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**ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM
QUARTERLY PROGRESS REPORT No. 1
NOVEMBER 1967 - JANUARY 1968**

COMPILED BY
F.H. MEGERTH

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

NUCLEAR FUELS DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM

MASTER

Quarterly Progress Report No. 1
November 1967 - January 1968

Compiled By
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SECTION I

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/cc (10,000 MWd/STU). To demonstrate at the earliest possible time the capability of Zircaloy-clad fuel to achieve average burnups of at least 6×10^{20} fissions/cc (20,000 MWd/STU) and to take advantage of the available lead time in achieving these burn-up targets, 98 of the higher exposure Fuel Cycle Program rods were incorporated in a special assembly, designated SA-1, and inserted in the Dresden reactor for additional irradiation. The assembly consists 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 has been operated continuously from June 1964 to the present time 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, 10 rods were removed from the assembly in February 1967 and were shipped to the Vallecitos Nuclear Center. The examination of these 10 rods is now in progress.

SECTION II

SUMMARY2.1 Assembly Operation

The assembly continued to be operated through the present quarter at an estimated peak heat flux of 67 watts/cm² (212,000 Btu/h-ft²). The 88 remaining rods have now been operated in Dresden approximately 25,000 hours. Their previous irradiation in the VBWR averaged about 8,000 hours. The current average exposure of the assembly, including VBWR as well as Dresden irradiation, is estimated to be 7.5×10^{20} fissions/cc (27,000 MWd/STU) and the estimated peak exposure is 12.2×10^{20} fissions/cc (44,000 MWd/STU).

2.2 Fuel Rod Examinations

Visual examination of the 10 rods removed from SA-1 did not reveal any significant defects.

The surfaces of the rods as received from Dresden were, typically, a bluish-gray color with varied amounts of reddish-brown speckling, and they appeared somewhat rough in texture. Some of the subassembly spacer locations along the rods showed a relative increase in crud deposition. This crud was completely removed from 6 of the 10 rods by dissolving it with hydrochloric acid. With the crud removed, the surfaces of the prefilmed rods were a solid black except for a few areas of fine white or silvery speckling. A surface roughness, which varied both with axial location and with orientation on a given rod, was observed. The degree of roughness also varied from rod to rod.

Marks where the SA-1 subassembly spacer springs had contacted the cladding surface were apparent on most of the rods

from which the crud had been removed. However, it did not look as though any significant cladding wear had taken place.

Measurements of rod length indicated that irradiation had effected a permanent increase in this dimension that ranged from 0.08 to 0.23 cm (1/32 to 3/32 inch) and averaged 0.15 cm (1/16 inch).

Post-irradiation diameter profiles of the rods as-received showed an average general increase in diameter of approximately 0.0045 cm (0.0018 inch) when compared with pre-irradiation measurements. This general increase ranged from about 0.0025 to 0.008 cm (0.001 to 0.003 inch) over various sections of the different rods.

Removal of the crud from some of the rods resulted in an over-all average decrease in diameter of about 0.0018 cm (0.0007 inch). Thus, these rods still showed a diameter increase with respect to the pre-irradiation measurements of approximately 0.0025 cm (0.001 inch). The diameter profiles imply that the circumferential-average crud thickness had a mean value of about 0.0009 cm (0.00035 inch) and, with the exception of some local peaks, a maximum value of about 0.0012 cm (0.0005 inch).

The difference between maximum and minimum diameters at a given axial location was as large as 0.010 cm (0.004 inch). This "apparent ovality" had an average value of 0.004 to 0.005 cm (0.0015 to 0.002 inch). Chemical removal of the crud generally did not decrease the amount of or markedly change the pattern of this ovality.

In addition to the general increase in rod diameter that occurred during operation, local peaks in rod diameter often were present near both the SA-1 subassembly spacer locations and the VBWR spacer locations. These peaks averaged 0.004 to 0.005 cm (0.0015 to 0.002 inch) above the typical rod diameter in the vicinity and they were as large as 0.011 cm (0.0045 inch). Chemical removal of the crud from the rods decreased the rod diameter at these peaks in only about one-half of the cases.

Some instances of diameter peaking at pellet-length intervals were noted. The difference in diameter between these peaks and the corresponding troughs was typically 0.0013 to 0.0019 cm (0.0005 to 0.00075 inch) and had a maximum value of about 0.0025 cm (0.001 inch).

SECTION III

DESCRIPTION OF FUEL

The fuel rods in SA-1 were selected from a group of nearly 400 irradiated rods of the same design and fabrication characteristics, some of which are listed in Table 1. They consist of sintered UO_2 pellets of about 95 percent of theoretical density, clad with 1.077-cm (0.424-inch) by 0.056-cm (0.022-inch) wall Zircaloy-2 tubing, and are 104 cm (40-3/4 inches) long. The pellet-to-cladding diametral gap ranges from 0.010 to 0.020 cm (4 to 8 mils).

The assembly consists of two 7×7 subassemblies stacked one on top of the other in a channel of standard dimensions for the Dresden reactor. One of these subassemblies is shown (Figure 1) before irradiation with a load of dummy fuel rods. A removable lifting tool, partially in view, is attached to the top. The rods in each subassembly rest on a bottom grid, shown in Figure 2, and are held in position by four spring-type spacers distributed axially along the length of the fuel.

TABLE 1

CHARACTERISTICS OF TYPE J
FUEL RODS SELECTED FOR ASSEMBLY SA-1

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)
Uranium Enrichment, percent U-235	2.76-3.5

The spacers are supported by corner angles which are attached to the bottom grid and extend the full length of the subassembly, to form an integral basket for the fuel rods. The corner angles are fastened at the top to a band which extends about 0.6 cm (1/4 inch) above the top of the fuel rods (see Figure 3).

The first subassembly sits on a stand attached to a standard Dresden channel nose-piece with a partially cut out grid (see Figure 4). The second subassembly rests on the first. The two stacked subassemblies form an active fuel length of 188 cm (74 inches). The fission gas plenums of the rods in the bottom subassembly are pointed toward the bottom grid, and those of the rods in the top

subassembly are pointed toward the top band, so that the nonfueled gap between the subassemblies is minimized at about 3 cm (1-1/4 inches). The subassemblies are held down by a spring-loaded fixture attached to a clamp (Figure 5) which fits into slots in the sides of the channel near the top. A standard-shape handle is attached to the clamp for lifting the assembly. The relative positions of the handle, clamp, and channel when the assembly is ready to be inserted in the reactor are indicated in Figure 6.

The UO_2 in the various fuel rods is of three different initial enrichments. The original loading pattern for rods of the various enrichments in each subassembly is shown in Figure 7.

FIGURE 1. SA-1 SUBASSEMBLY

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FIGURE 2. BOTTOM OF SUBASSEMBLY

FIGURE 3. TOP OF SUBASSEMBLY

FIGURE 4. CHANNEL NOSEPIECE AND STAND

FIGURE 5. HANDLE HOLDDOWN ASSEMBLY

FIGURE 6. TOP OF CHANNELED ASSEMBLY

2.76	2.76	2.76	2.76	2.76	2.76	2.76
2.76	3.5	3.2	3.5	3.2	3.5	2.76
2.76	3.2	3.5	3.5	3.5	3.2	2.76
2.76	3.5	3.5	3.2	3.5	3.5	2.76
2.76	3.2	3.5	3.5	3.2	3.2	2.76
2.76	3.5	3.2	3.5	3.2	3.5	2.76
2.76	2.76	2.76	2.76	2.76	2.76	2.76

CONTROL
ROD

FIGURE 7. FUEL ROD LOCATION BY INITIAL ENRICHMENT

SECTION IV

OPERATIONAL DATA4.1 VBWR

The fuel rods in Assembly SA-1 were selected from 12 of the Fuel Cycle Program's basic assemblies, each of which had its own unique history of operation in the VBWR. Irradiation of these assemblies began as early as June 1961 and continued until the reactor was shut down in December 1963. During this period they were operated between 7,200 and 9,100 hours to bundle-average burnups of 1.5×10^{20} to 2.6×10^{20} fissions/cc (5,400 to 9,500 MWd/STU). The peak heat flux attained was ~ 150 watts/cm² (480,000 Btu/h-ft²). A summary of the thermal performance and exposure characteristics of these assemblies is presented in Table 2.

4.2 Dresden Unit 14.2.1 Thermal Performance and Exposure

Assembly SA-1 was first inserted in the Dresden core in June 1964, at the beginning of reactor Cycle 3, and it has been operated continuously to the present time, with the exception of shutdown periods for reactor refueling and maintenance. The total operating time in Dresden is about 25,000 hours. The assembly attained a peak heat flux of 125 watts/cm² ($\sim 400,000$ Btu/h-ft²) early in Cycle 3. The estimated thermal performance history of Assembly SA-1 in Dresden is summarized in Table 3.

During the report period (November 1, 1967, through January 31, 1968) the reactor was operated at an average thermal power of about 590 MW and at a maximum power of 700 MW. Assembly SA-1 was operated at an estimated peak heat flux of 67 watts/cm² (212,000 Btu/h-ft²). The current assembly-average exposure, including VBWR as well

as Dresden irradiation, is estimated to be 7.5×10^{20} fissions/cc (27,000 MWd/STU), and the estimated peak exposure is 12.2×10^{20} fissions/cc (44,000 MWd/STU). Recent thermal performance and exposure data are presented in Table 4.

4.2.2 Coolant Environment

The reactor water chemistry data given in Table 5 were extracted from the October and November, 1967, monthly reports of the Commonwealth Edison Company on Dresden operation and are the most recent that are presently available.

4.2.3 Interim Tests, Inspections, and Fuel Rod Changes

At the conclusion of the first cycle of operation in Dresden (Cycle 3), Assembly SA-1 was leak tested by "sipping," an operation in which the assembly was isolated in a can and then the contained water sampled and analyzed for fission product iodine. No indication of rod failure was detected.

Assembly SA-1 was similarly sip tested at the end of reactor Cycle 4. The two subassemblies then were removed from the channel, and all sides were visually examined by means of both an underwater television camera and a borescope. A number of fuel rods were withdrawn from the subassemblies and individually inspected with the borescope. The rods, spacers, and structural members all appeared to be in good condition.

The 10 rods, indicated in Figure 9, were permanently removed from the subassemblies and were shipped to the Vallecitos Nuclear Center for a comprehensive program

TABLE 2

VBWR OPERATION OF SA-1 FUEL

VBWR Assembly	Initial Loading Date	Peak Surface Heat Flux*		Peak Fuel Center Temperature (°C)	Terminal Average Burnup		Hours at Temperature, >5 MW	Power Cycles <5 to >20 MW Back to <5	Thermal Cycles 0 to >5 MW Back to 0	Number of Rods in SA-1
		W/cm ²	Btu/h-ft ² × 10 ⁻³		Fissions/ cc × 10 ⁻²⁰	MWd/STU				
1J	6-7-61	92	291	1,316	1.49	5,440	9,075	179	300	4
4J	6-7-61	94	299	1,371	1.55	5,662	9,075	179	300	7
5J	6-7-61	104	331	1,399	1.75	6,400	9,075	179	300	10
6J	6-7-61	133	423	1,983	2.17	7,942	9,075	179	300	11
8J	6-7-61	105	334	1,482	1.46	5,327	7,347	164	280	10
9J	6-7-61	109	345	1,538	1.95	7,135	9,075	179	300	10
11J	7-15-61	145	460	2,177	2.59	9,481	8,747	170	273	9
12J	7-15-61	151	479	2,343	2.54	9,297	8,747	170	273	8
13J	7-15-61	139	442	2,065	2.49	9,107	8,747	170	273	10
14J	7-15-61	137	436	1,870	2.24	8,189	8,747	170	273	3
16J	8-28-61	122	386	1,792	1.85	6,771	8,041	157	250	12
17J	11-1-61	110	349	1,538	1.49	5,458	7,168	137	192	4

*Local peak sustained sometime during irradiation.

TABLE 3

THERMAL PERFORMANCE OF SA-1 IN DRESDEN

Reactor Cycle	SA-1 Core Location (Figure 8)	Period	Number of Months	Assembly Average Heat Flux, W/cm ² (Btu/h-ft ²)		Assembly Peak Heat Flux, W/cm ² (Btu/h-ft ²)	
				At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power
3	57-14	6/9 - 6/30/64	2/3	45 (144,000)	71 (225,000)	71 (225,000)	125 (398,000)
		7/1 - 9/30/64	3	44 (139,000)	69 (218,000)	78 (246,000)	122 (386,000)
		10/1 - 12/31/64	3	46 (147,000)	51 (162,000)	82 (260,000)	90 (287,000)
		1/1 - 3/28/65	3	46 (147,000)	46 (147,000)	82 (260,000)	82 (260,000)
4	54-16	5/29 - 12/31/65	7	37 (118,000)	55 (175,000)	66 (208,000)	97 (309,000)
		1/1 - 3/31/66	3	46 (147,000)	54 (172,000)	82 (260,000)	96 (304,000)
		4/1 - 6/30/66	3	45 (144,000)	53 (168,000)	80 (254,000)	93 (297,000)
		7/1 - 9/30/66	3	43 (136,000)	50 (159,000)	76 (241,000)	89 (281,000)
		10/1 - 12/31/66	3	33 (106,000)	41 (131,000)	59 (187,000)	73 (232,000)
		1/1 - 1/13/67	1/2	32 (101,000)	32 (101,000)	56 (179,000)	56 (179,000)
5	53-11	5/23 - 6/30/67	1-1/3	24 (76,000)	28 (89,000)	43 (135,000)	50 (158,000)
		7/1 - 10/31/67	4	23 (72,000)	26 (84,000)	40 (127,000)	47 (149,000)

FIGURE 8. LOCATIONS AND ORIENTATIONS OF SA-1 IN CYCLE 3 (57-14), CYCLE 4 (54-16), AND CYCLE 5 (53-11)

of destructive examination. To assure satisfactory power distribution and thermal-hydraulic characteristics in Cycle 5 operation, some of the 88 remaining fuel rods were rearranged, as shown in Figure 10.

4.2.4 Future Operation

The current cycle of operation (Cycle 5) is tentatively scheduled to end in February

1968. During the succeeding refueling outage, SA-1 will be sip tested and, possibly, visually inspected. If the assembly is determined to be in satisfactory condition, it will be returned to the core for further irradiation. The operation of SA-1 will be terminated at the conclusion of the next reactor cycle, estimated to be in spring, 1969, and the assembly will be transferred from the reactor site for final destructive examinations.

TABLE 4

THERMAL PERFORMANCE AND EXPOSURE OF SA-1

November, December 1967 and January 1968

Reactor Power (MWT) SA-1 Thermal Performance	590 (Average)		700 (Maximum)	
	Average	Peak	Average	Peak
Heat Flux, watts/cm ² (Btu/h-ft ²)	32 (101,000)	56 (178,000)	38 (120,000)	67 (212,000)
Specific Power, kw/kgU	16.6	29.3	19.8	35.0
Power Density, kw/l	29.3	51.9	34.9	61.8
SA-1 Exposures f/cc × 10 ⁻²⁰ (MWd/STU)	November 1, 1967		January 31, 1968	
Assembly Average	7.1 (25,900)		7.5 (27,200)	
Lead Rod Average	8.9 (32,500)		9.3 (34,100)	
Lead Rod Peak	11.7 (42,600)		12.2 (44,500)	

TABLE 5

DRESDEN REACTOR WATER CHEMISTRY

	October			November		
	Min.	Avg.	Max.	Min.	Avg.	Max.
pH	6.3	7.2	8.3	6.2	7.4	8.3
Conductivity, μ mhos	0.43	0.60	0.80	0.30	0.53	0.73
Turbidity, APHA	2.6	3.9	6.0	3.4	6.5	32.0
Chloride, ppm	0.024	0.034	0.046	0.020	0.038	0.092

SECTION V

DESTRUCTIVE EXAMINATIONS OF FUEL RODS5.1 Fuel Rod Characteristics

In general, the 10 rods removed from SA-1 for destructive examination at the end of reactor Cycle 4 had comparatively high

combinations of exposure and initial fuel density and, thus, should tend to demonstrate relatively high degrees of fission-product-induced UO₂ swelling. In Table 6 is listed some of the pertinent information on these fuel rods.

FIGURE 9. SA-1 ROD PATTERN DURING DRESDEN CYCLES 3 AND 4

FIGURE 10. ARRANGEMENT OF FUEL RODS IN SA-1 FOR CYCLE 5 OPERATION

TABLE 6

SA-1 RODS SHIPPED TO VNC FOR EXAMINATION

SA-1 Rod	As-Fabricated Enrichment (%U-235)	Estimated Terminal Exposure ^(a)		As-Fabricated Fuel Density (%T.D.)		Remarks
		Average Fissions/cc × 10 ⁻²⁰ (MWd/STU)	Peak Fissions/cc × 10 ⁻²⁰ (MWd/STU)	Smeared ^(b)	Pellet Average (Range)	
Sub-Assembly A-1 (Bottom)						
A 4	2.76	5.8 (21,000)	7.4 (27,000)	91.6	95.1 (94.1-96.0)	{ Diameter of each pellet in this rod was recorded
A13	3.5	7.9 (29,000)	10.4 (38,000)	91.5	94.4 (92.7-95.2)	
A28	2.76	6.8 (25,000)	8.8 (32,000)	92.9	96.0 (95.5-96.6)	
A41	3.5	8.5 (31,000)	11.2 (41,000)	91.2	94.8 (94.3-95.3)	
A45	2.76	6.6 (24,000)	8.5 (31,000)	92.9	96.0 (95.5-96.6)	
A46	2.76	6.8 (25,000)	8.8 (32,000)	92.7	96.0 (95.5-96.6)	
Sub-Assembly B-1 (Top)						
B70	2.76	6.6 (24,000)	8.5 (31,000)	91.6	95.1 (94.1-96.0)	{ Diameter of each pellet in this rod was recorded
B76	3.5	7.9 (29,000)	10.4 (38,000)	91.2	94.4 (92.7-95.2)	
B88	3.5	7.9 (29,000)	10.4 (38,000)	91.2	95.0 (94.5-95.5)	
B97	2.76	7.7 (28,000)	9.9 (36,000)	91.6	95.3 (94.4-96.2)	

a. The listed values are subject to adjustment, pending the results of chemical burnup analyses and gamma scans to be performed on some of the rods as part of the examination.

b. Smeared density (percent of theoretical) is defined as
$$\frac{\text{Weight UO}_2 \text{ in rod (gm)} \times 100}{\frac{\pi}{4} \times (\text{cladding i.d. in cm})^2 \times (\text{fuel column length in cm}) \times 10.97}$$

5.2 Examinations

5.2.1 Visual

5.2.1.1 Procedure

The 10 rods were transferred from temporary storage in the Remote Handling Operations (RHO) pool to the hot cells. The external surfaces of each rod were thoroughly examined with a Kollmorgen periscope at magnifications between approximately 2× and 3.5×. All fuel rods were examined in the "as-received" condition, i.e., prior to any cleaning or wiping of the surfaces. The surfaces of six of the rods, (A4, A13, A28, A41, B70, and B76), were later treated chemically as described below, to remove any crud deposits. These rods were then examined again.

The position of any point of interest on the surface of a rod was defined in terms of distance from the short end plug shoulder (Figure 11) and angular degrees from the identifying number stamped on the long end plug (Figure 12). [Note: During their previous exposure in the VBWR, all of the SA-1 rods operated with the short end plugs pointed downward. In Dresden, the "B" rods (B70, B76, B88, and B97) operated in the top SA-1 subassembly with their short end plugs pointed downward while the "A" rods, (A4, A13, A28, A41, A45, and A46), operated in the bottom subassembly with their short end plugs pointed upward. Thus, in all cases, the short plugs were located near the middle of the full SA-1 assembly, while the long end plugs (and plenums) were located at either the top or bottom.]

5.2.1.2 Results

Visual examination of the external rod surfaces did not reveal any significant anomalies.

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. An example of this type of surface is shown in Figure 13. This roughness generally tended to decrease with increasing distance from the short end plug. The crud film seemed to be quite adherent over most of the rod surface. This was particularly true of the bluish-gray portion of the film.

Some of the subassembly spacer locations along the rod showed a relative increase in crud deposition, as shown in Figure 14.

Portions of most of the rods were found to be coated with a white deposit when they were removed from the shipping container (Figure 15). It was possible to remove this material quite easily and completely with either a dry or water-moistened cloth. This material has not been chemically analyzed, but it is presumed to be aluminum oxide that resulted from corrosion of the shipping container.

A yellowish film, which covered about 3 cm² (~0.5 in.²), was noted near the small end plug weld on rod B76. A sample of the film was taken for possible later analysis.

After the crud had been completely removed by chemical dissolution, the surfaces of the pre-filmed rods were a solid black except for a few areas of fine white or silvery speckling. Most of this speckling appeared to be associated with an abrasion of the rod surface. A surface roughness, which had the appearance of small, closely

FIGURE 11. SHORT END PLUG OF SA-1 FUEL ROD

FIGURE 12. LONG END PLUG OF SA-1 FUEL ROD

GEAP-5598

2X MAG.

~3X MAG.

FIGURE 13. TYPICAL SPECKLED SURFACE FILM (FUEL ROD A46)

FIGURE 14. SUBASSEMBLY SPACER LOCATION ON FUEL ROD B88, SHOWING INCREASED CRUD DEPOSITION

FIGURE 15. WHITE DEPOSIT ON FUEL ROD A28 AT 94-cm (37 in.) LOCATION

spaced blisters, was observed on the heat transfer surfaces of all six rods cleaned. On a given rod this roughness varied both with orientation, as indicated in Figure 16, and with axial location. The roughness generally tended to decrease toward the long end plug. There were, however, exceptions to this general pattern. In the case of rod A28, the roughest portion of the surface was that in the vicinity of the short end plug. The surface was quite smooth over approximately the middle one-third of the rod, but it then showed an increasing roughness from about the 75-cm (30-inch) location to the plenum area. Rod B76 followed a pattern similar to that of Rod A28 over about 120 degrees of its circumference, but over the rest of the surface it followed a more nearly typical pattern, i.e., one of decreasing roughness with increasing distance from the short end plug.

The extent and degree of surface roughness varied somewhat from rod to rod. Rod A41, which is estimated to have the highest burnup of the group now being examined, probably had, over-all, the smoothest surface among the six rods from which the crud was chemically removed.

Rings of "blisters" were noted on Rod A13 at 45 cm (17-5/8 inches) from the short end plug shoulder, on Rod B76 at about 46 cm (18 inches), and on Rod A41 at 56 cm (22 inches). The rings on Rod A13 are shown in Figure 17. Also observed near the middle of Rod A41 was a 2.5-cm (1-inch) longitudinally oriented string of minute protrusions which appeared to have formed along a scratch (Figure 18).

Marks where the SA-1 subassembly spacer springs had contacted the cladding surface were apparent on most of the rods from which the crud had been removed. Two of the relatively more noticeable markings, one in direct view and the other in profile, are shown in Figure 19. Penetration of the cladding did not appear to be particularly deep. The

photograph indicates that some buildup of material had taken place.

Although most of the rods had wear marks caused by contact with the wire-type spacers during VBWR operation, this previous wear did not appear to have any deleterious effect on their operation in Dresden. The rod shown in Figure 20 in the "as-received" condition represents a case of comparatively deep VBWR spacer wire wear. A pronounced localized increase in surface roughness near the VBWR spacer location was noted on one rod from which the crud had been chemically removed (Figure 21).

5.2.2 Dimensional

5.2.2.1 Length

Procedure

The distance between the two end plug shoulders, i.e., the over-all rod length, was measured on all 10 rods to ± 0.04 cm ($\pm 1/64$ inch) with a steel rule. Inasmuch as the principal value of these measurements is obtained through comparison with pre-irradiation lengths, and since the latter were recorded to ± 0.08 cm ($\pm 1/32$ inch), the accuracy of the method employed in the post-irradiation measurements was adequate.

Results

A comparison of pre- and post-irradiation length measurements is presented in Table 7. The data indicate that irradiation effected a permanent increase in length that ranged from 0.08 cm (1/32 inch) to 0.23 cm (3/32 inch). The average increase was 0.15 cm (1/16 inch).

5.2.2.2 Diameter

Procedure

A profilometer was used to measure diametral variations along the length of the

90°

270°

FIGURE 16. FUEL ROD B76 AT 25-cm (10 in.) LOCATION AFTER CHEMICALLY REMOVING CRUD

0°

180°

FIGURE 17. RINGS OF "BLISTERS" AT 45-cm (17-5/8-in) LOCATION OF FUEL ROD A13

FIGURE 18. PROTRUSIONS ON FUEL ROD A41

FIGURE 19. SUBASSEMBLY SPACER MARKINGS AT 36-cm (14-in.) LOCATION OF FUEL ROD B70

FIGURE 20. VBWR SPACER WIRE WEAR ON FUEL ROD B97

FIGURE 21. VBWR SPACER REGION ON FUEL ROD B70 AFTER CRUD REMOVAL

TABLE 7

LENGTH OF SA-1 RODS

<u>Rod</u>	<u>Post-Irradiation Length cm (inches)</u>	<u>Pre-Irradiation Length cm (inches)</u>	<u>Change cm (inch)</u>
A4	103.46 (40-47/64)	103.35 (40-11/16) ↓	+0.11 (3/64)
A13	103.46 (40-47/64)		+0.11 (3/64)
A28	103.43 (40-23/32)		+0.08 (1/32)
A41	103.50 (40-3/4)		+0.15 (1/16)
A45	103.50 (40-3/4)		+0.15 (1/16)
A46	103.50 (40-3/4)		+0.15 (1/16)
B70	103.50 (40-3/4)		+0.15 (1/16)
B76	103.55 (40-49/64)		+0.20 (5/64)
B88	103.58 (40-25/32)		+0.23 (3/32)
B97	103.50 (40-3/4)		+0.15 (1/16)

fuel rods. The fuel rod was scanned by a pair of probes bearing on diametrically opposed sides of the rod. Probe travel perpendicular to the axis of the fuel rod was converted to an electrical signal by transducers. The output voltage was directly proportional to the displacement of the probes; the signal was continuously recorded by an x-y recorder. The instrument recorded the algebraic sum of the movement of the probes. The scans, therefore, showed the deviation from a standard diameter.

Three scans were made along the entire length of each rod in the "as-received" condition. One scan was made with the rod oriented to measure the diameter in the 0 - 180 degree plane; a second was made to measure the diameter in the 90 - 270 degree plane; and a third scan was made while the rod was rotating. In the rotational scan the rod made approximately 3 revolutions for every 2.5 cm (1 inch) of probe travel along the rod length.

The procedure above was repeated on Rods A4, A13, A28, A41, B70, and B76 after the crud had been chemically removed from these rods.

Results

The curves shown in Figures 22 through 31 indicate the variations along the rod axis in average diameter and in maximum and minimum diameters (i.e., apparent ovality). Each curve was plotted by estimating from the rotational profilometer trace a mean value for each 2.5 cm (1 inch) of rod length. Prior to any irradiation, the diameter of each rod was measured to the nearest ~0.001 cm (0.0005 inch) with a micrometer at the top, middle, and bottom. These values have been plotted for comparison, although the exact locations of these measurements are not known.

The average-diameter profiles of the rods in the as-received condition showed an increase in diameter over the pre-irradiation measurements that ranged from about 0.0025 to 0.008 cm (0.001 to 0.003 inch) and had a mean value of approximately 0.0045 cm (0.0018 inch). Removal of the crud from some of the rods resulted in a decrease in diameter that ranged from 0 to about 0.0025 cm (0.001 inch) over various portions of the different rods and averaged approximately 0.0018 cm (0.0007 inch).

FIGURE 22. DIAMETER PROFILES OF FUEL ROD A4

FIGURE 23. DIAMETER PROFILES OF FUEL ROD A13

FIGURE 24. DIAMETER PROFILES OF FUEL ROD A28

FIGURE 25. DIAMETER PROFILES OF FUEL ROD A41

FIGURE 26. DIAMETER PROFILES OF FUEL ROD A45

FIGURE 27. DIAMETER PROFILES OF FUEL ROD A46

FIGURE 28. DIAMETER PROFILES OF FUEL ROD B70

FIGURE 29. DIAMETER PROFILES OF FUEL ROD B76

FIGURE 30. DIAMETER PROFILES OF FUEL ROD B88

FIGURE 31. DIAMETER PROFILES OF FUEL ROD B97

These profiles imply, then, that the circumferential-average crud thickness had a mean value of about 0.0009 cm (0.00035 inch) and, with the exception of some local peaks, a maximum value of about 0.0012 cm (0.0005 inch). Most of the rods that were profiled before and after crud removal tended to show a decrease in crud thickness with increasing distance from the short end plug, i.e., toward the top or bottom of the assembly. However, this pattern was reversed in the case of Rod A4, and the crud on rod B70 was quite even over the length. It must be pointed out that, while these thickness determinations are believed to be generally valid, some crud was removed from some areas of the rods during handling and shipping.

After the crud was chemically removed, the rods still showed a diameter increase, with respect to the pre-irradiation measurements, that ranged from 0 to about 0.006 cm (0.0025 inch) over various portions of the different rods. The mean value of this increase was approximately 0.0025 cm (0.001 inch). With both Rods B70 and B76 the largest increase occurred at locations closer to the long end plug than to the short one (i.e., at the top of the assembly). Rods A4 and A28 had their greatest increases near the short end plug, or midassembly, but this pattern was reversed in the case of Rod A41, and with Rod A13 the increase in diameter was quite uniform over its length.

The rods exhibited an average ovality of 0.004 to 0.005 cm (0.0015 to 0.002 inch), and in some locations the ovality was as great as 0.010 cm (0.004 inch). Ovality here is taken to mean simply the difference between the maximum outside diameter and minimum outside diameter at a given axial location regardless of the cause of this difference. The "A" rods tended to show the greatest ovality either toward the short end plug or near the midlength. Two of the "B" rods

showed the greatest ovality near the short end plug, and with the other two, the greatest ovality was located near the long end plug. Chemical removal of the crud generally did not decrease the amount of or markedly change the pattern of ovality. In some instances the ovality was increased slightly by removing the crud.

In addition to the general increase in diameter that occurred during operation, local peaks in rod diameter often were present near spacer locations. Some of these peaks show up in Figures 22 through 31 at approximately the following locations: 2.5 to 5 cm (1 to 2 inches), 36 cm (14 inches), 51 cm (20 inches), and 69 cm (27 inches). However, they are more clearly defined on the original profilometer traces, particularly on those made while the rod was held in a fixed position.

All of the rods exhibited local diameter peaking at the VBWR-spacer location (51 cm) and at the 4-cm (1.5-inch) subassembly spacer location; all but one of the rods showed localized increases in at least one additional subassembly spacer location. The VBWR-spacer peaks averaged about 0.005 cm (0.002 inch) above the typical rod diameter in the vicinity, and they were as large as 0.009 cm (0.0035 inch). The peaks at the SA-1 subassembly spacer locations ranged from about 0.0025 to 0.011 cm (0.001 to 0.0045 inch) and averaged approximately 0.004 cm (0.0015 inch).

Chemical removal of the crud from the rods decreased the rod diameter at these peaks in only about one-half of the cases. Thus, the peaks frequently were somewhat more pronounced after crud removal than before.

The diameter profiles of Rod A41 showed peaks at pellet-length intervals between the 8-cm (3-inch) and 36-cm (14-inch)

locations and between the 56-cm (22-inch) and 61-cm (24 inch) locations. The difference in diameter between these peaks and the corresponding troughs was typically 0.0013 cm (0.0005 inch) to 0.0019 cm (0.00075 inch) and had a maximum value of about 0.0025 cm (0.001 inch). The profiles of most of the other rods showed some degree of this type of peaking. However, the locations where such peaks could be identified were generally less frequent and more scattered than in the case of Rod A41. The roughness of the surface of some of the rods may have decreased the definition of some peaks.

5.3 Removal and Sampling of Crud

5.3.1 Chemical Method

5.3.1.1 Procedure

The removal of crud, i.e., those corrosion products that had been deposited from the coolant onto the fuel rod surfaces, was made in the following manner. The fuel rod was placed in a 1000-ml buret that contained a known quantity of concentrated hydrochloric acid. The quantity of acid used was such that approximately one-half of the rod was immersed when it was placed in the buret. The remainder of the rod extended through a hole in a stopper which was inserted in the top of the buret. By means of heating tape wrapped around the buret, the acid was heated to approximately 70°C and held at this temperature for 4 hours. The resulting solution was allowed to cool and then was drawn off into a plastic bottle. The rod was

removed from the buret and rinsed with sodium carbonate solution and clear water. The portion of the rod from which the crud had been removed was measured for length.

The above procedure was then repeated on the other half of the rod.

5.3.1.2 Results

The crud components appeared to have been completely removed from the surfaces of Rods A4, A13, A28, A41, B70, and B76. The zirconium oxide on these pre-filmed rods remained intact. Chemical analysis of the solutions is in progress.

5.3.2 Mechanical Method

5.3.2.1 Procedure

Solid samples of crud were obtained primarily to determine, by x-ray diffraction analysis, the compounds or phases present. The crud was scraped from the rod surface with a scraper made from stainless steel sheet. In taking a sample, the full circumference of the rod was scraped over a length of 2.5 to 5 cm (1 to 2 inches). The material removed was collected and placed in a plastic vial. The samples taken are indicated in Table 8.

5.3.2.2 Results

No analyses have yet been made on the above samples.

TABLE 8

SOLID CRUD SAMPLE LOCATIONS

<u>Rod</u>	<u>Distance of Sample Center from Short End Plug - cm (inches)</u>	<u>Remarks</u>
A45	43 (17)	
A45	94 (37)	
A46	2 (1)	SA-1 spacer location
A46	18 (7)	
A46	58 (23)	
B88	10 (4)	
B88	58 (23)	
B88	69 (27)	SA-1 spacer location
B97	43 (17)	
B97	94 (37)	

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