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**ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM
QUARTERLY PROGRESS REPORT NO. 12
AUGUST - OCTOBER 1970**

COMPILED BY
F.H. MEGERTH

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 41

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EVALUATION PROGRAM

Quarterly Progress Report No. 12
August–October 1970

Compiled by
F. H. Megerth

Approved:

F. H. Megerth
Project Engineer

Approved:

M. F. Lyons, Manager
Fuel Development–Water Reactors.

Prepared for the
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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 Unit No. 1 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 shutdowns 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 were shipped last March to VNC, where the final phase of the program is now 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).
- i. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 10, February—April 1970," May 1970 (GEAP-10204).
- j. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 11, May—July 1970," August 1970 (GEAP-10217).

2. SUMMARY

Diameter profiles were obtained on four fuel rods as a means of further investigating certain areas that were believed to possibly be defective. The profiles of three rods revealed no evidence of defects. The fourth rod did show two peaks of uncertain causes up to 0.0064 cm (0.0025 in.) on the diameter. Nothing specific was noted during the visual examinations or on the neutrographs of this rod that would give rise to these peaks. The lack of any difficulty in maintaining a vacuum on this rod during the collection of the contained free gases and the normal analysis obtained are evidence that the rod was sound.

Length measurements made on 12 rods indicated increases over the pre-irradiation lengths of 0.15 to 0.33 cm (0.06 to 0.13 in.). The average increase in length was 0.23 cm (0.09 in.), or 0.23 percent. However, uncertainties in the pre-irradiation lengths reduce the accuracy of the data, and, at present, there is some question as to whether the plenum support tubes inside the rods may have been a factor in the length increases.

The free gas contained in selected fuel rods was analyzed for fission gas release and composition. The percentages of fission-generated Kr-85 that were released from the UO_2 matrix to the internal void volume ranged from 0.1 to 0.7 percent. The compositions of the gas samples, determined by chromatographic analysis and mass spectrometry, appeared quite normal.

The cladding and fuel of several transverse fuel rod sections were examined metallographically. The hydrogen content of the cladding was visually estimated to be no greater than 100 ppm; distribution of the hydride platelets was uniform. Oxide weight gains, determined from thickness measurements made on the external ZrO_2 layers, ranged from 170 to 1090 mg/dm^2 among the different metallography specimens and had a mean value of 490 mg/dm^2 . The thickness of the ZrO_2 layer varied considerably around the circumference of some specimens. The specimens showed circumferential-average crud thicknesses between 4 and 18 microns (0.00016 and 0.00071 in.) for 1500 days of Dresden operation. The mean thickness for the group of specimens was 14 microns. The ZrO_2 films on the internal cladding surfaces were quite even and continuous in some cases and spotty in others. Where the films were continuous, the thicknesses averaged 4 to 9 microns among the different specimens and had a mean value of 8 microns. The UO_2 of three specimens was examined in the as-polished and etched conditions, and evidence of equiaxed central grain growth was observed in two of them. Precipitates were seen within the grains of the etched fuel. The highest concentrations were near the pellet peripheries and also in areas of various sizes that extended from the centers to points $\leq 1/2$ of the pellet radius.

Samples from the peak exposure locations of eight rods were analyzed for burnup by measuring the neodymium isotopes. The sample burnups ranged from 9×10^{20} to 1×10^{21} fissions/ cm^3 (32,000 to 37,000 MWd/t U). The ratios of peak burnup to average burnup, obtained from the gamma scans, were applied to determine the rod-average burnups. These values ranged from 8×10^{20} to 9×10^{20} fissions/ cm^3 (28,000 to 33,000 MWd/t U).

3. EXAMINATIONS AND ANALYSES OF FUEL RODS

3.1 FUEL ROD PERFORMANCE EVALUATION

3.1.1 Rod Diameter Measurements (G. P. Ferguson)

Diameter profiles were obtained on four fuel rods in addition to the six that were reported in the preceding quarterly progress report.¹ During the visual examinations of these four additional rods, areas were noted that were believed to possibly be defective. The main reason for obtaining diameter profiles on these rods then was to detect any sharp diameter changes in these areas, as, for example, might be caused by a bulge. The rods, which are discussed individually below, were not decruded before profiling.

Rod A40

This rod contained a rather deep-appearing gouge or possible crack 0.6 cm (1/4 in.) long and longitudinally oriented 56.2 cm (22-1/8 in.) from the short end plug (Figure 1) and an ~ 0.3 -cm (1/8-in.) diameter group of fine cracks of uncertain depth located 92.7 cm (36-1/2 in.) from the short end plug (Figure 2).

Figure 3 shows two diameter profiles obtained while the rod was held stationary in the orientations of the suspected defects and one run while the rod was rotating. The profiles do not show any variation indicative of a defect at either of the above locations. The diameters at these positions are on the low side compared to the measurements over most of the rod. An increase in $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ ("apparent ovality") from 0.0025 or 0.003 cm (0.001 or 0.0012 in.) up to about 0.0063 cm (0.0025 in.) can be seen between the 57.8-cm (22-3/4-in.) and 60.3-cm (23-3/4-in.) locations.

Rod A43

Corner rod A43 showed a 0.6-cm (1/4-in.) long, longitudinally oriented apparent crack at the 91.8-cm (36-1/8-in.) location near the area where a recess in the subassembly corner angle contacted the rod (Figure 4). A 0.6-cm (1/4-in.) $\times$ 0.3-cm (1/8-in.) area where the crud was cracking and lifting up also was noted at the 3.8-cm (1-1/2-in.) location (Figure 5). The surface appearance suggested that some cladding penetration might have taken place.

Figure 1. Gouge or Possible Crack in Rod A40.

*Figure 2. Group of Fine Cracks 92.7 cm (36-1/2 in.)
from Short End Plug Shoulder of Rod A40.*

Figure 3. Diameter Profiles of Fuel Rod A40.

Figure 4. Apparent Crack in the Rod Near Location of the Corner Angle Contact Point.

Figure 5. Crack in the Surface of Rod A43 Near Spacer Spring Contact Point 3.8 cm (1-1/2 in.) from Short End Plug.

The approximate 91-cm (~36-in.) location of the rotational rod diameter profile (Figure 6) looks normal for a corner angle recess contact location. However, stationary profile scans made at this location in orientations near those of the apparent crack reveal a ~0.004-cm (0.0015-in.) depression over a ~1.5-cm (0.6-in.) length. As one can see in Figure 4, the area around the apparent crack is relatively smooth and free of crud, and these factors may account, at least in part, for the rather sharp diameter decrease. It is also possible, however, that some cladding wear has taken place.

Although the rod diameter is greater between the short end plug and the ~6-cm (2-1/2-in.) location compared with the rest of the rod, this condition was typical of most of the rods that were profiled and is postulated to be the result of comparatively thick ZrO₂.

Rod A38

This rod had a 0.08-cm X 0.04-cm (1/32-in. X 1/64-in.) pit or gouge (possibly a small area where the crud had spalled away), 64.1 cm (25-1/4 in.) from the short end plug shoulder, and a ~0.3-cm (1/8-in.) diameter discolored area at the 63.5-cm (25-in.) location (Figure 7).

The rotational diameter profile of rod A38 is shown in Figure 8. At the locations mentioned above the profile looks normal, and the diameter is relatively small. The diameter does undergo a ~0.0025-cm (0.001-in.) increase between ~65.4 cm (25-3/4 in.) and ~69.2 cm (27-1/4 in.), and the "apparent ovality" increases from ~0.0025 cm (0.001 in.) to ~0.005 cm (0.002 in.) over the same portion of the length.

Rod A11

Rod A11 showed four brown circular spots of ~0.3-cm (1/8-in.) diameter 17.5 cm, 19.7 cm, 21.6 cm, and 23.8 cm (6-7/8 in., 7-3/4 in., 8-1/2 in., and 9-3/8 in.) from the short end plug and two brown circumferential rings about 1.1 cm (7/16 in.) apart at the 27.6-cm (10-7/8-in.) location (Figure 9). The general rod coloration was dark gray in the vicinity of the rings and spots, which probably came about from variations in crud deposition. It was believed that such variations might indicate localized differences in rod diameter.

Diameter profiles run with the rod held in the 0–180° and 90–270° orientations are shown in Figure 10. Series of peaks and troughs can be seen on the two profiles in the vicinity of the circular spots, but the profiles are rather flat near the brown rings. The maximum difference between any peak and a corresponding trough is about 0.0035 cm (0.0014 in.). Comparing the profiles with the neutrographs showed a reasonably good correspondence between the peak locations and pellet interfaces. The peaks may be indicative of mechanical interaction between the UO₂ and cladding. Local variations in the degree of cladding corrosion along the length of the rod also could contribute to this type of diameter peaking.

The 90–270° profile of this rod also shows peaks at 35 cm (14 in.), 45 cm (18 in.), 52 cm (20.5 in.), and 72 cm (28.5 in.) from the short end plug shoulder. The peak at 35 cm corresponds to a subassembly spacer location, while that at 52 cm corresponds to the VBWR spacer location. Diameter increases at such locations, generally caused by greater than normal crud deposition and/or ZrO₂ formation, are not unusual. The cause of the other two peaks, however, is not certain. Although there was some variation in surface roughness along the length, nothing specific was noted during the visual examinations or on the neutrographs that would give rise to these peaks. It is possible that, for some unknown reason, the crud deposition and/or cladding corrosion was unusually heavy in these regions also.

In conclusion, with the remotely possible exception of rod A11, the diameter profiles of the four rods in question did not reveal anything to indicate they might be defective. The profiles tend to indicate that those surface features previously regarded as possible cracks were either handling gouges or cracks that extended no deeper than the crud or ZrO₂ layers. At least some of the surface discolorations observed may have been due, as suggested earlier, to differences in crud deposition associated with variations in diameter; however, these variations did not appear to be indicative of a defective rod.

As was mentioned in the preceding quarterly progress report, neutrographs taken of rods A11 and A43 failed to show anything that would indicate that these rods were defective.¹ Additional evidence that rod A11 was sound was provided by collecting the contained free gases and analyzing them. No difficulties were encountered in maintaining a vacuum on this rod during gas collection, and the gas composition was normal.

PRE-IRRADIATION ROD DIAMETER AT THREE AXIAL LOCATIONS [cm (in.)]

1.074 (0.423)   1.077 (0.424)   1.077 (0.424)

Figure 6. Diameter Profiles of Fuel Rod A43.

*Figure 7. Small Pit or Gouge and Discolored Area Located
About 64 cm (25 in.) from Short Eng Plug of Rod A38.*

Figure 8. Diameter Profile of Fuel Rod A38.

Figure 9. Brown Rings and Spots on Rod A11 Between 17.5 cm (6-7/8 in.) and 27.6 cm (10-7/8 in.) from Short End Plug.

PRE-IRRADIATION ROD DIAMETER AT THREE AXIAL LOCATIONS [cm (in.)]

1.074 (0.423)

1.074 (0.423)

1.074 (0.423)

Figure 10. Diameter Profiles of Fuel Rod A11.

3.1.2 Rod Length Measurements (G. P. Ferguson)

The distance between the two end plug shoulders (i.e., the overall rod length) was measured on 12 rods to ± 0.013 cm (± 0.005 in.) with dial indicator calipers. The dial indicator was zeroed with a reference rod of a length similar to the lengths of the SA-1 fuel rods.

The lengths determined above showed increases over the pre-irradiation lengths of 0.15 to 0.33 cm (0.06 to 0.13 in.) (Table 1). The average increase in length was 0.23 cm (0.09 in.) or 0.23 percent, based on the 100.23-cm (39.462-in.) nominal tube length. In comparison, the increases in length shown by the 10 rods removed from SA-1 in January 1967 ranged from 0.08 to 0.23 cm (0.03 to 0.09 in.) and averaged 0.15 cm (0.06 in.).² The estimated rod average fast fluence exposures ($E > 1$ MeV) were between 4×10^{21} and 5×10^{21} nvt for the present rods, and between 3×10^{21} and 4×10^{21} nvt for the rods removed earlier. Length measurements made under the Fuel Cycle Program on a Zircaloy-2-clad rod and on a Zircaloy-4-clad rod at the end of VBWR irradiation indicated respective increases of 0.13 cm (0.05 in.) and 0.10 cm (0.04 in.) relative to the as-fabricated dimensions.³ The rods were estimated to have been exposed to fast fluences of about 1×10^{21} and 0.6×10^{21} nvt.

The significance of rod-to-rod comparisons is clouded by the fact that the as-fabricated lengths of the SA-1 rods, which were purposely made on a production line basis, were recorded as being accurate to ± 0.08 cm ($\pm 1/32$ in.). The fabrication records indicate that all rods were 103.35 cm (40-11/16 in.) long.

In addition, a feature of the SA-1 fuel rod design causes some concern in assessing the increases in rod length. The fission gas plenum of each rod contains a 0.076-cm (0.030-in.)-wall stainless steel support tube that extends nearly the full length of the plenum. Since the axial thermal expansion of the fuel column and support tube was greater than that of the cladding, it is very likely that "interference" which would have applied an axial tensile stress to the tubing occurred in some rods at times during operation. Fission-product-induced UO_2 swelling also may have contributed to such interference. An attempt to estimate the magnitudes of the interference and determine the possible effect on final rod lengths is in progress.

3.1.3 Gas Analysis and Fission Gas Release (D. E. Rey, M. M. Csicsery)

During the preceding quarter, the free gas contained in nine of the fuel rods was collected by puncturing and evacuating the rods at room temperature. The rods differed from each other with respect to UO_2 powder lot, as-fabricated pellet density, and peak heat flux. All of the rods attained their peak heat fluxes early in life during VBWR operation and operated at generally decreasing powers during Dresden irradiation. The rod-average burnups ranged from 8.0×10^{20} to 9.2×10^{20} fissions/cm³ (29,200 to 33,500 MWd/t U).

Table 1
CHANGE IN LENGTH OF SA-1 RODS

Rod No.	Estimated Fast Fluence Exposure Of Cladding ($E > 1$ MeV)* nvt $\times 10^{-21}$	Post - Irradiation Length		Pre - Irradiation Length		Change	
		cm (in.)		cm (in.)		cm (in.)	percent**
A1	4.5	103.49	(40.745)	103.35 (40.688)		+0.14 (0.06)	+0.15
A7	4.6	103.54	(40.765)			+0.19 (0.08)	+0.20
A9	4.5	103.61	(40.790)			+0.26 (0.10)	+0.25
A11	4.6	103.59	(40.785)			+0.24 (0.10)	+0.25
A22	4.2	103.52	(40.755)			+0.17 (0.07)	+0.18
A37	4.7	103.59	(40.785)			+0.24 (0.10)	+0.25
A40	4.2	103.57	(40.775)			+0.22 (0.09)	+0.23
A43	4.3	103.61	(40.790)			+0.26 (0.10)	+0.25
A49	4.3	103.57	(40.775)			+0.22 (0.09)	+0.23
B50	4.8	103.50	(40.750)			+0.15 (0.06)	+0.15
B52	4.7	103.57	(40.775)			+0.22 (0.09)	+0.23
B62	5.2	103.67	(40.815)			+0.32 (0.13)	+0.33

*Preliminary values subject to later adjustment

**Based on 100.23-cm (39.462-in.) nominal tube length

The gas from selected rods was analyzed recently by gas chromatography, gamma counting of Kr-85, and mass spectrometry. The compositions of the gas from rods A9, A11, and B90, as determined by chromatographic analysis, appear quite normal (Table 2). The comparatively high CO content in the gas from rod B90 may be a consequence of a relatively high carbon content in powder lot 122360-6 (90 ppm as against < 10 ppm for lots J01DD and J02DD). The compositions of the gas from rods A9 and B90 also were qualitatively determined by mass spectrometric analysis. No species in addition to those listed in Table 2 were detected.

The percentage of fission-generated Kr-85 that was released from the UO_2 matrix to the internal void volume is given for five rods in Table 2. The values range from 0.10 to 0.69 percent. Rods A1, A18, A35, and B52 also were punctured and evacuated primarily as a means of determining their integrity. However, by comparing the total volumes of gas contained in these rods with the amounts of gas contained in rods A7, A9, A11, A37, and B90, a reasonably accurate estimate of fission gas release can be obtained. One would expect the release values for rods A1, A35, and B52 to be about the same as that for rod A7 and the release value for rod A18 to be between those for rods A9 and A11.

The rods that operated at the relatively higher peak heat fluxes generally show greater than average gas release values; however, these same rods also contained pellets of relatively lower density. The pellets in rods A1, A7, A35, and B52 (average density 95.4 to 96.0 percent of theoretical) were ~ 1.5 cm (0.6 in.) long, while those in the other rods (average density 93.8 to 94.7 percent of theoretical) were ~ 2.3 cm (0.9 in.) long.

The isotopic compositions of the krypton and xenon released from rods A9 and B90 and the $\text{Xe}/(\text{Xe} + \text{Kr})$ ratios, determined by mass spectrometry, are given in Table 3.

3.1.4 Metallographic Examination of Rod Sections (D. L. Orton, R. E. Smith)

Transverse sections of 11 fuel rods were examined at up to 500X to determine the form and extent of cladding corrosion and zirconium hydride precipitation, and the natures of the cladding and UO_2 microstructures. Crud thickness was measured on those specimens on which chemical removal had not previously been carried out.

The exposure times were nearly the same for the different rods — 1,795 to 1,874 days. Most of the specimens were taken from near the maximum burnup locations of the rods — 21.7 to 28.3 cm (8-9/16 to 11-1/8 in.) from the middle of the assembly; four were taken from within ~ 20 cm (~ 8 in.) of the upper or lower ends of the SA-1 fuel column.

3.1.4.1 Cladding. Examples of the cladding microstructure are shown in Figures 11 and 12. The microstructures appeared very similar to those of the cladding specimens examined during the initial phase of the program. In general, very few platelets of zirconium hydride were observed, but those that were present appeared to be uniformly distributed. The cladding hydrogen content was visually estimated to be no greater than 100 ppm in any of the specimens. The cladding grain size was estimated to be between ASTM No. 7 and No. 8, essentially the same as that determined on samples of unirradiated material.

The external corrosion layers, which consisted of even ZrO_2 films and intermittent thicker patches of oxide, appeared similar, in general, to previously examined SA-1 rod specimens (Figures 13 and 15a). Measurements of oxide thickness made on 13 specimens are listed in Table 4. In making these measurements, each specimen was divided into octants. The average thicknesses of the even film- and patch-type ZrO_2 , and the proportion of the sector covered by the latter type, were determined for each octant. Octant No. 1 represents the 0-degree orientation of each rod, where said orientation was taken as that point on the circumference directed toward the "identification mark" side of its subassembly (Figure 14). Thus, it was possible to record variations in corrosion behavior about the specimen circumference and attempt to relate these to the orientation of the rod in the subassembly during operation. In addition, an overall circumferential-average ZrO_2 thickness was calculated for each specimen by taking a weighted average of the two forms of oxide for each octant, summing these values, and dividing by eight.

The circumferential-average thickness of the even films typically ranged from 8 to 30μ (0.0003 to 0.0012 in.) on the different specimens; that of the patches ranged from 23 to 110μ (0.0009 to 0.0043 in.), and the proportion of the rod circumference covered by the patch-type ZrO_2 ranged from < 0.1 to 0.5. The thickest single patch of oxide observed on any of the specimens was 160μ (0.0063 in.). It represents a metal penetration of ~ 20 percent of the 0.056-cm (0.022-in.) cladding wall.

Abnormally thick, fairly even layers of ZrO_2 were observed over 45 to 90 degrees of specimens from rods B50 (A609), B83 (A611), and B85 (A592). A portion of such a region on specimen No. A611 is shown in Figure 15b. The corrosion layer on specimen No. A592 reached an octant-average thickness of 119μ (0.0047 in.).

Table 2
GAS COMPOSITION AND RELEASE

Fuel Rod Number	Total U In Unirradiated Rod (gm)	Average Burnup Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)	Life-Averaged Rod-Average Heat Flux ^(b) W/cm ² (Btu/h-ft ²)	Estimated Peak Heat Flux ^(b) W/cm ² (Btu/h-ft ²)	UO ₂ Powder Lot	Average As-Fabricated Pellet Density Percent of Theoretical	Total Volume Of Gas Collected (STP) cm ³ (in. ³)	Composition (Vol/%)											Kr-85 Release (%)
								Kr	Xe	He	Ne	Ar	N ₂	O ₂	H ₂	CO	CO ₂	CH ₄	
A1	611	8.5(a) (31,800)	35.9 (114,000)	85 (270,000)	JO3HB	95.4	5.3 (0.32)	NA ^(c)											
A7	611	8.9(a) (32,500)	38.7 (119,000)	110 (350,000)	JO3HB	95.7	5.5 (0.34)	NA											0.10
A9	610	8.7 (31,900)	37.4 (115,000)	137 (435,000)	JO1DD/ JO2DD	94.7	7.6 (0.46)	3.70	29.31	65.01	0.08	0.04	0.31	0.03	0.01	0.03	0.02	0.03	0.25
A11	605	9.0 (33,000)	38.4 (118,000)	126 (400,000)	JO1DD	94.0	9.8 (0.60)	5.07	39.98	55.56	0.05	0.03	0.24	0.02	0.01	0.02	0.02	0.02	0.43
A18	606	8.6(a) (31,500)	35.6 (113,000)	123 (390,000)	JO1DD/ JO2DD	94.2	8.9 (0.54)	NA											
A35	611	8.0(a) (29,200)	33.1 (105,000)	95 (300,000)	JO3HB	95.4	5.3 (0.32)	NA											
A37	603	9.2 (33,500)	39.0 (120,000)	132 (420,000)	122360-6/ JO1DD	94.1	11.5 (0.70)	NA											0.51
B52	621	8.1(a) (29,500)	33.7 (107,000)	85 (270,000)	JO5HB	96.0	5.1 (0.31)	NA											
B90	600	9.0(a) (32,800)	37.7 (116,000)	132 (420,000)	122360-6/ JO1DD	93.8	12.5 (0.76)	5.74	49.10	45.16	0.05	0.02	0.40	0.02	0.01	0.27	0.01	0.02	0.69

(a) Values were obtained from Cs-137 gamma scan data using A37 as the standard rod.

(b) To obtain linear power in kW/ft of rod length, multiply W/cm² by 0.103.

(c) NA = not analyzed.

Table 3
ISOTOPIC COMPOSITION OF KRYPTON AND XENON
BY MASS SPECTROMETRY

Fuel Rod		
	A9	B90
	Composition (atom percent)	
Krypton Isotopes		
Kr-83	8.16 ± 0.26	8.80 ± 0.24
Kr-84	34.69 ± 0.41	34.25 ± 0.25
Kr-85	4.74 ± 0.12	4.96 ± 0.12
Kr-86	52.41 ± 0.47	51.99 ± 0.42
Xenon Isotopes		
Xe-131	6.67 ± 0.08	7.21 ± 0.11
Xe-132	22.51 ± 0.12	22.19 ± 0.14
Xe-134	29.14 ± 0.16	28.91 ± 0.14
Xe-136	41.68 ± 0.18	41.69 ± 0.21
	Xe/(Xe + Kr) Atom Ratio	
	0.893	0.881

Most of the other specimens also showed noticeable variations in the form and extent of external corrosion over different portions of their peripheries, particularly those that showed the comparatively greater circumferential-average corrosion. With these specimens the orientation of maximum overall corrosion was determined largely by the proportion and thickness of patch-type oxide, which, in turn, generally increased together. The orientation of the thickest even film also generally corresponded to that of maximum overall corrosion, but the maximum thickness often was $\leq 5\mu$ greater than the minimum. One rather notable exception was specimen No. A594 from rod A49 where the even film in one octant was 20μ thick compared to 9 to 11μ over the remainder. The octant of maximum film thickness was 135 degrees away from that of maximum overall corrosion.

Among the specimens that showed the most significant variations in overall corrosion about the circumference, corner rod specimens No. A594 (rod A49) and No. A609 (rod B50) showed the most corrosion on those portions toward the corresponding channel corner (and of course, also toward the corner of the adjacent stainless steel subassembly structural angle). In three other cases, the orientation of heaviest corrosion was directed toward the water gap caused by the removal of an adjacent rod at the end of Dresden Cycle No. 4 (specimens No. A582 [rod A11],* No. A590 [rod A15], and No. A592 [rod B85]). However, specimen No. A593 from near the top of the rod B85 fuel column showed the thickest ZrO_2 toward the adjacent corner rod instead of toward the rod vacancy, and the maximum corrosion on specimen No. A611 from rod B83 also occurred 90 degrees away from the direction of the rod vacancy water gap.

The oxide weight gains, determined by multiplying the overall circumferential-average ZrO_2 thicknesses by 15.6, ranged from 170 to $1,090 \text{ mg/dm}^2$ among the 13 specimens and had a mean value of 490 mg/dm^2 . The weight gain values presented in Table 4 give full weight to all octants of every specimen and thus include those regions which might be considered abnormally corroded. In comparison with the present results, specimens from those rods that were removed from SA-1 after about 1,200 days of VBWR and Dresden operation showed weight gains from 210 to 610 mg/dm^2 and an average value of 340 mg/dm^2 ,^{4 5} and specimens from like fuel rods irradiated under the AEC Fuel Cycle Program showed an average weight gain of 125 mg/dm^2 after 365 days of operation in the VBWR.³

* Between Cycle Nos. 4 and 5, rod A11 was moved to its final assembly position from the adjacent rod vacancy position (Figure 14). Its orientation during Cycle Nos. 3 and 4 is unknown. The other rods listed in Table 4 were not removed from their original subassembly locations until their examination at Vallecitos Nuclear Center (VNC).

(a)

CLADDING ETCHED

250X

PHOTOGRAPHED UNDER NORMAL LIGHT

(b)

CLADDING ETCHED

250X

PHOTOGRAPHED UNDER POLARIZED LIGHT

Figure 11. Cladding Microstructure of Specimen No. A580 (Rod A37).

(a)

(b)

CLADDING ETCHED

250X

PHOTOGRAPHED UNDER POLARIZED LIGHT

Figure 12. Cladding Microstructure of Specimen No. A609 (Rod B50).

(a)

AS-POLISHED

100X

(b)

AS-POLISHED

500X

Figure 13. Example of Corrosion of Outside Cladding Surface,
(a) Rod B50 (Specimen No. A609), (b) Rod B57 (Specimen A613).

Table 4
THICKNESS OF CRUD AND ZrO₂ ON THE CLADDING
OF TRANSVERSE METALLOGRAPHY SPECIMENS

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant	ZrO ₂ on Outside Surface			Overall	Weight Gain (mg/dm ² O ₂)**	Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		Even Film Average Thickness (microns)	Patches Average Thickness (microns)	Relative Amount				
A11 A582	1(0°)	10	25	0.04	11		12	9
a) 20.2 (7-15/16)	2	11	41	0.19	17		12	8
b) 133.8 (52-11/16)	3	14	72	0.71	55		22	9
c) 1860	4	11	63	0.53	39		25	9
d) 9.9 (36,200)	5	10	34	0.10	12		17	10
e) 40.7 (129,000)	6	11	25	0.02	11		13	9
f) 110 (350,000)	7	10	23	0.03	10		15	9
g) CA-4	8	10	23	0.03	10		13	9
	1 through							
	8	11	60	0.21	21	328	16	9
A15 A590	1(0°)	13	106	1.00	106		18	
a) 25.7 (10-1/8)	2	11	68	0.15	20		12	
b) 128.3 (50-1/2)	3	11	41	0.02	12		10	
c) 1795	4	11	36	0.08	13		9	
d) 8.9 (32,700)	5	11	40	0.17	16		8	
e) 38.8 (123,000)	6	10	27	0.06	11		9	
f) 98 (310,000)	7	10	50	0.04	12		9	
g) CA-5	8	11	70	0.44	37		11	
	1 through							
	8	11	82	0.24	28	443	11	
A15 A591	1(0°)	8	29	0.05	9		3	
a) 89.9 (35-3/8)	2	7	29	0.12	10		4	
b) 64.1 (25-1/4)	3	8	42	0.08	11		4	
c) 1795	4	8	30	0.12	11		3	
d) 6.7 (24,600)	5	7	39	0.18	13		3	
e) 29.0 (92,000)	6	8	33	0.19	13		4	
f) 44 (140,000)	7	8	32	0.23	14		4	
g) CA-5	8	7	32	0.13	10		3	
	1 through							
	8	8	33	0.14	11	177	4	

12μ to 1/2μ spots
-to-trace
↓
8
↑
trace with
scattered spots
↓
low
4
5
↑
scattered
spots
↓
4(0.25)***

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Table 4 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant	Even Film Average Thickness (microns)	ZrO ₂ on Outside Surface Patches		Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**	Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
			Average Thickness (microns)	Relative Amount				
A32 A610 1(0°)		11	23	0.02	11		8	7
a) 26.7 (13-1/2)	2	10	24	0.03	10		8	8
b) 127.3 (50-1/8)	3	10	24	0.03	10		8	8
c) 1860	4	10	24	0.05	11		8	7
d) 9.2 (33,500)	5	10	25	0.05	11		9	10
e) 37.8 (120,000)	6	11	20	0.05	11		8	8
f) 123 (390,000)	7	11	23	0.04	11		8	8
g) CA-4	8	11	21	0.01	11		9	8
	1 through							
	8	11	23	0.04	11	172	8	8
A37 A580 1(0°)		10	47	0.37	24			8
a) 20.2 (7-15/16)	2	9	45	0.28	19			8
b) 133.8 (52-11/16)	3	11	23	0.06	12		Crud chemically removed	8
c) 1860	4	10	21	0.05	11			7
d) 10.0 (36,800)	5	8	21	0.05	9			8
e) 41.3 (131,000)	6	8	24	0.20	11			8
f) 117 (370,000)	7	8	17	0.13	9			8
g) CA-1	8	10	23	0.08	11			8
	1 through							
	8	9	35	0.15	13	203		8
A47 A612 1(0°)		11	66	0.23	24		9	7
a) 25.7 (10-1/8)	2	11	65	0.16	20		8	8
b) 128.3 (50-1/2)	3	11	75	0.44	33		9	7(0.2)
c) 1874	4	12	72	0.40	36		13	8(0.5)
d) 9.2 (33,500)	5	11	58	0.26	23		12	7(0.3)
e) 37.5 (119,000)	6	11	54	0.22	20		9	7(0.3)
f) 107 (340,000)	7	11	79	0.17	23		10	trace to spotty
g) CA-2	8	11	64	0.12	17		10	8
	1 through							
	8	11	68	0.25	25	390	10	7(0.54)***

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Table 4 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant	Even Film Average Thickness (microns)	ZrO ₂ on Outside Surface Patches		Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**	Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
			Average Thickness (microns)	Relative Amount				
A49 A594	1(0°)	8	106	0.34	41			trace with 4 to
a) 76.8 (30-1/4)	2	9	46	0.16	15			10μ spots
b) 77.2 (30-3/8)	3	9	74	0.17	20			0
c) 1874	4	9	85	0.35	36			0(0.5)
d) 7.7 (28,100)	5	20	96	0.52	60		Crud chemically removed	6(0.5)
e) 31.5 (100,000)	6	9	116	0.64	77			0(0.5)
f) 73 (230,000)	7	11	108	0.73	82			7(0.5)
g) CA-2	8	9	121	0.94	114			0(0.6)
	1 through							6(0.4)
	8	10	105	0.48	56	868		0(0.5)
								7(0.5)
B50 A609	1(0°)	10	61	0.25	23			6
a) 74.9 (29-1/2)	2	11	64	0.51	38			
b) 230.2 (90-5/8)	3	12	69	0.46	38			trace to
c) 1874	4	13	88	0.39	42			6μ spots
d) 7.4 (27,100)	5	94	89	0.37	92		Crud chemically removed	5(0.6)
e) 30.9 (98,000)	6	105	—	0.00	105			7(0.5)
f) 47 (150,000)	7	78(0.1)	78	0.33	39			5(0.2)
		14(0.9)						
g) CA-2	8	11	68	0.39	33			spotty
	1 through							
	8	40	74	0.34	51	796		6(0.16)***
B57 A613	1(0°)	12	81	0.35	36		19	5(0.3)
a) 25.7 (10-1/8)	2	12	84	0.29	33		19	trace with
b) 181.0 (71-1/4)	3	13	65	0.26	27		18	spots up to
c) 1874	4	12	73	0.38	35		18	9μ
d) 8.6 (31,600)	5	12	48	0.22	20		17	8(0.5)
e) 35.9 (114,000)	6	12	45	0.12	16		17	7(0.6)
f) 79 (250,000)	7	10	37	0.07	12		15	8
g) CA-1	8	12	56	0.21	21		16	7(0.6)
	1 through							
	8	12	68	0.24	25	390	17	7(0.38)***

Table 4 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant	ZrO ₂ on Outside Surface Patches			Overall Weight Gain (mg/dm ² O ₂)**	Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		Even Film Average Thickness (microns)	Average Thickness (microns)	Relative Amount			
B62 A581	1(0°)	11	35	0.10	13	14	9
a) 24.6 (9-11/16)	2	11	33	0.14	14	15	9
b) 179.9 (70-13/16)	3	12	30	0.16	15	16	8
c) 1860	4	12	28	0.06	13	16	8
d) 10.2 (37,400)	5	12	20	0.01	12	16	10
e) 42.2 (134,000)	6	11	20	0.01	11	16	9
f) 126 (400,000)	7	11	28	0.09	13	16	9
g) CA-1	8	10	46	0.14	15	15	9
	1 through						
	8	11	34	0.09	13	203	9
B83 A611	1(0°)	15	45	0.17	20	17	8
a) 26.7 (10-1/2)	2	13	61	0.20	23	15	7
b) 181.9 (71-5/8)	3	17(0.8)	71	0.21	35	19	7
		61(0.2)					
c) 1874	4	99	—	0.00	99	20	8
d) 8.4 (30,800)	5	87	—	0.00	87	20	8
e) 35.0 (111,000)	6	16	72	0.49	43	20	8
f) 98 (310,000)	7	20	65	0.38	37	17	8
g) CA-3	8	16	63	0.37	33	19	8
	1 through						
	8	42	65	0.23	47	733	8
B85 A592	1(0°)	119	—	0.00	119	11	7
a) 25.7 (10-1/8)	2	25	107	0.52	68	18	spotty (0.4)
							6(0.6)
b) 181.0 (71-1/4)	3	36	128	0.72	102	23	6
c) 1831	4	33	124	0.43	72	20	7
d) 8.9 (32,600)	5	30	98	0.20	44	18	trace-to-spotty
e) 37.8 (120,000)	6	25	91	0.29	44	16	7
f) 98 (310,000)	7	19	72	0.25	32	15	7
g) CA-5	8	22	100	0.35	79	17	7
		108	—	0.00			
	1 through						
	8	51	110	0.32	70	1092	7(0.82)***

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Table 4 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*			ZrO ₂ on Outside Surface					ZrO ₂ on Inside Surface	
			Even Film Average Thickness (microns)	Patches		Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**	Crud Average Thickness (microns)	Average Thickness (microns)
Octant				Average Thickness (microns)	Relative Amount				
B85	A593	1(0°)	21	39	0.36	27		0(0.5) 16(0.5)	↑ trace and scattered spots up to 8μ ↓
a) 89.9 (35-3/8)		2	35	73	0.40	50		18	
b) 245.1 (96-1/2)		3	44	105	0.40	68		16	
c) 1831		4	37	66	0.37	48		17	
d) 5.6 (20,400)		5	29	48	0.01	29		16	
e) 23.6 (75,000)		6	19	45	0.05	20		19(0.1) 0(0.9)	
f) 41 (130,000)		7	17	—	0.00	17		0	
g) CA-5		8	21	58	0.03	22		0(0.5) 15(0.5)	
1 through 8									
		8	26	70	0.20	35	548	17(0.64)***	low

*a) Distance from center of specimen to shoulder of short end plug (cm [in.]).

b) Distance from bottom of Dresden Reactor active fuel zone (cm [in.]). (The SA-1 fuel column was approximately 192 cm [75-9/16 in.] long, which dimension includes a ~3 cm [1-1/4 in.] nonfueled gap between the top and bottom subassemblies. The bottom of the column was 58.6 cm [23-1/16 in.] above the bottom of the reactor active fuel zone, and the top of the column was 28.7 ± 4.4 cm [11-5/16 ± 1-3/4 in.] below the top of the reactor active fuel zone.)

c) Total days of operation (hours VBWF thermal power greater than 5 MW ÷ 24 + hours of Dresden turbine-generator operation ÷ 24).

d) Specimen burnup (fissions/cm³ × 10⁻²⁰ [MWd/tU]).

e) Life-averaged heat flux for specimen (W/cm² [Btu/h-ft²]).

f) Estimated maximum heat flux attained during operation (W/cm² [Btu/h-ft²]).

g) Tubing lot.

** Weight gain in mg per dm² of rod surface = 15.6 × ZrO₂ thickness in microns.

*** Average thickness where ZrO₂ or crud is present. Portion of circumference included is given in parenthesis.

Figure 14. SA-1 Fuel Rod Patterns During Dresden Cycles 3 and 4 (a) and 5 and 6 (b).
 (Locations of Subassembly Identification Marks are Indicated).

(a)

AS-POLISHED

100X

(b)

AS-POLISHED

100X

Figure 15. ZrO_2 Layer on Outside Cladding Surface of Specimen No. A611 of Rod B83, (a) Octant No. 8 (b) Octant No. 4.

Where two specimens were taken from a fuel rod of the present group (rods A15 and B85), the specimen nearer the bottom or top of the full assembly showed a lower weight gain than that nearer the middle of the assembly in the maximum power region. On the other hand, the specimens from rods A49 and B50 also were taken from within 20 cm (8 in.) of the ends of the total SA-1 fuel column, and thus operated at powers somewhat below the averages of the respective rods. The diameter profiles of these rods indicate that the specimens were located in regions of maximum increase in diameter over pre-irradiation measurements; this fact suggests that the corrosion weight gains shown by the specimens were near the maximum values for the rods. ZrO_2 thickness measurements made during the initial phase of the examination program also indicate that the "corrosion profile" for a given rod does not necessarily correspond to the burnup profile.^{4 5} On the average, specimens from the B rods (top subassembly) showed larger weight gains than did those from the A rods (bottom subassembly); however, there is considerable overlapping in the ranges of values obtained on specimens from both groups. With the exception of rod B83, specimens from interior rods showed lower weight gains than did those from rods with outside locations in assembly SA-1.

Representative cross-sectional views of deposited crud are shown in Figures 13b and 15. The circumferential-average crud thicknesses measured on 10 of the specimens ranged from 4 to 18μ (0.0002 to 0.0007 in.) and had a mean value of 14μ . The lowest deposition was measured on a specimen located near the bottom of the SA-1 fuel column. The crud thicknesses measured on the metallography specimens agree reasonably well with those determined from diameter profiles run on rods that operated in Dresden for the same length of time (i.e., $\sim 1,500$ days).^{*} The average crud thickness measured over the full lengths of six rods was 0.0012 cm (0.0005 in.). The maximum circumferential-average thickness at any axial location of any of these six rods was 0.0028 cm (0.0011 in.) (i.e., somewhat greater than that measured on any metallography specimen).¹ Comparable crud thicknesses measured on metallography specimens from SA-1 rods that operated in Dresden 840 days ranged from 3 to 10μ (0.0004 in.) and had a mean value of 9μ (0.00035 in.).^{4 5}

The thickness of the crud deposit also varied considerably about the periphery of some specimens. In such cases, the crud was generally thickest, or at least thicker than average, in the orientation of heaviest corrosion. However, specimen No. A592 (rod B85) represents an exception to this relationship. The crud on this specimen was thinnest over the octant of maximum overall corrosion, but was thickest over the octant with the greatest average patch-type ZrO_2 thickness. In other instances, the variation in crud thickness was rather small compared to that in ZrO_2 thickness (e.g., specimen No. A611 [rod B83]).

The reason(s) for the wide variation in corrosion behavior shown by the external surfaces of the specimens is not clear. The maximum exposure time is only 4 percent greater than the minimum, and over this narrow range the relationship between exposure time and weight gain is quite random. Large differences in weight gains were determined on specimens with approximately the same circumferential-average crud thicknesses. The degree of corrosion does not correlate well with heat flux within the range of values attained. The limited sampling represented by the group of specimens makes it difficult to ascertain any consistent differences in corrosion behavior among the five lots of tubing. The weight gains varied considerably among specimens from the same lot, particularly with lots CA-2 and CA-5. The corrosion of specimens from lots CA-1 and CA-4 was generally somewhat lower than that of specimens from the other lots. Only one specimen from lot CA-3 was examined, and it showed a greater than average weight gain. Chemical analyses of unirradiated samples from the various lots do not appear to offer any clues that might help to explain differences in corrosion behavior of specimens from different lots.

The ZrO_2 films on the internal cladding surfaces were quite even and continuous in some cases (Figure 16a) and were spotty in others (Figure 16b). It is possible that portions of some of these films were lost during sample preparation. Fuel was often bonded to the ZrO_2 films, as noted in previous examinations.^{3 4} Where the films were continuous, the thicknesses averaged 4 to 9μ among the different specimens and had a mean value of 8μ . Specimens from rods that were removed from the assembly at the end of Cycle No. 4 for the initial phase of the examination program showed specimen-average internal film thicknesses that ranged from less than 1 to 5μ and had a mean value of 3 to 4μ .^{4 5} The thicknesses of the internal and external ZrO_2 on the current specimens were not related in any particular way.

* At the end of VBWR operation, most of the crud, which was quite soft and nonadherent, was wiped with a dry cotton pad from those rods that were to be incorporated in SA-1. Hence, essentially all of the crud measured at the end of Cycle Nos. 4 and 6 was deposited during Dresden operation.

Figure 16. ZrO₂ Films on Inside Cladding Surfaces (a) Specimen No. A610 (Rod A32), (b) Specimen No. A613 (Rod B57).

3.1.4.2 Fuel. The UO_2 of the three specimens with highest burnups was examined in the as-polished and etched conditions. Micrographs of the fuel of these three specimens (No. A580 from rod A37, No. A581 from rod B62, and No. A582 from rod A11) are shown in Figures 17, 18, and 19. Evidence of equiaxed central grain growth can be seen in the micrographs of specimen No. A582 (Figure 18) and, somewhat less pronounced, in the micrographs of specimen No. A581 (Figure 19b). Specimen No. A580, which has larger grains near the pellet periphery than the other two specimens, does not show any significant radial variation in grain size (Figure 19a).

Precipitates of appearance and distribution similar to those noted during the initial phase of the examination program were again observed in the etched fuel.^{4 5} They are located within the grains near the pellet peripheries in all three specimens. A significant fraction of the grains in these locations fell out as a result of etchant attack at the grain boundaries. Concentrations of intragranular precipitates are present also at interior locations. In the case of specimen No. A581, these precipitates are most pronounced at the pellet center (Figure 19b). Precipitates can also be seen at the centers of specimen Nos. A580 and A582; however, in these cases the concentrations attain their maxima at mid-radial locations (Figures 19a and 18). Differences can be seen in the three specimens with respect to the distribution of precipitates within the central grains. The central grains of specimen No. A580 show precipitate-free bands extending inward from the boundaries, while in No. A582 the precipitates are more highly concentrated next to the boundaries than in the grain centers. The precipitates are comparatively evenly distributed over the central grains of specimen No. A581.

Additional work directed toward the identification of these precipitates is in progress.

3.2 FUEL BURNUP AND ISOTOPIC COMPOSITION ANALYSES (C. P. Ruiz, Technical Director, J. P. Peterson, F. R. Smith)

Twenty-four full cross-section 1.3-cm (1/2-in.)-long samples of fuel and cladding were cut from 16 rods for burnup and isotopic composition analyses. The fuel of each sample was dissolved at ambient temperature in nitric acid. A small sample of each solution was transferred from the Radioactive Materials Laboratory hot cells to the Radiochemistry Laboratory for analysis.

Samples from near the peak exposure locations of eight of the rods were analyzed for burnup by measuring the neodymium isotopes (Table 5). The sample burnups ranged from 9×10^{20} to 1×10^{21} fissions/cm³ (32,000 to 37,000 MWd/t U). The rod-average burnups were calculated by applying sample-to-average burnup ratios determined from the Cs-137 gamma scan traces on these rods. These values ranged from 8×10^{20} to 9×10^{20} fissions/cm³ (28,000 to 33,000 MWd/t U).

Burnup analyses on the remainder of the samples and the isotopic composition analyses will be presented in the next report.

Figure 17. UO_2 Microstructure of Specimen No. A582 from Rod A11 (As-polished).

Figure 18. UO_2 Microstructure of Specimen No. A582 from Rod A11 (Fuel Etched).

OUTSIDE OF PELLE

500X

MID-RADIUS OF PELLE

500X

CENTER OF PELLE

500X

(a)

OUTSIDE

500X

MID-RADIUS

500X

CENTER

500X

(b)

Figure 19. UO_2 Microstructures of (a) Specimen No. A580 (Rod A37) and (b) Specimen No. A581 (Rod B62) (Fuel Etched).

Table 5
FUEL BURNUP

Fuel Rod	Sample Number	Sample Location		Sample Burnup Fissions/cm ³ X 10 ⁻²⁰	MWd/tU	Rod-Average Burnup	
		Distance From Short End Plug Shoulder (cm [in.])	Distance From Bottom of Dresden Reactor Active Fuel Zone* (cm [in.])			Fissions/cm ³ X 10 ⁻²⁰	MWd/tU
A9	100	26.4 (10-3/8)	127.6 (50-1/4)	9.51	34,770	8.73	31,900
A11	101	↓	↓	9.92	36,250	9.03	33,000
A37	105	↓	↓	10.09	36,880	9.17	33,500
A40	110	↓	↓	8.85	32,360	8.13	29,700
A43	112	↓	↓	8.80	32,150	8.29	30,300
A49	115	↓	↓	9.05	33,080	8.37	30,600
B62	116	29.4 (11-9/16)	184.6 (72-11/16)	10.23	37,400	8.97	32,800
B98	123	29.4 (11-9/16)	184.6 (72-11/16)	8.97	32,770	7.66	28,000

*The SA-1 fuel column was approximately 192 cm [75-9/16 in.] long, which dimension includes a ~3 cm (1-1/4 in.) nonfueled gap between the top and bottom subassemblies. The bottom of the column was 58.6 cm (23-1/16 in.) above the bottom of the reactor active fuel zone, and the top of the column was 28.7 ± 4.4 cm (11-5/16 ± 1-3/4 in.) below the top of the reactor active fuel zone.

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G. P. Ferguson	}	IPO Materials Investigation
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F. R. Smith		
E. B. Young		
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M. W. Kirkland	}	RF&RD Fuel Development—Water Reactors
F. H. Megerth		

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