the rods in subassembly B-1 showed this type of marking, but several of the "B" rods did show dark, more or less "U-shaped" stains at about 5 cm (2 in.) from the long end plug (Figure 18). What caused these rings and stains is not certain. One conjecture is that there may not have been enough water in the shipping cask to completely cover the subassemblies, which were positioned side-by-side in an aluminum liner placed in the cask, and that these markings formed at or near the surfaces of the water.

Discolorations of several other types were observed on the rods less frequently than those discussed thus far. Dark gray oval-shape lines, usually about 0.6 cm (0.25 in.) across the larger diameter, were noted on seven "A" rods (Figure 19). They were somewhat similar in appearance to the "U-shaped" stains found on some subassembly B-1 rods and were usually located approximately 25 cm (10 in.) or 39 cm ($\sim 15\frac{1}{2}$ in.) from the short end plug. Brown circumferential rings and/or circular brown spots like those shown in Figure 20 were noted on about seven rods. Two rods showed primarily circumferential, but irregular, ringlike markings near the fuel column-plenum junctions (Figure 21). Thin white or light gray films in the forms of streaks and smeared regions, generally 2.5 cm (1 in.) long or less, were seen on various portions of eight rods. An example of some of this white material is shown in Figure 22, where it is present at the short end plug regions of two "B" rods, as well as at the bottom of the adjacent corner angle. At least some of this material is probably aluminum oxide resulting from the abrasion and oxidation of portions of the cask liner.

Approximately 20 fuel rods were marked with fine longitudinally oriented lines which varied in length from less than 1 cm ($\sim \frac{1}{2}$ in.) to greater than 20 cm (~ 8 in.). Most of these lines appeared to be shallow surface penetrations that had resulted from handling (Figures 23a-d), but in some cases portions of the lines appeared to protrude from the surface

a

b

c

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Figure 9. Areas of Crud Spalling on Rod B56 at Various Distances from the Short End Plug

d

e

Figure 9. Areas of Crud Spalling on Rod B56 at Various Distances from the Short End Plug

Figure 10. Increased Crud Deposition at a Spacer Location on Rod B60
(Note: Rule Indicates Distances from Long End Plug Shoulder in This Figure)

a

b

Figure 11. Flaky Crud Buildups at Spacer Locations on (a) Rod B51 and (b) Rod B60
(Note: Rule in Figure 11b Indicates Distances from Long End Plug Shoulder)

Figure 12. Crud Flakes at Bottom Edge of Spacer Band (Rods A8, A15, A22 and A29 at Second Spacer from Top)

Figure 13. Spalling and Cracking of Crud on Rods B51, B52, B53 and B54 at Bottom Spacer Band Locations. (Rods Have Been Removed Somewhat from Normal Subassembly Position)

Figure 14. Surface Cracks at 67.7 cm (26-21/32 in.) Spacer Location on Rod B53

Figure 15. Red and Orange Material Near Spacer Spring Contact Point on Rod A20

Figure 16. Reddish-Orange Material on Rod A42 at Band-Rod Contact Points

Figure 17. Light Gray Rings on Rods A8, A15, A22, A29 and A36 Below Top Spacer

Figure 18. Stained Areas on Rods B51, B52, B53, B54 and B55 Below Top Spacer

Figure 19. Dark Gray Lines on Rod A39

Figure 20. Brown Rings and Spots on Rod A11 Between 19 cm (7-3/8 in.) and 29 cm (11-3/8 in.) From Short End Plug

a

b

Figure 21. Irregular Ringlike Markings on (a) Rod A8 and (b) Rod A30

Figure 22. White Film on Bottom of Rods B51, B52 and Adjacent Corner Angle

Figure 23. Fine Longitudinally Oriented Lines on (a) Rod A18

b

c

Figure 23. Fine Longitudinally Oriented Lines on (b) Rod A23, (c) Rod A43

d

e

Figure 23. Fine Longitudinally Oriented Lines on (d) Rod A15 and (e) Rod B95

(Figure 23e). As Figures 23d and e indicate, these lines were observed on some of the outside rods before they were removed from the subassemblies. It is remotely possible that some of these marks might be hairline cladding cracks, and additional investigation of some of the rods with neutron radiography and possibly pressure testing is planned.

In addition to the fine longitudinal marks, approximately five rods exhibited pitlike surface penetrations that were generally 0.2 cm ($\sim 1/16$ in.) or less across (Figure 24), about ten rods contained small, rather jagged cracks or crack networks (Figure 25), and one or two rods showed 0.2 cm diameter blisterlike protrusions (Figure 26). Many of these anomalies were located near subassembly spacers and may have come about because of an unusual pattern of crud deposition or ZrO_2 formation. In any case, their exact natures and depths of penetration could not be determined solely by visual inspection of the external surfaces and, again, some further investigations are planned.

Most of the rods showed some wear near midlength, i.e., approximately 52 cm (20-1/2 in.) from the short end plugs, and several showed some wear on the long end plugs, which had been caused by contact with the wire type spacer during VBWR operation. However, this previous wear did not appear to have any deleterious effect on their operation in Dresden. The rod shown in Figure 27 represents a case of comparatively deep VBWR spacer wire wear at the 52 cm location. Some increases in surface roughness typically was observed for 0.5 to 1 cm ($\sim 1/4$ to $1/2$ in.) on either side of the middle spacer wire contact points.

Rod B95 exhibited a series of six or seven raised circumferentially oriented marks between 5.0 and 5.6 cm (2 and 2-3/16 in.) from the long end plug, over the plenum. All of these marks were approximately 0.04 cm (1/64 in.) wide and ranged from 0.1 to 0.5 cm (1/32 to 3/16 in.) in length (Figure 28).

As was previously indicated, the subassembly structures were in generally good condition: No distortion in or significant damage to corner angles, bottom grids, top horizontal straps, or spacer bands was apparent. All band-to-angle and other weldments appeared to be in satisfactory condition. No damage to spacer cross members could be detected, and there was no apparent loss, damage, or misalignment of spacer springs.

Some blue and red discolored areas about 1 cm by 2 cm ($\sim 1/2$ in. by $3/4$ in.) were observed on the corner angles of subassembly A-1 just below the top spacer bands (see Figure 17).

Subassembly B-1 showed 1 cm by 1 cm ($\sim 1/2$ in. by $1/2$ in.) areas of greater than normal wear on the corner angles just below the top spacer and about 10 cm (4 in.) below the second spacer from the top. Two corner angles of one side of this subassembly had rather deep, fresh scratches over the entire length.

3.2 ELECTRON MICROSCOPIC EXAMINATIONS OF UO_2

(H. S. Rosenbaum, Technical Director, U. E. Wolff, E. S. Darlin)

The examination of irradiated UO_2 by replication electron microscopy during the initial phase of the program⁴ had shown two superimposed distributions of precipitates: one was a bimodal distribution of intragranular precipitates with peaks near the clad and in a ring at about half the fuel radius. The other was a distribution of grain boundary precipitates, the amount of which decreased monotonically with distance from the clad. Since the resolution limit of replicas is about 100-200 Å, irradiation induced defects smaller than that could not be detected by this method. Such defects can only be studied by transmission electron microscopy of thin foils.

Subsequently efforts were directed towards the development of thinning procedures for bulk UO_2 ⁵ and the examination of unirradiated UO_2 by thin foil transmission electron microscopy with 650 kV electrons.⁶ Two different thinning techniques were employed:

1. Bulk thinning by ion bombardment of a mechanically prethinned slice.^{5,6}
2. Extraction of thin slivers of UO_2 from fractured surfaces.^{5,7}

In this reporting period, both techniques were applied to irradiated UO_2 . The samples were obtained from metallography specimen No. 9954, which, in turn, was obtained from rod A13, one of the initial ten rods removed from SA-1. The specimen had an average burnup of 8.1×10^{20} fissions/cm³ (29,700 MWd/t U).

1. The initial steps for bulk thinning are mechanical grinding and polishing of both surfaces of a very thin slice of material (about 0.025 to 0.075 mm [0.001 to 0.003 in.] final thickness). Such a slice was prepared by remote handling techniques.
2. Thin slivers were obtained from the same metallography specimen. Hardness indentations were made with a 5000 g load at four different distances from the cladding to fracture the sample surface. About 20 five-mm-diameter replicas were then made from all portions of this surface with a new replicating material "Technovit."

a

b

Figure 24. Pitlike Surface Penetrations in (a) Rod A1 and (b) Rod A18

a

b

Figure 25. Small Cracks in Surface of Rod B52 at the (a) 80.3 cm (31-5/8 in.) Location and at (b) 69.8 cm (27-1/2 in.) Near a Spacer Location

Figure 26. Small Blister and Irregular Circumferential Crack at the 69.2 cm (27-1/2 in.) Location of Rod A-1

Figure 27. VBWR Spacer Wire Wear Near Middle of Rod A18

Figure 28. Raised Marks Over Plenum of Rod B95 Approximately 5.3 cm (2-3/32 in.) From Long End Plug Shoulder

This is a self-curing methyl methacrylic ester which adheres tenaciously to the replicated surface. Consequently, on separation, large and small UO_2 particles were pulled out of the surface. Figure 29 shows the polished and etched fuel cross section and one of the Technovit replicas with embedded UO_2 . Carbon replicas of about two mm diameter were made from the Technovit replicas by masking off the unwanted portions (i.e., those containing large UO_2 particles).

Some of the slivers embedded in the final replicas had edges thin enough for electron microscopy with 100 kV electrons. Figure 30 shows such a thin edge. Dislocation loops and several small pores are visible.

A number of replicas were examined in the 650 keV electron microscope at U.C. Berkeley.

(a) Area near cladding.

Figure 31 shows the edge of a sliver with numerous defects. These defects show up as dark spots in the bright field image and as spots with white-black contrast in the dark field image. In Figure 32 some rod or plate shaped inclusions are visible. These appear to have the same size and shape as those seen in replicas of the same general location (see Figure 16⁴).

(b) Area about 1.3 mm from cladding.

A small chip (Figure 33) was transparent in its entirety to 650 kV electrons. A dense dispersion of defects is seen in bright and dark field. Similarly, Figure 34 shows the edge of a sliver in bright field and dark field with two different diffraction vectors. The numerous spot defects are apparent. In addition a few long dislocations are present.

(c) Area near fuel center, about 3.8 mm from cladding.

Two small chips are shown in Figure 35. In the bright field image only a few defects are visible. In the dark field image, on the other hand, the structure of the larger chip looks severely disrupted.

The features such as defects and inclusions, seen in the high voltage electron micrographs will be analyzed in detail in the near future.

The technique of using thin chips or slivers has some definite advantages as well as disadvantages. Since the UO_2 is highly radioactive, the small volume of chips is a great help in handling the specimens. Also the slivers are firmly embedded in the carbon film and consequently not likely to contribute to contamination problems. On the other hand, most, if not all, chips will not contain grain boundaries, since fractures will occur preferentially along grain boundaries. Also, the places where slivers are pulled out of the sample cannot be controlled in advance, although the location from which a chip has come, was recorded within an accuracy of ± 1 mm (the radius of the final replica). This accuracy could be increased by using smaller carbon replicas.

Figure 29. Locating Procedure for Irradiated UO_2 Samples

GEAP-10204

Figure 30. Irradiated UO_2 , 8×10^{20} Fissions/ cm^3 1.3 ± 0.7 mm from Cladding

BRIGHT FIELD

DARK FIELD

650 KV ELECTRON MICROGRAPHS

Figure 31. Irradiated UO_2 , 8×10^{20} Fissions/cm³ 0.2 ± 0.7 mm From Cladding
 -0.2

650 KV ELECTRON MICROGRAPH

75,000x

Figure 32. Irradiated UO_2 , ~0.2 mm From Cladding. Platelet Precipitates in Matrix

DARK FIELD

75,000x

BRIGHT FIELD

75,000x

GEAP-10204

Figure 33. Irradiated UO_2 , ~1.3 mm From Cladding

Figure 34. Irradiated UO_2 , ~1.3 mm From Cladding

DARK FIELD

75,000x

BRIGHT FIELD

75,000x

Figure 35. Irradiated UO_2 , Near Fuel Center

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