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**ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM
FINAL REPORT
NOVEMBER 1967 - JUNE 1971**

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U.S. ATOMIC ENERGY COMMISSION
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PROJECT AGREEMENT 41

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ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM

Final Report

November 1967—June 1971

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ABSTRACT

The Zircaloy-clad UO_2 pellet fuel rods in Assembly SA-1 received their initial irradiation in the VBWR, and were subsequently exposed in Dresden-1 to an estimated average burnup of 8.2×10^{20} fissions/cm³ (29,800 MWd/tU). The peak and maximum rod-average burnups were 10.4×10^{20} fissions/cm³ (37,900 MWd/tU) and 9.3×10^{20} fissions/cm³ (33,900 MWd/tU), respectively. The total operating time in both reactors was 1827 days. Local peak powers of 14 kW/ft were attained by some rods early in operation. No full-wall cladding penetrations were detected.

The average external corrosion weight gain shown by the fuel rod cladding at the end of operation was 480 mg/dm², and the maximum hydrogen content measured was 146 ppm. Burst samples exposed to about 7×10^{21} nvt > 1 MeV showed hoop stresses at rupture of 5100 kg/cm² (72 kpsi) at 343°C (650°F) and 4400 kg/cm² (62 kpsi) at 454°C (850°F). Strains to fracture of 2 to 8 percent were obtained with no clear temperature dependence indicated. Maximum fission gas release was less than 1 percent. The irradiated UO_2 was examined by light and electron microscopy and by x-ray diffraction. Full cross-section and radially variant fuel samples were measured for burnup, uranium and plutonium isotopic composition, neptunium, americium, curium, and certain fission products. Relatively high levels of U-232, Pu-236, and Pu-238 were measured on some samples.

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/tU).

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/tU*) 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 Unit No. 1 of the Commonwealth Edison Company's Dresden Nuclear Power Station for additional irradiation. The assembly consisted of two 7 X 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 on the average, a total of 1827 days. The two 44-rod subassemblies were shipped to VNC in March 1970 for the final phase of the program.

The present report briefly reviews the design and fabrication characteristics of the SA-1 fuel, describes the conditions of operation, and gives a detailed account of the examination results.

Prior reports to the Atomic Energy Commission under the Zircaloy-Clad UO_2 Fuel Rod Evaluation Program are listed in Appendix A.

2. SUMMARY

The 88 rods that operated in Assembly SA-1 to the end of Dresden Reactor Cycle No. 6 attained an estimated average terminal burnup of 8.2×10^{20} fissions/cm³ (29,800 MWd/tU). The maximum rod-average burnup measured was 9.3×10^{20} fissions/cm³ (33,900 MWd/tU) and the axial peak burnup measured was 10.4×10^{20} fissions/cm³ (37,900 MWd/tU). These rods operated in Dresden 1468 days. The total days of operation, including those in the VBWR, then ranged from 1767 to 1846.

* Megawatt days per short ton of uranium

All of the rods that were selected for incorporation in Assembly SA-1 were determined to be sound at the conclusion of their operation in the VBWR. The interim leak tests and examinations conducted during Dresden operation, as well as all tests and examinations performed at the conclusion of SA-1's operation, failed to detect any full-wall cladding penetration in any rod.

The assembly operated at an estimated peak heat flux of 117 W/cm^2 ($372,000 \text{ Btu/h-ft}^2$) early in Dresden operation and underwent a fairly continuous decrease in power level with increasing exposure. The estimated peak heat flux attained during the fourth and final cycle of operation was about one-half of that attained during the first cycle. Most of the rods operated in the VBWR, for relatively brief periods, at power levels above those attained in Dresden. The maximum peak heat flux attained in the VBWR by any of the rods is estimated to have been 137 W/cm^2 ($435,000 \text{ Btu/h-ft}^2$ or 14 kW/ft^2). The estimated peak centerline temperature associated with this heat flux is $\sim 2050^\circ \text{C}$ (3700°F).

The two subassemblies appeared to be in generally good condition at the end of operation. The corrosion product, or crud, film that was deposited on the rods during Dresden 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. There were no distinct differences in appearance between rods that operated two cycles in Dresden and those that operated four cycles.

Essentially all of the crud observed on the SA-1 rods was deposited during Dresden operation, inasmuch as most of the crud deposited during VBWR operation was wiped from the rods before they were selected for further irradiation. The crud film was quite adherent over most of the rod surface. This was particularly true of the bluish-gray portion of the film. Chemical analysis indicated that nickel, iron, copper, and chromium were the principal metallic elements present, with the nickel concentration amounting to between 65 and 75 percent of the total. The mean and maximum rod-average crud thicknesses measured on selected rods that had operated 840 days in Dresden were about 0.0009 cm (0.00035 in.) and 0.0012 cm (0.0005 in.), respectively. The corresponding values determined on a group of rods that had operated 1468 days were about 0.0012 cm (0.0005 in.) and 0.0017 cm (0.0007 in.). The maximum circumferential-average crud thickness measured at any axial location of any rod was 0.0028 cm (0.0011 in.). One corner rod exhibited a rather extensive spalling of the crud layer but, generally, only minor amounts of spalling were observed.

The rough, blistered appearance of portions of the rod surfaces was found to be primarily a consequence of the type of cladding corrosion that typically occurred, i.e., the formation of a relatively thin and even ZrO_2 film in combination with a pitting attack that resulted in intermittent thicker patches of ZrO_2 . Among rods that operated to the end of Cycle No. 6, the average thickness of the even film-type ZrO_2 was 14μ (0.0006 in.) and that of the patch-type was 68μ (0.0027 in.). The circumferential-average corrosion weight gain determined from thickness measurements on metallography specimens had a mean value of 480 mg/dm^2 for these rods. Rods that were removed from SA-1 at the end of Cycle No. 4 after an average total exposure time of approximately 1200 days showed a mean weight gain of 320 mg/dm^2 , while comparable rods that saw only VBWR operation (~ 365 days) showed a mean weight gain of 125 mg/dm^2 . Thus the post-transition corrosion rate of the SA-1 cladding was approximately $0.24 \text{ mg/dm}^2/\text{day}$. It must be pointed out, however, that due to uncertain causes, the weight gains determined on some of the individual SA-1 rods deviated considerably from the mean value. A specimen from one rod that saw 1803 days of exposure showed a circumferential-average weight gain of about 1100 mg/dm^2 . In addition, abnormally thick, fairly even layers of ZrO_2 were observed over 45 to 90 degrees of about 15 percent of the specimens examined. On one specimen the corrosion layer reached an average thickness of 119μ (0.0047 in.) over one octant of its circumference.

Some increase in corrosion occurred near some of the subassembly spacer spring contact locations and also in the vicinity of some of the wire-type spacers employed during VBWR irradiation.

Oxidation of the inside cladding surface also apparently increased throughout the period of operation. Most of the specimens from rods that operated to the end of Cycle No. 6 showed internal ZrO_2 films 8 to 9μ thick.

In general, very few platelets of zirconium hydride were observed in the metallographic examination of the cladding, but those that were present were uniformly distributed. The hydrogen contents, determined on samples from selected rods by hot vacuum extraction followed by gas chromatography, ranged from 45 to 146 ppm . The average contents of samples from rods that operated in Dresden two cycles and four cycles were 66 ppm and 92 ppm , respectively. The average pre-irradiation content was about 28 ppm . Hydrogen constituted 72 to 96 percent by volume of the gas evolved from the different samples. The gas also contained significant amounts of carbon monoxide and lesser amounts of carbon dioxide, nitrogen, oxygen, and methane. The carbon monoxide content ran as high as ~ 20 percent in some samples from rods that operated to the end of Cycle No. 6.

Tritium analyses were performed on samples of cladding from some of the rods removed from the assembly at the end of Cycle No. 4. The tritium contents ranged from approximately 5 to 58 ppb, equivalent to about 2 to 16 percent of the tritium generated during operation.

Changes in outside diameter were determined on some of the fuel rods by comparing the results of post-irradiation profilometer scans, made after the crud had been chemically removed from the rod surfaces, with pre-irradiation micrometer measurements. The rods showed diameter increases which, averaged over the rod lengths, ranged from 0.001 cm (0.0005 in.) to 0.004 cm (0.0015 in.) and had a mean value of 0.003 cm (0.001 in.). The results were nearly the same for rods removed at the end of Cycle No. 4 and those that operated to the end of Cycle No. 6. Some of the diameter increase was due to formation of ZrO_2 on the rod surfaces. It is estimated that with the effect of corrosion taken into account the maximum "true" rod-average increase was between 0.001 cm (0.0005 in.) and 0.003 cm (0.001 in.).

Length measurements made on the rods removed from SA-1 for the initial phase of the examination program indicated increases over the pre-irradiation lengths which ranged from 0.08 to 0.24 cm (1/32 to 3/32 in.) and averaged 0.16 cm (1/16 in.), or 0.16 percent. Similar measurements made during the final phase of the program showed increases that ranged from 0.15 to 0.33 cm (0.06 to 0.13 in.) and averaged 0.23 cm (0.09 in.), or 0.23 percent. However, uncertainties in the pre-irradiation lengths reduce the accuracy of the data, and there is some question as to whether the plenum support tubes inside the rods may have been a factor in the length increases.

Samples of irradiated fuel rod cladding that were burst tested at room temperature and at 343°C (650°F), 399°C (750°F), and 454°C (850°F) showed respective hoop stresses at rupture of approximately 8000 kg/cm² (114 kpsi), 5100 kg/cm² (72 kpsi), 4900 kg/cm² (69 kpsi), and 4400 kg/cm² (62 kpsi). Irradiation to estimated fast fluences of 6×10^{21} to 7×10^{21} nvt ($E > 1$ MeV) increased the stress values 1400 to 1800 kg/cm² (19 to 25 kpsi) above those of comparable unirradiated samples. The strain to fracture values ranged from 2 to 8 percent among the irradiated samples, and did not show any clear temperature dependence between 343°C and 454°C. Longitudinally oriented cladding coupon specimens exposed to between $\sim 3.5 \times 10^{21}$ and 5×10^{21} nvt showed ultimate tensile strengths generally somewhat lower than the ultimate hoop stresses of the above burst samples and total elongations also somewhat lower, in general, than the strain-to-fracture values of the burst samples. The difference in strengths increased and the difference in elongations decreased with increasing test temperature. The total elongations shown by the longitudinal specimens in 343°C tests were only approximately 1 percent.

Cladding "ring-on-mandrel" tests showed strains to fracture of 13 to 27 percent in room temperature tests and of 34 to 45 percent in tests at 454°C (850°F) on specimens exposed to an estimated fast fluence of approximately 5×10^{21} nvt > 1 MeV. Specimens tested at 343°C (650°F) were strained as much as 69 percent without fracturing. In this type of test a narrow transverse section, i.e., the ring of cladding is centered on a metal cylinder somewhat taller than the ring width and is increased in diameter by compressing the ends of the cylinder. The high strains achieved are attributed to the suppression of localized necking through the development of shear forces which support the entire gage length of the specimen. The results are in marked contrast to those obtained in the coupon tensile and burst tests in which necking instabilities are not suppressed.

The free gas contained in selected fuel rods from both the initial and final phase groups 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 about 0.1 to 0.9 percent. There was little difference between the two rod groups with respect to release percentage. The compositions of the gas samples, determined by chromatographic analysis and mass spectrometry, in general, appeared normal.

The irradiated UO_2 fuel was examined by light microscopy and by replication and transmission electron microscopy. Evidence of some equiaxed central grain growth was observed in some of the specimens. The maximum ratio of central-to-peripheral grain size was approximately 3 to 1.

All specimens showed platelet-shaped precipitates of uncertain identity within the grains of the etched fuel near the outside surfaces of the pellets. Intragranular precipitates were observed also at interior locations of most specimens. In some of these cases the precipitates were most pronounced near the pellet center, while in others the maximum concentration occurred at mid-radial locations. Inclusions that appeared to have the same size and shape as those observed by light and replication electron microscopy at the peripheral locations were observed in the same general location by transmission electron microscopy. Some second phase particles that did not have the same appearance as the intragranular precipitates were seen on grain boundary surfaces in examinations by replication electron microscopy.

Lattice parameter measurements made on UO_2 samples from one of the most highly exposed fuel rods showed values that ranged from 5.475 Å at the pellet center to 5.477 Å at the periphery compared with a value of 5.470 Å for an unirradiated control specimen. The average increase in lattice parameter, which is attributed to radiation damage, was 0.10 percent. No phases other than UO_2 could be detected by x-ray diffraction analysis.

Burnup and isotopic composition were determined on selected fuel samples in both the initial and final phases of the program by measuring Nd-148 and the uranium and plutonium isotopes by mass spectrometry and applying the computer code BURNUP. Np-237, U-232, Pu-236, Pu-238, americium, curium, and some of the fission products also were measured on some of the above samples. The concentrations of U-232 relative to U-235 in four high exposure samples ranged from 400 to 500 ppb. The atom ratios of Pu-236 and Pu-238 relative to U-238 averaged 9×10^{-10} and 2×10^{-4} , respectively.

Cs-137 was determined to be an adequate burnup monitor for use in gamma scanning. By providing data on relative rod-average burnups and traces of axial burnup profiles, the Cs-137 gamma scanning technique combined with the Nd-148 data allowed rapid, nondestructive determinations of absolute average and peak burnups on a significant fraction of the SA-1 rods. The possibility of using gamma scan data to measure the plutonium fission rate relative to that of uranium also was demonstrated.

The fast fluences were measured by two methods, one based on the analysis of fuel samples and the other on the analysis of cladding samples. Good agreement was obtained between the two sets of data.

In conclusion, the SA-1 fuel rods and other parts of the assembly operated satisfactorily to relatively high burnups and long exposures. As far as could be determined, no full-wall cladding penetrations occurred, and none of the few areas that were suspected of being defective during the early stages of examination could be confirmed as defective upon further examination. Furthermore, none of the observations or results of the examinations, tests, and analyses revealed any conditions indicative of imminent fuel rod failure.

However, the operating mode of the SA-1 fuel rods was not unfavorable to the attainment of relatively high exposure levels without cladding failure. The fuel rod heat ratings almost steadily decreased toward end-of-life from the initial peak value in Dresden reached immediately after installation. Had the end-of-life power levels been close to those attained earlier, the UO_2 temperatures would have been much higher and, conceivably, conducive to enhanced fission product induced fuel swelling. This swelling in turn could lead to larger fuel-cladding interaction strains, i.e., strains approaching or exceeding the irradiation-impaired strain capability of the cladding. The ductility of the cladding, as measured by longitudinal tensile and burst test results was, of course, significantly reduced during operation. At the conclusion of VBWR operation the room temperature and 343°C (650°F) total elongation values of longitudinal coupon specimens had been decreased to 2 to 5 percent and 1 to 2 percent, respectively, after estimated fast fluence exposures of 1×10^{21} nvt > 1 MeV. However, the room temperature strain-to-fracture values shown by burst specimens were still as high as 13 to 16 percent at the same exposure level. Additional exposure to 3.5×10^{21} to 5×10^{21} nvt changed the total elongations of the longitudinal specimens relatively little, but additional exposure to 6×10^{21} to 7×10^{21} nvt decreased the room temperature burst test results to approximately one-half the post-VBWR values, and the strains to fracture determined at elevated temperatures were somewhat lower than the room temperature values.

It also should be noted that although the assembly power level underwent a rather continuous, significant decrease, the average external ZrO_2 thickness increased at a constant rate. Hence, one would expect that had higher power levels been maintained, with the associated higher cladding temperatures, corrosion might have been a factor of much greater concern, particularly in such local areas as those that showed unusually thick oxide layers.

The relatively high levels of Pu-236 and Pu-238 must be considered in working with plutonium separated from high exposure fuel. It is noted also that the concentrations of U-232 measured in the fuel samples exceeded the current specification limit of 110 ppb U-232 relative to U-235 for reenrichment in all cases. However, the fact that the SA-1 fuel exceeded its design nuclear lifetime and thus contained somewhat less residual U-235 than one would normally expect for fuel operated to the same burnup levels was partly responsible for the high ratios.

3. DESCRIPTION OF FUEL ^{1,2}

The fuel rods in Assembly 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. The rods consisted of cold-pressed, sintered, and ground UO_2 pellets clad with annealed Zircaloy-2 tubing. The nominal o.d. and wall thickness of the tubing, which was designed to be "free-standing," were 1.077 cm (0.424 in.) and 0.056 cm (0.022 in.), respectively. The nominal pellet-to-cladding gap was 0.010 cm (0.004 in.). The overall rod length was 103.4 cm (40.7 in.).

The seamless tubing was fabricated by the cold drawing process. The inside and outside surfaces of the tubes were pre-filmed with oxide by autoclaving them in 105 kg/cm^2 (1500 psi), 399°C (750°F) steam for 36 hours.

The cylindrical pellets were made from ceramic grade UO_2 powder produced from UF_6 by the ammonium diuranate method.

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, cm (in.)	0.056 ± 0.0056 (0.022 ± 0.0022)
Cladding i.d., cm (in.)	0.965 ± 0.0041 (0.380 ± 0.0016)
Cladding o.d., nominal, cm (in.)	1.077 (0.424)
Total Rod Length, nominal, cm (in.)	103.408 (40.712)
Pellet Diameter, cm (in.)	$0.955^{+0.000}_{-0.008}$ ($0.376^{+0.000}_{-0.003}$)
Pellet Density, percent of theoretical	95 ± 1
Active Fuel Length, nominal, cm (in.)	94 (37)
Plenum Length, nominal, cm (in.) *	4.831 (1.902)
Wall thickness of Plenum Support Tube, nominal, cm (in.)	0.076 (0.030)
Initial Uranium Enrichment, weight percent U-235	2.76, 3.20, and 3.49

* The length of the plenum support tube in most rods is believed to have been 4.420 cm (1.740 in.). However, post-irradiation examination revealed two such tubes (out of 18 from SA-1 rods that were actually measured) that were 4.826 cm (1.900 in.) long.

An exploded view of a typical fuel rod is shown in Figure 1. The Zircaloy-2 wafer and stainless steel plenum support tube held the pellets in place and maintained a plenum space for the fission gases. The end plugs were welded to the cladding to provide closure at each end of the tube.*

The assembly consisted of two 7 X 7, 105-cm (41-1/4-in.) long, subassemblies stacked one on top of the other in a channel of standard dimensions for the Dresden reactor. A sketch of the assembly viewed with a side of the channel removed is shown in Figure 2. One of the subassemblies is shown before irradiation with a load of dummy fuel rods in Figure 3. A removable lifting tool, partially in view, is attached to the top. The rods in each subassembly rested on a bottom grid, as shown in Figure 4, and were held in position by four spring-type spacers distributed axially along the length of the fuel. The fuel rod pitch was 1.511 cm (0.595 in.).

The spacers were supported by corner angles which were attached to the bottom grid and extended the full length of the subassembly, to form an integral basket for the fuel rods. The corner angles were fastened at the top to a band which extended about 0.6 cm (1/4 in.) above the top of the fuel rods (see Figure 5).

The lower subassembly was supported by a stand attached to a standard Dresden assembly nosepiece with a partially cut out grid (see Figure 6). The second subassembly rested on the first. The fission gas plenums of the rods in the bottom subassembly were pointed toward the bottom grid, and those of the rods in the top subassembly were pointed toward the top band.

The SA-1 fuel column was approximately 192 cm (75-9/16 in.) long, which included an approximate 3 cm (~1-1/4 in.) nonfueled gap between the subassemblies. The bottom of the total fuel 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 ($11-5/16 \pm 1-3/4$ in.) below the top of the reactor active fuel zone. The subassemblies were held down by a spring-loaded fixture attached to a clamp (Figure 7) which fitted into slots in the sides of the channel near the top. A standard-shape handle was attached to the clamp for lifting the assembly. The relative positions of the handle, clamp, and channel when the assembly was ready to be inserted in the reactor are indicated in Figure 8.

*The shanks of the shorter end plugs were cut off before the rods were inserted into the SA-1 subassemblies.

Figure 1. Exploded View of Fuel Rod

NOTE: DIMENSIONS ARE IN cm (in.)

Figure 2. Assembly SA-1

Figure 4. Bottom of Subassembly

Figure 5. Top of Subassembly

Figure 6. Assembly Nosepiece and Stand

Figure 7. Handle Holddown Assembly

Figure 8. Top of Channeled Assembly

The spacer springs were made of Inconel "X," the leaf springs at the top of the assembly were made of Inconel "X" 750, and the hold-down springs were made of Inconel "X." Except for the fuel rods, the rest of the assembly, including the channel, was Type 304 stainless steel.

4. OPERATION

4.1 VBWR

Most of the information contained in this section was extracted from GEAP-4597, "AEC Fuel Cycle Program—Examination of Zircaloy-Clad UO_2 Fuel Rods Operated in the VBWR to 10,000 MWd/tU," by H. E. Williamson, C. J. Baroch, J. P. Hoffmann, and D. T. Ikeuye.³

4.1.1 Assembly Description

The fuel rods in Assembly SA-1 were selected from 12 of the Fuel Cycle Program's Type J basic assemblies. Each of these assemblies contained sixteen rods arranged in a 4 X 4 array at center-to-center distances of 1.93 cm (0.760 in.). The rods in each bundle were held in position by a cast steel bottom tie plate, a combination wire spacer-top tie plate, and a single-layer wire spacer at mid-length. The longer end plugs and plenums of the rods were located at the top of every assembly.

4.1.2 Reactor Environment and Operation

The fuel assemblies were cooled by recirculating water at 70 kg/cm² (1000 psig) pressure. The water was sub-cooled about 10°C as it entered the bottom of each assembly. The heat transferred to the water as it passed upward through the assembly caused bulk boiling (286°C [546°F] saturation temperature) over most of the 94-cm (37-in.) active fuel length.

The water was normally maintained at a pH of 7 at room temperature, and at a conductance of less than 1 micromho. The oxygen content of the steam phase was about 30 ppm.

Samples of the VBWR water were analyzed daily, or more frequently when a buildup of impurities was indicated. The analysis included the measurement of the amount of crud, resistivity, and chloride ion content. Typically, the chloride ion content of the water was maintained at less than 0.02 ppm; however, on occasion it exceeded this level. Normally, the reactor power was reduced when the chloride ion level exceeded 0.15 ppm, and shut down when greater than 0.35 ppm. The insoluble corrosion products in the coolant generally contained from 1 to 100 ppb (parts per billion) iron, 1 to 10 ppb nickel, 1 to 50 ppb copper, and 1 to 5 ppb chromium.

VBWR operation was divided into a series of runs, most of which were of one to three weeks duration. The rather frequent shutdowns were required to allow the addition of new fuel assemblies, the changing of assembly core positions, and the removal of assemblies for examination, rod changes, etc., in order to satisfy the objectives of several different irradiation programs.

The reactor operated at maximum powers between 30 and 40 MWt in most of the runs. One hundred seventy-nine power cycles and 300 thermal cycles occurred during the irradiation period of those Type J assemblies with the longest operating times. A power cycle was defined as a variation in reactor thermal power from less than 5 MW to more than 20 MW and back to less than 5 MW. A thermal cycle was defined as a reactor thermal power variation from zero to greater than 5 MW and back to zero. The power and thermal cycles that each assembly underwent during each reactor run and the total numbers of such cycles are given in Appendix B.

4.1.3 Assembly Operation

Irradiation of the 12 assemblies began as early as June 1961 and continued until the reactor was shut down in December 1963. Figure 9 is a plot of the VBWR core which indicates the initial locations of the assemblies and also shows the locations of the flux trap-type control rods. Most of the assemblies were moved to other locations during the period of operation; one assembly (9J) operated in nine different locations. The location of each assembly during each reactor run is given in Appendix B.

4.1.3.1 Exposure and Thermal Performance

The rods that were later selected for continued irradiation in Dresden operated between 299 and 378 days* in the VBWR to rod-average burnups of 1.3×10^{20} to 2.6×10^{20} fissions/cm³ (4800 to 9500 MWd/tU). The overall average VBWR burnup of the 98 SA-1 rods was 1.9×10^{20} fissions/cm³ (7100 MWd/tU). The peak heat flux attained in the VBWR by any of the SA-1 rods was estimated to have been 137 W/cm² (435,000 Btu/h-ft²). The calculated centerline temperature at this heat flux is approximately 2050°C (3720°F). (See Figure 10.) The hours of operation and the average burnup and estimated peak heat flux attained in the VBWR are listed for each of the SA-1 rods in Table 2. The estimated peak heat flux values for the different rods for each VBWR run are given in Appendix B. The values of rod burnup and heat flux were based on values determined for the different assemblies by reactor physics analysis. The following approximation was employed:

Position in Assembly	Burnup and Heat Flux
Corner (4 rods)	10% higher than assembly-average
Outside non-corner (8 rods)	Equal to assembly-average
Inside (4 rods)	10% lower than assembly-average

Twenty-five of the SA-1 fuel rods operated in inside positions in the VBWR assemblies; the rest operated in outside non-corner positions. An indication of the variation in burnup along the axes of the rods was provided by scans of gross gamma ray activity made on four Type J fuel rods at the end of the VBWR operation. The ratios of peak activity to rod-average activity ranged from 1.42 to 1.50 and had an average value of 1.47 for these four rods. The points of peak activity were located 31 to 35 cm (12 to 14 in.) up from the bottom end plug shoulders. A scan of one of the rods is shown in Figure 11.

*Hours reactor thermal power > 5 MW ÷ 24.

Figure 9. VBWR Core, Showing Initial Locations of Type J Assemblies

Figure 10. Fuel Centerline Temperature Versus Circumferential-Average Rod Surface Heat Flux

Figure 11. Gamma Scan of Fuel Rod 11J-R1D71 at End of VBWR Irradiation

Table 2
OPERATIONAL DATA ON THE SA-1 FUEL RODS

SA-1 Number	VBWR Assembly Designation ^a	Rod-Average Burnup			Final Peak Burnup	Days of Operation ^b		Estimated Peak Heat Flux ^c		Time-Averaged Rod-Average Heat Flux ^c		
		Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)			Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)	VBWR	Total	W/cm ² (Btu/h-ft ² X 10 ⁻³)		W/cm ² (Btu/h-ft ² X 10 ⁻³)		
		VBWR	Dresden	Total	VBWR			Dresden	VBWR	Dresden	Overall	
A1	5J-6	1.6 (5,800)	7.2 (26,400)	8.8 (32,200)	9.3 (34,100)	378	1,846	85 (271)	90 (284)	32 (102)	38 (121)	37 (117)
A2	1J-2	1.5 (5,400)	6.7 (24,600)	8.2 (30,000)	—	378	1,846	84 (265)	87 (275)	31 (98)	36 (113)	35 (110)
A3	17J-5	1.5 (5,500)	6.5 (23,900)	8.0 (29,400)	—	299	1,767	100 (317)	86 (272)	39 (123)	34 (109)	35 (112)
A4 ^d	17J-8	1.5 (5,500)	4.0 (14,700)	5.5 (20,200)	6.5 (23,800)	299	1,139	100 (317)	88 (278)	39 (123)	37 (117)	38 (119)
A5	4J-15	1.6 (5,700)	6.5 (23,700)	8.0 (29,400)	—	378	1,846	86 (272)	92 (291)	32 (102)	35 (110)	34 (108)
A6	16J-11	1.7 (6,100)	6.7 (24,400)	8.3 (30,500)	—	335	1,803	100 (316)	93 (294)	38 (122)	35 (112)	36 (114)
A7	16J-2	1.9 (6,800)	7.1 (26,100)	9.0 (32,900)	10.0 (36,500)	335	1,803	111 (351)	102 (325)	43 (136)	38 (119)	39 (123)
A8	1J-3	1.5 (5,400)	6.7 (24,600)	8.2 (30,000)	—	378	1,846	84 (265)	87 (275)	30 (96)	35 (112)	34 (108)
A9	12J-2	2.5 (9,300)	6.3 (22,900)	8.8 (32,200)	9.6 (35,100)	364	1,832	137 (435)	102 (322)	54 (171)	33 (105)	37 (118)
A10	8J-9	1.5 (5,300)	6.5 (23,900)	8.0 (29,200)	—	306	1,774	96 (304)	94 (297)	37 (117)	35 (110)	35 (111)
A11	13J-12	2.5 (9,100)	6.6 (24,200)	9.1 (33,300)	10.0 (36,600)	364	1,832	127 (402)	100 (316)	53 (167)	35 (110)	38 (121)
A12	8J-2	1.5 (5,300)	6.5 (23,700)	7.9 (29,000)	—	306	1,774	96 (304)	96 (306)	37 (117)	34 (109)	35 (110)
A13 ^d	11J-14	2.6 (9,500)	4.4 (16,100)	7.0 (25,600)	8.1 (29,700)	364	1,204	132 (418)	109 (347)	55 (175)	41 (129)	45 (143)
A14	5J-9	1.8 (6,400)	6.3 (23,200)	8.1 (29,600)	—	378	1,846	95 (301)	100 (316)	36 (114)	33 (106)	34 (108)
A15	17J-2	1.5 (5,500)	6.6 (24,300)	8.2 (29,800)	9.1 (33,100)	299	1,767	100 (317)	86 (272)	39 (123)	35 (112)	34 (114)
A16	8J-12	1.5 (5,300)	6.1 (22,300)	7.6 (27,600)	—	306	1,774	96 (304)	94 (297)	37 (117)	32 (102)	33 (105)
A17	12J-7	2.3 (8,400)	6.5 (23,700)	8.8 (32,100)	—	364	1,832	124 (392)	94 (297)	48 (153)	34 (108)	37 (118)
A18	14J-12	2.2 (8,200)	6.5 (23,700)	8.7 (31,900)	9.8 (35,700)	364	1,832	125 (396)	95 (300)	47 (150)	34 (107)	37 (116)
A19	11J-11	2.3 (8,500)	6.3 (23,200)	8.7 (31,700)	—	364	1,832	119 (376)	96 (303)	49 (156)	33 (105)	36 (115)
A20	9J-8	1.9 (7,100)	6.2 (22,800)	8.2 (29,900)	—	378	1,846	99 (314)	101 (319)	40 (120)	32 (103)	34 (108)
A21	5J-12	1.8 (6,400)	6.2 (22,500)	7.9 (28,900)	—	378	1,846	95 (301)	99 (313)	36 (115)	33 (104)	33 (106)
A22	17J-3	1.5 (5,500)	6.6 (24,300)	8.2 (29,800)	8.9 (32,500)	299	1,767	100 (317)	88 (278)	38 (122)	35 (111)	36 (113)
A23	13J-14	2.5 (9,100)	6.7 (24,400)	9.2 (33,500)	—	364	1,832	127 (402)	100 (316)	52 (166)	35 (110)	38 (121)
A24	14J-9	2.2 (8,200)	6.3 (23,200)	8.6 (31,400)	—	364	1,832	125 (396)	95 (300)	47 (150)	33 (105)	36 (114)
A25	8J-10	1.3 (4,800)	6.0 (21,900)	7.3 (26,700)	—	306	1,774	86 (274)	96 (303)	33 (106)	32 (100)	32 (101)
A26	13J-8	2.5 (9,100)	6.2 (22,800)	8.7 (31,900)	9.5 (34,800)	364	1,832	127 (402)	102 (322)	53 (167)	33 (104)	37 (116)
A27	12J-3	2.5 (9,300)	6.3 (23,200)	8.9 (32,500)	9.9 (36,100)	364	1,832	137 (435)	108 (341)	54 (171)	33 (106)	38 (119)
A28 ^d	5J-2	1.8 (6,400)	4.0 (14,800)	5.8 (21,200)	6.6 (24,000)	378	1,218	95 (301)	101 (319)	36 (115)	38 (120)	37 (118)
A29	4J-12	1.6 (5,700)	6.3 (23,200)	7.9 (28,900)	—	378	1,846	86 (272)	92 (291)	32 (102)	34 (107)	33 (106)
A30	8J-3	1.5 (5,300)	6.0 (21,900)	7.4 (27,200)	—	306	1,774	98 (304)	98 (308)	37 (118)	31 (99)	32 (102)
A31	11J-6	2.3 (8,500)	6.3 (23,200)	8.7 (31,700)	—	364	1,832	119 (376)	96 (303)	49 (155)	33 (105)	36 (115)
A32	13J-9	2.5 (9,100)	5.9 (21,400)	8.3 (30,500)	9.3 (33,900)	364	1,832	127 (402)	102 (322)	53 (167)	31 (97)	35 (111)
A33	9J-10	1.8 (6,400)	6.6 (24,300)	8.4 (30,700)	9.0 (32,900)	378	1,846	89 (283)	102 (325)	36 (115)	35 (112)	35 (112)
A34	9J-12	1.9 (7,100)	6.3 (23,200)	8.2 (30,100)	8.8 (32,200)	378	1,846	99 (314)	103 (328)	40 (127)	33 (105)	35 (110)
A35	5J-5	1.8 (6,400)	6.7 (22,400)	7.9 (28,800)	8.4 (30,800)	378	1,846	95 (301)	103 (328)	36 (114)	32 (102)	33 (105)
A36	16J-10	1.7 (6,100)	6.3 (23,000)	8.0 (29,100)	—	335	1,803	100 (316)	93 (294)	38 (122)	33 (105)	34 (108)
A37	11J-5	2.6 (9,500)	6.7 (24,400)	9.3 (33,900)	10.2 (37,300)	364	1,832	132 (418)	109 (347)	55 (173)	35 (110)	39 (123)
A38	9J-9	1.9 (7,100)	6.2 (22,700)	8.2 (29,800)	8.8 (32,200)	378	1,846	99 (314)	101 (319)	40 (127)	33 (104)	34 (109)
A39	13J-2	2.5 (9,100)	6.4 (23,400)	8.9 (32,500)	9.8 (35,100)	364	1,832	127 (402)	108 (341)	53 (167)	33 (106)	37 (118)
A40	9J-2	1.9 (7,100)	6.5 (23,900)	8.5 (31,000)	9.2 (33,800)	378	1,846	99 (314)	103 (328)	40 (127)	35 (110)	36 (113)
A41 ^d	11J-15	2.6 (9,500)	4.0 (14,500)	6.6 (24,000)	7.8 (28,500)	364	1,204	132 (418)	117 (372)	55 (174)	36 (115)	42 (133)
A42	6J-15	2.2 (7,900)	6.2 (22,700)	8.4 (30,600)	9.0 (33,000)	378	1,846	121 (385)	105 (334)	44 (141)	32 (103)	35 (111)
A43	16J-3	1.9 (6,800)	6.4 (23,400)	8.3 (30,200)	8.8 (32,000)	335	1,803	111 (351)	102 (325)	43 (135)	34 (107)	35 (112)
A44	5J-14	1.8 (6,400)	5.9 (21,400)	7.6 (27,800)	—	378	1,846	95 (301)	100 (316)	36 (114)	31 (98)	32 (101)
A45 ^d	5J-15	1.8 (6,400)	4.2 (15,400)	6.0 (21,800)	6.9 (25,300)	378	1,218	95 (301)	99 (313)	36 (115)	39 (125)	38 (122)
A46 ^d	5J-8	1.8 (6,400)	4.3 (15,600)	6.0 (22,000)	6.9 (25,300)	378	1,218	95 (301)	101 (319)	36 (115)	40 (126)	39 (123)

Table 2 (continued)

SA-1 Number	VBWR Assembly Designation ^a	Rod-Average Burnup			Final Peak	Days of		Estimated		Time-Averaged Rod-Average Heat Flux ^c		
		Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)			Burnup	Operation ^b		Peak Heat Flux ^c		W/cm ² (Btu/h-ft ² X 10 ⁻³)		
		VBWR	Dresden	Total	Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)	VBWR	Total	W/cm ² (Btu/h-ft ² X 10 ⁻³)	Dresden	VBWR	Dresden	Overall
A47	6J-10	2.0 (7,200)	6.3 (23,000)	8.3 (30,200)	9.1 (33,100)	378	1,846	109 (346)	103 (328)	40 (126)	33 (104)	34 (109)
A48	6J-9	2.2 (7,900)	6.3 (22,900)	8.4 (30,800)	9.2 (33,600)	378	1,846	121 (385)	105 (334)	44 (140)	33 (104)	35 (111)
A49	6J-5	2.2 (7,900)	6.3 (23,200)	8.5 (31,100)	9.2 (33,600)	378	1,846	121 (385)	115 (366)	44 (141)	33 (106)	36 (113)
B50	5J-7	1.6 (5,800)	6.8 (25,000)	8.4 (30,800)	9.5 (34,800)	378	1,846	85 (271)	90 (284)	33 (104)	37 (116)	36 (113)
B51	1J-12	1.5 (5,400)	6.7 (24,400)	8.2 (29,800)	—	378	1,846	84 (265)	87 (275)	30 (96)	35 (111)	34 (108)
B52	4J-2	1.6 (5,700)	6.6 (24,100)	8.2 (29,800)	9.0 (32,800)	378	1,846	86 (272)	86 (272)	32 (102)	35 (112)	35 (110)
B53	4J-3	1.6 (5,700)	6.3 (23,200)	7.9 (28,900)	—	378	1,846	86 (272)	88 (278)	32 (102)	34 (107)	33 (106)
B54	5J-11	1.6 (5,800)	6.1 (22,300)	7.7 (28,100)	—	378	1,846	85 (271)	92 (291)	33 (104)	32 (103)	32 (103)
B55	16J-6	1.7 (6,100)	6.0 (22,100)	7.7 (28,200)	—	335	1,803	100 (316)	93 (294)	38 (122)	32 (101)	33 (105)
B56	6J-12	2.2 (7,900)	6.4 (23,300)	8.5 (31,200)	9.5 (34,900)	378	1,846	121 (385)	102 (325)	44 (141)	33 (106)	36 (113)
B57	1J-14	1.5 (5,400)	6.4 (23,400)	7.9 (28,800)	8.8 (32,000)	378	1,846	84 (265)	87 (275)	31 (97)	34 (108)	33 (105)
B58	12J-8	2.5 (9,300)	6.0 (21,900)	8.5 (31,200)	9.9 (36,200)	364	1,832	137 (435)	102 (322)	54 (170)	31 (99)	36 (113)
B59	8J-14	1.5 (5,300)	5.6 (20,500)	7.1 (25,800)	—	306	1,774	96 (304)	94 (297)	37 (117)	30 (94)	31 (98)
B60	13J-16	2.5 (9,100)	6.3 (23,100)	8.8 (32,200)	10.2 (37,400)	364	1,832	127 (402)	100 (316)	52 (166)	33 (105)	37 (117)
B61	8J-5	1.5 (5,300)	6.2 (22,500)	7.6 (27,800)	8.4 (30,600)	306	1,774	96 (304)	96 (306)	37 (117)	32 (103)	33 (105)
B62	11J-2	2.6 (9,500)	6.5 (23,700)	9.1 (33,200)	10.4 (37,900)	364	1,832	132 (418)	109 (347)	55 (173)	34 (107)	38 (121)
B63	16J-5	1.9 (6,800)	5.9 (21,400)	7.7 (28,200)	—	335	1,803	111 (351)	100 (316)	43 (136)	31 (98)	33 (105)
B64	4J-5	1.6 (5,700)	6.2 (22,800)	7.8 (28,500)	—	378	1,846	86 (272)	86 (272)	32 (102)	33 (106)	33 (105)
B65	8J-15	1.5 (5,300)	6.2 (22,800)	7.7 (28,100)	—	306	1,774	96 (304)	94 (297)	37 (118)	33 (105)	34 (107)
B66	13J-7	2.2 (8,200)	6.3 (23,000)	8.5 (31,200)	—	364	1,832	114 (362)	94 (297)	47 (150)	33 (105)	36 (114)
B67	14J-2	2.2 (8,200)	6.1 (22,300)	8.3 (30,500)	—	364	1,832	125 (396)	95 (300)	48 (151)	32 (102)	35 (111)
B68	12J-6	2.3 (8,400)	6.0 (21,900)	8.3 (30,300)	—	364	1,832	124 (392)	96 (303)	49 (154)	32 (100)	35 (111)
B69	9J-6	1.8 (6,400)	5.9 (21,600)	7.7 (28,000)	—	378	1,846	89 (283)	101 (319)	36 (114)	31 (99)	32 (102)
B70 ^d	16J-8	1.9 (6,800)	3.7 (13,400)	5.5 (20,200)	6.9 (25,300)	335	1,175	111 (351)	99 (313)	43 (136)	34 (107)	35 (111)
B71	4J-8	1.6 (5,700)	6.1 (22,300)	7.7 (28,000)	—	378	1,846	86 (272)	88 (278)	32 (101)	32 (103)	32 (102)
B72	11J-10	2.3 (8,500)	6.3 (23,000)	8.6 (31,500)	—	364	1,832	119 (376)	100 (316)	49 (155)	33 (104)	36 (114)
B73	13J-11	2.2 (8,200)	5.7 (21,000)	8.0 (29,200)	—	364	1,832	114 (362)	95 (300)	48 (152)	30 (96)	34 (107)
B74	8J-7	1.3 (4,800)	5.8 (21,200)	7.1 (26,000)	—	306	1,774	86 (274)	96 (303)	33 (105)	31 (97)	31 (98)
B75	13J-3	2.5 (9,100)	5.9 (21,600)	8.4 (30,700)	—	364	1,832	127 (402)	102 (322)	53 (167)	31 (98)	35 (111)
B76 ^d	12J-14	2.5 (9,300)	3.6 (13,100)	6.1 (22,400)	8.0 (29,100)	364	1,204	137 (435)	108 (341)	54 (171)	33 (104)	39 (124)
B77	16J-9	1.9 (6,800)	5.3 (19,400)	7.2 (26,200)	—	335	1,803	111 (351)	101 (319)	43 (135)	28 (88)	31 (97)
B78	4J-9	1.6 (5,700)	6.0 (22,100)	7.6 (27,800)	—	378	1,846	86 (272)	92 (291)	32 (102)	32 (102)	32 (102)
B79	8J-8	1.5 (5,300)	6.1 (22,300)	7.6 (27,600)	—	306	1,774	96 (304)	96 (306)	37 (117)	32 (102)	33 (104)
B80	12J-10	2.3 (8,400)	6.0 (21,900)	8.3 (30,300)	—	364	1,832	124 (392)	96 (303)	49 (154)	32 (100)	35 (111)
B81	13J-5	2.5 (9,100)	6.0 (21,900)	8.5 (31,000)	—	364	1,832	127 (402)	102 (322)	53 (167)	31 (99)	36 (113)
B82	9J-11	1.8 (6,400)	6.0 (22,100)	7.8 (28,500)	—	378	1,846	89 (283)	102 (325)	36 (114)	32 (101)	33 (104)
B83	9J-3	1.9 (7,100)	5.9 (21,700)	7.9 (28,800)	8.5 (31,100)	378	1,846	99 (314)	103 (328)	40 (127)	32 (100)	33 (105)
B84	6J-6	2.0 (7,200)	5.3 (19,400)	7.3 (26,600)	—	378	1,846	109 (346)	103 (328)	40 (127)	28 (88)	30 (96)
B85	16J-7	1.7 (6,100)	6.4 (23,400)	8.1 (29,500)	9.0 (33,000)	335	1,803	100 (316)	93 (294)	38 (122)	34 (107)	35 (110)
B86	11J-3	2.6 (9,500)	6.2 (22,700)	8.8 (32,200)	10.0 (36,400)	364	1,832	132 (418)	109 (347)	54 (172)	32 (102)	37 (116)
B87	9J-7	1.8 (6,400)	6.0 (21,900)	7.7 (28,300)	—	378	1,846	89 (283)	101 (319)	36 (114)	32 (100)	32 (103)
B88 ^d	12J-9	2.5 (9,300)	3.6 (13,100)	6.1 (22,400)	7.7 (28,000)	364	1,204	137 (435)	108 (341)	54 (171)	33 (104)	39 (124)
B89	9J-5	1.9 (7,100)	5.9 (21,400)	7.8 (28,500)	8.3 (30,200)	378	1,846	99 (314)	103 (328)	40 (127)	31 (98)	33 (104)
B90 ^e	11J-9	2.6 (9,500)	6.5 (23,700)	9.1 (33,200)	10.3 (37,500)	364	1,832	132 (418)	117 (372)	54 (172)	34 (107)	38 (120)
B91	6J-2	2.2 (7,900)	5.6 (20,300)	7.7 (28,200)	8.9 (32,400)	378	1,846	121 (385)	105 (334)	44 (140)	29 (92)	32 (102)

Table 2 (Continued)

SA-1 Number	VBWR Assembly Designation ^a	Rod-Average Burnup			Final Peak Burnup Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)	Days of Operation ^b		Estimated Peak Heat Flux ^c		Time-Averaged Rod-Average Heat Flux ^c		
		Fissions/cm ³ X 10 ⁻²⁰ (MWd/tU)				VBWR	Total	W/cm ² (Btu/h-ft ² X 10 ⁻³)		W/cm ² (Btu/h-ft ² X 10 ⁻³)		
		VBWR	Dresden	Total				VBWR	Dresden	VBWR	Dresden	Overall
B92	6J-11	2.0 (7,200)	6.5 (23,600)	8.4 (30,800)	9.8 (35,700)	378	1,846	109 (346)	102 (325)	40 (127)	34 (108)	35 (112)
B93	16J-12	1.9 (6,800)	6.1 (22,400)	8.0 (29,200)	9.2 (33,600)	335	1,803	111 (351)	100 (316)	43 (136)	32 (103)	34 (109)
B94	16J-14	1.9 (6,800)	5.9 (21,400)	7.7 (28,200)	—	335	1,803	111 (351)	99 (313)	43 (136)	31 (98)	33 (105)
B95	16J-15	1.9 (6,800)	5.9 (21,700)	7.8 (28,500)	8.6 (31,600)	335	1,803	111 (351)	101 (319)	43 (136)	31 (99)	33 (106)
B96	6J-7	2.0 (7,200)	5.7 (20,700)	7.6 (27,900)	8.8 (32,100)	378	1,846	109 (346)	103 (328)	40 (127)	30 (94)	32 (101)
B97 ^d	6J-3	2.2 (7,900)	3.9 (14,300)	6.1 (22,200)	7.3 (26,600)	378	1,218	121 (385)	105 (334)	44 (141)	36 (114)	38 (122)
B98	6J-8	2.2 (7,900)	5.6 (20,500)	7.8 (28,400)	9.1 (33,200)	378	1,846	121 (385)	115 (366)	44 (140)	29 (93)	32 (102)

a) Rod is designated by assembly number (e.g., 5J) followed by position number as indicated below:

- b) Days of operation in VBWR = hours reactor thermal power >5MW ÷ 24. Days of operation in Dresden = hours of turbine-generator operation ÷ 24.
- c) To obtain linear power in kW/ft of rod length, multiply W/cm² by 0.103.
- d) Indicates rods removed from assembly at conclusion of reactor Cycle No. 4.
- e) Indicates rod transferred from Subassembly B-1 to Subassembly A-1 between reactor Cycle Nos. 4 and 5.

4.1.3.2 Leak Testing

At the terminal shutdown of the VBWR, eleven of the fuel assemblies from which the SA-1 rods were selected were leak tested by a "wet sipping" technique. The sipping test is performed following a shutdown to detect assemblies in which the cladding has been penetrated, exposing UO_2 fuel to the coolant. To perform this test the assembly was sealed in a can and, after it was allowed to soak for about 20 minutes, a 1-liter water sample was withdrawn. The sample was analyzed for fission product iodine and the concentration compared with the concentration of fission product iodine in the surrounding pool water (background). A higher concentration of radioactive iodine was generally interpreted as being indicative of a fuel rod cladding failure.

From the results of the sipping tests, two of these assemblies (12J and 16J) were suspected of containing one or more rods with cladding defects. The signals were of relatively low levels, however, and when repeat tests were run on them, the indications were too low to be conclusive. The one assembly (14J) that was not given a post-irradiation sip test was suspected of containing one or more failed rods on the basis of the activity release detected during earlier in-core monitoring.

During the subsequent visual examinations of the fuel rods, a full-wall fretting wear defect caused by the single-layer wire middle spacer was found in the cladding of one rod from Assembly 14J. The rest of the rods in this assembly and all of those in the other eleven assemblies appeared to be sound.

4.2 DRESDEN UNIT NO. 1

4.2.1 Reactor Environment and Operation

The reactor of the Dresden Nuclear Power Station Unit No. 1 is a dual cycle boiling water reactor that operates at a pressure of 71.5 kg/cm^2 or 1017 psia (286°C saturation temperature). During the SA-1 operating period the reactor water had an average pH of 7.5 and an average conductivity of $0.44 \mu \text{ mho}$. The turbidity of the water averaged 5.5 APHA units, and the mean concentration of chloride was 0.040 ppm. A record of the reactor water chemistry data is given on a monthly basis in Appendix C.

Assembly SA-1 operated in Dresden throughout Cycles 3, 4, 5, and 6. During these cycles the station followed two basic patterns of operation. During the initial portions of Cycles 3 and 4, scheduled operation was on a daily load cycle to match the system demands. Generally speaking, this type of load schedule called for plant operation at approximately half power from about 11:00 p.m. to about 8:00 a.m. and at or near full power during the remainder of the day except for reductions to three-quarters power during the noon and late afternoon hours. This pattern was altered on Saturdays with a load reduction to half power from noon to early evening. Sunday operation was constant at half power. During most of the remainder of the four cycles the plant was base loaded. The power was more nearly constant with this type of operation than with the previously mentioned pattern. Although periods of operation below the base power level occurred, these reductions were generally less frequent, of smaller magnitude, and of shorter duration than the daily half- to full-power swings called for by the system demand following type of load schedule. The period and number of days of operation and information on the reactor thermal power levels are given for each of the four cycles in Table 3.

4.2.2 Assembly Operation

4.2.2.1 Calculated Operational Characteristics

The approximate axial power distribution for Assembly SA-1 at the beginning of Dresden operation is depicted in Figure 12. The ratio of axial peak-to-average power without consideration of end pellet peaking is 1.23. The end pellet factor is 1.15. Since the location of the pellets adjacent to the short end plugs of the "A" or bottom rods very nearly coincides with the previously mentioned peak, the overall axial factor becomes 1.41.

The relative radial powers for the different subassembly rod locations at the beginning of Dresden operation are shown in Figure 13 for zero voids and for 40% voids. The relative power in the nonvoided region for the maximum power rod is 1.19.

The overall power peaking factor for the assembly therefore is the product of the overall axial factor (1.41) and the local radial factor (1.19) and equals 1.68.

4.2.2.2 Core Locations and Fuel Rod Patterns

Assembly SA-1 operated continuously from June 1964 to September 1969 with the exception of shutdown periods for reactor refueling and maintenance. Figures 14 and 15 indicate where SA-1 was located in the reactor core and the types of fuel assemblies that surrounded it during its four cycles of operation.

Table 3
DNPS UNIT NO. 1 REACTOR OPERATING DATA

Cycle Number	Dates Cycle Started and Completed	Total Days of Operation ^a	Type of Operation	Period	Typical Reactor Thermal Powers (MWt)			Peak Power Attained ^b (MWt)	Number of Times Reactor Power Reduced to Zero ^c
					Daily Maximum ^b	Daily Average	Daily Minimum ^b		
3	6/9/64-3/28/65	281	System demand following	6/9/64-3/7/64	600-685	~500	~350	690	3
			Base loaded	9/8/64-11/1/64	510	505	500	515	1
			Base loaded	10/2/64-3/9/65	460	460	460	475	1
			—	3/9/65-3/28/65	Gradual decrease to ~415			—	1
4	5/29/65-1/13/67	559	System demand following	5/29/65-1/7/66	650-685	~525	~350	695	6
			Base loaded	1/8/66-11/4/66	600-650	590-640	~570	700	9
			Base loaded	10/9/66-1/13/67	~520	505-520	475-520	675	1
5	5/23/67-2/3/68	214	Base loaded	5/23/67-2/3/68	600-680	590-675	≥500	695	7
6	6/2/68-9/5/69	414	Base loaded	6/2/68-3/12/69	625-675	600-650	550-650	695	16
			d	3/13/69-5/12/69	650-675	525-625	350	700	3
			Base loaded	5/13/69-5/27/69	~515	~505	—	—	0
			Base loaded	5/28/69-3/8/69	~550	~535	—	650	0
			Base loaded	6/9/69-6/23/69	~580	~575	—	630	0
			Base loaded	6/24/69-3/5/69	~500	~495	—	580	4

a Hours of turbine-generator operation ÷ 24.

b To obtain these values, conversion factors calculated from corresponding values of electrical and thermal energy outputs, were applied to the daily maximum and minimum electrical power levels. These data were obtained from the Commonwealth Edison Company's daily reports on Unit Number 1 operation.

c Excludes end-of-cycle shutdowns.

d Special load schedule that called for ~16 hours of operation near full power and ~8 hours of half-power operation per day.

Figure 12. Approximate Axial Power Distribution for Assembly SA-1 at the Beginning of Dresden Operation

CONTROL ROD	1.17	1.07		1.02		1.01	1.04	0.0 VOIDS
	1.07	1.19	1.05	1.09	1.02	1.11	0.94	
		1.05				0.98		
	1.02	1.09		0.97		1.01	0.89	
		1.02				0.95		
	1.01	1.11	0.98	1.01	0.95	1.03	0.88	
	1.04	0.94		0.89		0.88	0.91	

CONTROL ROD	1.23	1.12		1.03		1.03	1.07	0.4 VOIDS
	1.12	1.21	1.06	1.09	1.01	1.11	0.95	
		1.06				0.96		
	1.03	1.09		0.95		0.99	0.87	
		1.01				0.92		
	1.03	1.11	0.96	0.99	0.92	1.01	0.87	
	1.07	0.95		0.87		0.87	0.91	

NOTE: Blanks indicate that value for location not specifically determined during initial analysis

Figure 13. Relative Radial Powers for Various Subassembly Rod Locations in Assembly SA-1 at the Beginning of Dresden Operation

TYPE OF ASSEMBLY

1
11
111B (3)
111B (4) & 111F (4)
V

ZIRCALOY-2-CLAD SEGMENTED RODS - FIRST LOADING
STAINLESS STEEL-CLAD THROUGH RODS - FIRST REFUELING
ZIRCALOY-2-CLAD THROUGH RODS - SECOND REFUELING
ZIRCALOY-2-CLAD THROUGH RODS - THIRD REFUELING
ZIRCALOY-2-CLAD THROUGH RODS - FOURTH REFUELING

STARTED OPERATION

JUNE 1960
MARCH 1963
JUNE 1964
MAY 1965
MAY 1967

Figure 14. Locations of SA-1 and Types of Surrounding Fuel Assemblies in Cycle No. 3 (57-14), Cycle No. 4 (54-16), and Cycle No. 5 (53-11)

TYPE OF ASSEMBLY

111B (3)
 111B (4) & 111F (4)
 UN

ZIRCALOY-2-CLAD THROUGH RODS - SECOND REFUELING
 ZIRCALOY-2-CLAD THROUGH RODS - THIRD REFUELING
 ZIRCALOY-2-CLAD THROUGH RODS - FIFTH REFUELING

STARTED OPERATION

JUNE 1964
 MAY 1965
 JUNE 1968

Figure 15. Location of SA-1 and Types of Surrounding Fuel Assemblies in Cycle No. 6

The locations of the fuel rods in the two subassemblies and the orientations of the subassemblies with respect to the adjacent control rod are shown in Figure 16. At the end of the assembly's second cycle of operation (reactor Cycle No. 4), the 10 rods indicated in Figure 16(a) were permanently removed for examination purposes.

To assure satisfactory power distribution and thermal-hydraulic characteristics in subsequent cycles, some of the 88 remaining fuel rods were rearranged, as shown in Figure 16(b), and the orientation of the assembly with respect to the adjacent control rod was changed by 180 degrees. The control rod at which SA-1 was located in each of the four cycles was, in every case, fully withdrawn throughout that particular cycle.

4.2.2.3 Exposure and Thermal Performance

Most of the SA-1 fuel rods operated 1468 days* in Dresden. The total days of operation for these rods, including VBWR exposure, ranged from 1767 days to 1846 days and averaged 1827. The 10 rods that were removed from the assembly at the end of Cycle No. 4 operated 840 days* in Dresden and ranged from 1139 days to 1218 days in total exposure time.

The 88 rods that operated through four cycles received an average additional burnup in Dresden of 6.2×10^{20} fissions/cm³ (22,800 MWd/tU). The assembly-average burnup, including VBWR exposure, was 8.2×10^{20} fissions/cm³ (29,800 MWd/tU). The terminal rod-average burnups ranged from 7.1×10^{20} to 9.3×10^{20} fissions/cm³ (25,800 to 33,900 MWd/tU), and the highest local peak burnup for any rod was 10.4×10^{20} fissions/cm³ (37,900 MWd/tU). The exposure times and average burnups of all 98 SA-1 fuel rods and the peak terminal burnups of those rods that were gamma scanned at the end of operation are given in Table 2. The methods employed to analyze some of the rods for burnup are described in detail in Section 5.3. In brief, they were as follows: 51 rods, including the 10 that were removed from the assembly at the end of Cycle No. 4, were gamma scanned for Cs-137 with a Ge (Li) detector system to obtain both the axial burnup distribution for each rod and the relative rod-average burnups among these several rods. Fuel samples were taken from the peak burnup locations of 20 of these rods (25 to 30 cm [10 to 12 in.] above or below the middle of the assembly) and analyzed for burnup by measuring the neodymium isotopes. These burnup values then were applied to the gamma scan results to obtain the average and peak burnups of all 51 rods. The average burnups of the remaining 47 were determined by estimating their burnups in Dresden from the rods that were analyzed and taking the differences in VBWR burnups into consideration.

The power at which Assembly SA-1 operated was highest early in the first cycle (reactor Cycle 3) and decreased rather continuously with increasing burnup. As Table 4 indicates, the local peak heat flux attained by the assembly was 117 W/cm² (372,000 Btu/h-ft²), and the maximum assembly-average heat flux was 87 W/cm² (277,000 Btu/h-ft²).* The time-averaged assembly-average heat flux for Dresden operation was 33 W/cm² (104,000 Btu/h-ft²).

The peak heat flux attained and the time-averaged heat flux are given for each individual fuel rod in the assembly in Table 2. All rods, including those in the relatively lower power positions in the assembly during the first two cycles, attained their maximum heat fluxes early in Dresden operation. With about 60% of the rods, that heat flux was lower than the local peak heat flux attained during VBWR operation. Among rods that operated through four Dresden cycles, the maximum time-averaged rod-average heat flux for VBWR and Dresden operation combined was 39 W/cm² (123,000 Btu/h-ft²).

4.2.2.4 Leak Testing

At the conclusion of each of the four Dresden cycles, Assembly SA-1 was transferred to the fuel building pool and leak tested by wet sipping in a manner similar to that employed on the VBWR assemblies. No indication of fuel rod failure was detected in any of these tests.

* Hours of turbine-generator operation $\div$ 24.

** An overall peaking factor of 1.68 was used in all calculations of assembly peak heat flux given in Table 4. The accuracy of this value becomes more doubtful with increase in exposure, particularly for operation after the second cycle when rods were removed and underwent changes of position, and the assembly orientation was changed. However, because of the relatively low assembly power levels toward the end of operation, attempting to "update" the peaking factor did not seem warranted.

Figure 16. SA-1 Fuel Rod Patterns During Dresden Cycles 3 and 4 (a) and 5 and 6 (b)

Table 4
SA-1 THERMAL PERFORMANCE HISTORY IN DRESDEN

Δ Burnup		Cumulative Burnup		Assembly Average Heat Flux W/cm ² (Btu/h-ft ² X 10 ⁻³)		Assembly Peak Heat Flux W/cm ² (Btu/h-ft ² X 10 ⁻³)	
Fissions/cm ³ X 10 ⁻²⁰	MWd/tU	Fissions/cm ³ X 10 ⁻²⁰	MWd/tU	At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power
CYCLE NUMBER 3							
0.13	480	2.08	7,590	52 (165)	69 (220)	87 (277)	116 (370)
0.48	1,740	2.55	9,330	46 (146)	70 (221)	77 (245)	117 (372)
0.58	2,120	3.13	11,450	45 (142)	49 (155)	75 (238)	82 (260)
0.24	880	3.37	12,330	42 (133)	45 (142)	70 (223)	76 (239)
0.25	910	3.62	13,240	43 (138)	45 (144)	73 (231)	76 (242)
CYCLE NUMBER 4							
0.61	2,240	4.24	15,480	35 (110)	49 (156)	58 (185)	82 (262)
0.31	1,140	4.55	16,620	38 (120)	52 (166)	64 (201)	88 (278)
0.45	1,660	5.00	18,280	35 (110)	50 (157)	65 (207)	83 (264)
0.46	1,680	5.46	19,960	40 (126)	46 (145)	67 (212)	77 (244)
0.42	1,540	5.88	21,500	36 (115)	44 (139)	61 (194)	74 (233)
0.36	1,330	6.25	22,830	28 (89)	39 (123)	47 (150)	65 (207)
CYCLE NUMBER 5							
0.08	280	6.31	23,050	16 (49)	20 (62)	26 (82)	33 (104)
0.16	600	6.47	23,650	21 (68)	30 (94)	36 (114)	50 (158)
0.16	580	6.63	24,230	22 (69)	25 (79)	37 (117)	42 (134)
0.11	420	6.74	24,650	23 (72)	27 (85)	38 (121)	45 (142)
0.13	490	6.88	25,140	23 (73)	26 (84)	38 (122)	44 (141)
0.04	140	6.92	25,280	20 (64)	26 (84)	34 (108)	44 (141)
CYCLE NUMBER 6							
0.33	1,210	7.25	26,490	25 (79)	29 (91)	42 (133)	48 (152)
0.27	990	7.52	27,480	22 (69)	25 (80)	36 (115)	42 (134)
0.31	1,140	7.83	28,620	20 (64)	24 (75)	34 (107)	40 (127)
0.33	1,210	8.16	29,830	18 (58)	25 (78)	30 (97)	41 (131)

5. EXAMINATIONS AND ANALYSES OF THE SA-1 FUEL

5.1 FUEL ROD PERFORMANCE EVALUATION

5.1.1 Visual Examinations of Fuel Rods (G. P. Ferguson, F. H. Megerth)

5.1.1.1 Procedure and Scope

The external surfaces of most of the SA-1 fuel rods were visually examined on several occasions during the course of operation. Interim pool examinations were performed with an underwater periscope on the Type J assemblies during scheduled shutdown periods between VBWR runs. At the conclusion of VBWR operation, all of the rods that were ultimately selected for incorporation in Assembly SA-1 were transferred to the hot cells of the Radioactive Materials Laboratory at VNC and examined individually. All of these rods were wiped down with a dry cotton pad at this time to remove most of the deposited corrosion products, or crud.

At the end of Dresden Reactor Cycle No. 4, all sides of the two SA-1 subassemblies were examined by means of both an underwater television camera and a borescope. Nineteen fuel rods were withdrawn from the subassemblies and individually inspected with the borescope, and ten of these were shipped to VNC where they were examined in-cell during the initial phase of the PA-41 examination program.

Finally, after the assembly had operated to the end of reactor Cycle No. 6, the two subassemblies were transported to VNC for the final phase of the examination program. The four sides of each subassembly were examined in the hot cells 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. A Kollmorgen periscope was used in all of the hot cell work to examine the SA-1 fuel at magnifications between approximately 2X and 4X.

Twelve rods were re-examined after dissolving the crud layers with hydrochloric acid. The details of the dissolution procedure used are described in Section 5.1.9 (Crud Analysis). Half of these rods (A4, A13, A28, A41, B70, and B76) were removed from SA-1 at the end of Cycle No. 4; the rest (A7, A9, A22, A37, A49, and B50) operated to the end of Cycle No. 6.

In carrying out the visual examinations, the axial positions of points of interest on the rod surfaces generally were defined in terms of distance from the shoulder of the shorter end plug, regardless of whether a rod was from the top (B-1) or bottom (A-1) subassembly. In both cases, the shorter plugs were located near the middle of the full SA-1 assembly, while the longer end plugs (and plenums) were located at the top and bottom. The radial orientations of points of interest on the 10 rods removed at the end of Cycle No. 4 were arbitrarily defined in terms of degrees from the identifying numbers stamped on the longer end plugs. With the other 88 rods, however, the 0-degree orientation was taken as that point on the circumference of a rod that was directed toward the "identification mark" side of its subassembly. (See Figure 16.)

5.1.1.2 Results

At the conclusion of VBWR operation the surfaces of the Type J fuel rods were generally uniform in appearance and were evenly covered with deposited corrosion products, or crud. The crud was red-brown, soft, and easily removed by wiping with a dry cotton pad. The removal of the crud deposits revealed a reddish-black surface film which contained numerous shiny specks. About 5% of the rods inspected had some irregular surface patterns. An example of this mottling can be seen in Figure 17 on rod 14J-12, which later was selected for irradiation in SA-1 as rod A18.³

Evidence of fretting wear of the cladding caused by the single-layer wire spacers located at the middle of the VBWR assemblies was frequently noted. Some relatively severe cases of fretting wear are shown in Figure 18.³ The depths of the wear grooves were measured with a special gauge. The grooves in approximately three-fourths of those rods selected for further irradiation in Assembly SA-1 were ≤ 0.0076 cm (0.003 in.) deep. Seventeen of the SA-1 rods had wear grooves 0.013 cm (0.005 in.) or more deep. The deepest grooves in any of the SA-1 rods were shown by rods A24 and A31 (0.025 cm or 0.010 in.).²

The two subassemblies appeared to be in generally good condition after four cycles of Dresden operation. An overall view of subassembly B-1, which was in the top position during operation, is shown in Figure 19. The spacing between visible outside rods was uniform in both subassemblies. The four corner rods in each subassembly were completely hidden from view, and the rods next to the corner rods were partially hidden by the stainless steel corner

Figure 17. Irregular Patterns on Surface of Rod 14J-12 (SA-1, Rod A18)

Figure 18. Severe Fretting Wear at Single-Layer Wire Spacer Contacts

Figure 19. Subassembly B-1 at End of Irradiation

angles. 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.

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.

During Dresden operation, a film of crud deposited on the fuel rods that 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. Examples of this type of surface are shown in Figures 20, 21, and 22. Generally speaking, the appearance of the rods that had operated in Dresden for four cycles was similar to that of the ten rods that were permanently removed after two cycles of operation. 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. As Figures 21 and 22 show, the degree of speckling and roughness varied from rod to rod at a given elevation.

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 22). 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 entire 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 that had operated to the end of Cycle No. 6 (see Figure 23). 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. The long end plugs and plenum regions of the cladding generally were coated with a smooth reddish-brown film of crud (Figure 24).

Approximately ten rods showed spalling or cracking of the crud layer at locations between the subassembly spacers at the end of Cycle No. 6. 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 25).

Corner rod B56, which operated in the top assembly 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 $\sim 2-1/2$ to 40 cm (~ 1 to 16 in.) above the bottom of the subassembly (Figures 26A and 26B). Most of the spalled areas were $1/2$ cm wide by $1/2$ 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 deposition of reddish-brown crud generally was observed on a rod at one or more of the subassembly spring type spacer locations. The deposits at these locations typically extended a centimeter or so ($\sim 1/2$ in.) on either side of the apparent spring-rod contact point. 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 27, were as large as approximately 0.3 cm ($1/8$ in.) in diameter and were located 0.3 to 0.6 cm ($1/8$ to $1/4$ 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 28). 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 ($\sim 3/16$ in.) in diameter or less. An example of spalled crud at a spacer band location is shown in Figure 29.

2X MAG.

~3X MAG.

Figure 20. Typical Speckled Surface Film (Fuel Rod A46)

Figure 21. Surface Appearance of SA-1 Fuel Rods at Midlength (Rods A8, A15, A22, and A29 in Subassembly A-1)

Figure 22. Rough Surfaces on Rods B64, B78, and B85 at Bottom Spacer of Subassembly B-1

Figure 23. Bandlike Surface Pattern on Rod A15

Figure 24. Long End Plug and Plenum Regions of Rods B57, B64, B71, B78, and B85

Figure 25. Cracks in Crud Layer on Fuel Rod B53

Figure 26A. Areas of Crud Spalling on Rod B56 at Various Distances from the Short End Plug

d

e

Figure 26B. Areas of Crud Spalling on Rod B56 at Various Distances from the Short End Plug

a

b

Figure 27. Flaky Crud Buildups at Spacer Locations on (a) Rod B51 and (b) Rod B60
(Note: Rule in Figure 27b Indicates Distances from Long End Plug Shoulder)

*Figure 28. Crud Flakes at Bottom Edge of Spacer Band
(Rods A8, A15, A22, and A29 at Second Spacer from Top)*

*Figure 29. 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)*

Brown circumferential rings and/or circular brown spots like those shown in Figure 30 were noted on about seven rods. 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 31, 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 ($\sim 1/2$ in.) to greater than 20 cm (~ 8 in.). Most of these lines appeared to be shallow surface penetrations that had resulted from handling (Figures 32a-d), but in some cases portions of the lines appeared to protrude from the surface (Figure 32e). As Figures 32d and e indicate, these lines were observed on some of the outside rods before they were removed from the subassemblies.

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 33), about ten rods contained small, rather jagged cracks or crack networks (Figure 34), and one or two rods showed 0.2 cm diameter blisterlike protrusions (Figure 35).

The exact natures of many of these anomalies and the depths of penetration could not be determined solely by visual inspection of the external surfaces, and further investigations covered in subsequent sections were carried out on some of these rods.

The wear grooves in the cladding, which had been caused by contact with the wire type spacers during VBWR operation, did not appear to have any deleterious effect on the operation of the rods in Dresden. Some increase 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.

The surface appearance of some of the rods after the crud had been chemically removed from them is shown in Figures 36 through 39. A roughness similar to that shown by portions of nearly all rods in the "as-received" condition also was observed over portions of the decrudded heat transfer surfaces. This roughness had the appearance of small, closely spaced blisters, as shown in Figures 36b and 37.

The surfaces of the six rods that had been removed from the assembly at the end of Cycle No. 4 were a solid black over both relatively smooth and relatively rough areas, 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. The surfaces of the six rods that had operated to the end of Cycle No. 6 were primarily white or light gray over some areas, particularly those that were comparatively rough. Other areas were a dark brownish color, sometimes in combination with fine, white speckling.

The roughness on a given rod generally varied somewhat with radial orientation, as exemplified by rod B76 in Figure 36, and usually showed some variation along the length. The roughness generally tended to decrease toward the longer end plug, i.e., toward the relatively low power region, of the rods that were removed at the end of Cycle No. 4. However, the surfaces of most of the rods that operated throughout the life of SA-1 were about as rough at the low power ends as they were at the high power ends.

There were noticeable differences in the extent and degree of roughness among different rods in each six-rod group, although the average power ratings of most of the rods in each group were similar. The rods that operated to the end of Cycle No. 6 probably were, generally speaking, somewhat rougher in appearance than those that were removed two cycles earlier.

Rods A49 and B50, which were fabricated from the same tubing lot (CA-2) and were located in corner positions of their respective subassemblies, showed the roughest surfaces of all twelve rods. However, rod A9, which was relatively smooth, was also fabricated from lot CA-2, and corner rod A7 was about average with respect to roughness; hence the rough surfaces of rods A49 and B50 cannot be clearly attributed either to tubing lot or to some condition imposed by the proximity of the subassembly corner angles.

Four of the rods (A7, A22, A49, and B50) that had operated to the end of Cycle No. 6 showed smooth, dark brown circumferential rings spaced at pellet length intervals. The surface usually had a speckled light gray appearance between these rings (Figure 40). These rings were located between the 69-cm (27-inch) locations and the plenums; i.e., in relatively low power regions, on the "A" rods, but they were located on the higher power half of rod B50.

Oval-shaped marks were observed on most of the decrudded fuel rods near some of those locations where the subassembly spacer springs had contacted the cladding surface. The most prominent of these were found on rods B50 and B70, shown in Figure 41(a,b). As can be seen, at least some of the marks protruded from the cladding surface, particularly at their perimeters.

Figure 30. Brown Ring and Spots on Rod A11 Between 17.5 cm (6-7/8 in.) and 28.1 cm (11-1/16 in.) from Short End Plug

Figure 31. White Film on Bottom of Rods B51, B52, and Adjacent Corner Angle

Figure 32. Fine Longitudinally Oriented Lines on (a) Rod A18

b

c

Figure 32 (Continued). Fine Longitudinally Oriented Lines on (b) Rod A23, (c) Rod A43

d

e

Figure 32 (Continued). Fine Longitudinally Oriented Lines on (d) Rod A15 and (e) Rod B95

a

b

Figure 33. Pitlike Surface Penetrations in (a) Rod A1 and (b) Rod A18

a

b

Figure 34. 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 35. Small Blister and Irregular Circumferential Crack at the 69.2 cm (27-1/4 in.) Location of Rod A-1

(a)
90°

(b)
270°

Figure 36. Fuel Rod B76 at 25-cm (10-in.) Location After Chemically Removing Crud

Figure 37. Rough Surface on Rod B50 After Crud Had Been Chemically Removed

Figure 38. Peak Burnup Region of Rod A37 After Crud Removal

Figure 39. Surface Appearance of Rod A37—84 to 87 cm (33 to 34 in.) from Short End Plug Shoulder

Figure 40. Smooth Rings at Pellet—Length Intervals on Rod A7

(a) ROD B70

(b) ROD B50

Figure 41. Subassembly Spacer Markings at (a) 36-cm (14-in.) Location of Fuel Rod B70 and at (b) 67.9-cm (26-3/4-in.) Location of Fuel Rod B50

A few of the rods showed localized increases in surface roughness near those points where the VBWR spacers contacted the rods (Figure 42a). The surfaces of two other rods (A49 and B50) were fairly smooth near the VBWR spacer locations, but they contained fine cracks around the wire-rod contact points. It appeared that the corrosion layer was unusually thick over areas that extended ~ 1 cm or $1/2$ in. on either side of these contact points (Figure 42b).

Most of the rods had linear markings, primarily of longitudinal orientation, on their decrudded surfaces. They varied in length from 0.2 to 0.3 cm ($\sim 1/8$ in.) to 10 to 20 cm (~ 4 to 8 in.). Most, if not all, of these markings appeared to be scratches that resulted from either fabrication or post-irradiation handling. Examples of this type of marking are shown in Figure 43.

The depth of an ~ 0.05 cm by 0.025 cm (~ 0.02 by 0.01 in.) oval-shaped pit in rod A9 was determined after crud removal to be 0.010 to 0.012 cm (0.004 to 0.005 in.) deep. The pit was located 71.4 cm (28-1/8 in.) from the short end plug shoulder (Figure 44).

Again, some of the previously mentioned surface characteristics noted in the visual examinations, such as roughness and spacer markings, were subsequently investigated by other techniques and will be discussed further in some of the following sections.

5.1.2 Neutron Radiography of Fuel Rods (G. P. Ferguson, J. J. Haskins)

5.1.2.1 Procedure and Scope

Fuel rods selected to be examined by neutron radiography were mounted vertically in an aluminum holder and transferred by cask from the hot cells to the neutron radiographic facility at the Nuclear Test Reactor (NTR).

The NTR facility utilizes horizontal neutron beams obtained from the physical center of the NTR's annular core. One beam is allowed to leave the reactor building via a shuttered, conical hole in the 1-1/2-meter (5-foot) thick north wall. On the outside of this wall a large stationary concrete receiving cask has been constructed. A hole in one side is in alignment with the beam hole in the reactor wall and allows the neutron beam to enter a central cavity in the cask. The central cavity is open at the top of the cask where a lead and steel transfer cask can be positioned to discharge radioactive objects down into the neutron beam. A stepped plug, mounted on wheels, penetrates the receiving cask on the opposite side of the cask from the beam entrance. Neutron radiographic transfer plates up to 13 X 38 cm (5 X 15 in.) are positioned on the inside face of the plug and are changed only when the beam shutter is closed and the radioactive object is withdrawn into the transfer cask.⁴

Dysprosium transfer plates were used to produce neutrographs of the SA-1 rods. The neutron exposure time was 60 minutes. Three separate exposures were required to cover the full length of the rods. After irradiation the transfer plates were placed in contact with x-ray film for approximately 16 hours. Positive prints were then made from the exposed film. A variation in contrast was obtained by using two different developing times in the printing process.

One of the principal values of neutron radiography in the examination of irradiated fuel is the ability to detect regions of high hydride concentration in the cladding, which may be indicative of a defective fuel rod. These regions show up as dark areas on positive prints produced from the exposed film.

Neutron radiographs were taken of six of the ten rods that were removed from the assembly at the end of reactor Cycle No. 4* and of six rods that operated to the end of Cycle No. 6. The first six were selected at random, since no significant anomalies were observed during the visual examinations of the initial group of rods. Possible cracks, small pit-like penetrations, small blisters, or discolored areas were noted during visual examination of the external surfaces of the latter six rods [rods A1 (Figures 33 and 35), A9 (Figure 44), A11 (Figure 30), A18 (Figures 32 and 33), A43 (Figure 32), and B52 (Figure 34)].

5.1.2.2 Results

Nothing that appeared significant was detected on the neutrographs in those regions that were believed to be possibly defective on the basis of visual examinations. The neutrograph of rod A9, however, did show an ~ 0.1 -cm-(0.04-in.)-long, rather faint dark gray spot on the tube wall 29.8 cm (11-3/4-in.) from the short end plug shoulder, which suggested that the concentration of hydrogen might be somewhat higher than normal at that location (Figure 45).

Gaps in the fuel columns as large as 0.1 to 0.3 cm were noted in five or six instances in each group of six rods (Figure 46). Approximately 5 percent of the pellets in each group were fractured or showed marked cracking. However, whereas the pellet cracking detected during the initial phase occurred quite at random, 50 percent of the cracked pellets in the later rods were located within 10 cm (4 in.) of the short end plug shoulder and 85 percent were located within 40 cm (16 in.) of it.

*A13, A28, A41, B70, B76, and B97.

(a) ROD B70

(b) ROD B50

Figure 42. VBWR Spacer Regions After Crud Removal on (a) Rod B70 and (b) Rod B50

Figure 43. Fine, Linear Penetrations in Surface of Rod B50

Figure 44. Pit in Surface of Fuel Rod A9—71.4 cm (28-1/8 in.) from Short End Plug Shoulder

Figure 45. Neutron Radiographs of Short End Plug Portions of Rods A43, B52, and A9. Dark Gray Spot on Cladding of Rod A9 Is Indicated.

Figure 46. Neutron Radiographs of Short End Plug Portions of Six SA-1 Rods. Fuel Column Gaps and Pellet Cracking Are Indicated.

5.1.3 Rod Dimensional Measurements (G. P. Ferguson, F. H. Megerth)

5.1.3.1 Diameter

5.1.3.1.1 Procedure and Scope

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

In general, each set of diameter measurements made on a rod consisted of three separate scans. 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. The 0-degree orientation was defined in the preceding section on visual examinations. All scans were made from the shorter end plugs to the longer end plugs of the rods.

Ten rods were scanned in the "as-received" condition during each of the two phases of the examination program, and six rods in each group were rescanned after the crud had been chemically removed from them. The rods selected for diameter measurements are listed in Table 5. Most of these rods had comparatively high combinations of exposure and fuel density, and thus would tend to demonstrate relatively high degrees of fission product-induced UO_2 swelling. Prior to any irradiation, the diameter of each rod was measured to the nearest ~ 0.001 cm (0.0005 in.) with a micrometer at the top, middle, and bottom; the exact locations of these measurements are not known. Diameter profiles were obtained on rods A11, A38, A40, and A43, which operated through Dresden Reactor Cycle No. 6, primarily to further investigate certain areas that were believed to be possibly defective.

5.1.3.1.2 Results

The general thickness of crud was determined on those rods, in both phases of the examination program, that were scanned before and after decrudding. The thickness determinations made in this manner are believed to be generally valid; however, it must be pointed out that some crud was removed from some areas of the rods during handling and shipping. Essentially, all of the crud measured at the end of Cycles No. 4 and No. 6 was deposited during Dresden operation, since most of the crud that was deposited during VBWR operation was wiped off. The six rods that operated in Dresden 840 days to the end of Cycle No. 4 showed an average crud thickness of about 0.0009 cm (0.00035 in.). The maximum thickness averaged over the length of any of these rods was 0.0012 cm (0.0005 in.). The diameter profiles of the six decrudded rods that operated in Dresden 1468 days to the end of Cycle No. 6 are shown in Figures 47 through 52.

As Table 6 indicates, the rod average thicknesses ranged from 0.00084 cm (0.00033 in.) for rod A37 to 0.00173 cm (0.00068 in.) for rod B50. The mean crud thickness for this group was 0.00122 cm (0.00048 in.). Rod A7 showed a local maximum crud thickness of 0.0028 cm (0.0011 in.), which was the highest value among all rods. The thickest crud on most rods in each group was located between the short end plug and mid length; i.e., on the higher power half of the rod.

As Table 7 indicates, all decrudded rods showed some diameter increase with respect to the pre-irradiation measurements. The rod-average increases ranged from 0.001 cm (0.0005 in.) to 0.004 cm (0.0015 in.). Interestingly, the overall average increase of the group of rods removed at the end of Cycle No. 4 was as large as that of the group removed at the end of Cycle No. 6—0.003 cm (0.001 in.), and the maximum rod-average increase was the same for both groups—0.004 cm (0.0015 in.).

If one considers full thirds of the rod length over the fuel column, most rods in the latter group showed the greatest average diameter increase over the section that includes the long end plug and plenum and which operated at a power somewhat below the average for a given rod. The lowest diameter increases took place over the middle thirds of the rods with the exception of rod A22. The earlier rods showed more variation with respect to the locations of greatest and least diameter increase.

It is of some interest to compare the preceding data with diameter measurements made on two Zircaloy-2-clad fuel rods, of the same type as those incorporated in Assembly SA-1, after they had operated 364 days in the VBWR to rod-average burnups of 2.24×10^{20} fissions/cm³ (8190 MWd/tU) and 2.85×10^{20} fissions/cm³ (10,430 MWd/tU). The measurements were made with a micrometer at several points along the length. The lower burnup rod, which was

Table 5
RODS SELECTED FOR DIAMETER PROFILE MEASUREMENTS

Rod Number	Tubing Lot	Burnup (Fissions/cm ³ × 10 ⁻²⁰ [MWd/tU])		As-Fabricated Fuel Density (Percent of Theoretical)	
		Rod-Average	Peak	Smeared*	Pellet**
					Average-Range
Initial Phase					
A4	CA-5	5.5 (20,200)	6.5 (23,800)	91.6	95.1 (94.1 - 96.0)
A13	CA-2	7.0 (25,600)	8.1 (29,700)	91.5	94.4 (92.7 - 95.2)
A28	CA-2	5.8 (21,200)	6.6 (24,000)	92.9	96.0 (95.5 - 96.6)
A41	CA-4	6.6 (24,000)	7.8 (28,500)	91.2	94.8 (94.3 - 95.3)
A45	CA-2	6.0 (21,800)	6.9 (25,300)	92.9	96.0 (95.5 - 96.6)
A46	CA-2	6.0 (22,000)	6.9 (25,300)	92.7	96.0 (95.5 - 96.6)
B70	CA-5	5.5 (20,200)	6.9 (25,300)	91.6	95.1 (94.1 - 96.0)
B76	CA-2	6.1 (22,400)	8.0 (29,100)	91.2	94.4 (92.7 - 95.2)
B88	CA-2	6.1 (22,400)	7.7 (28,000)	91.2	95.0 (94.5 - 95.5)
B97	CA-2	6.1 (22,200)	7.3 (26,600)	91.6	95.3 (94.4 - 96.2)
Final Phase					
A7	CA-5	9.0 (32,900)	10.0 (36,500)	91.6	95.7 (95.0 - 96.4)
A9	CA-2	8.8 (32,200)	9.6 (35,100)	91.6	94.7 (94.2 - 95.3)
A11	CA-4	9.1 (33,300)	10.0 (36,600)	90.7	94.0 (92.7 - 95.2)
A22	CA-5	8.2 (29,800)	8.9 (32,500)	91.3	95.1 (94.1 - 96.0)
A37	CA-1	9.3 (33,900)	10.2 (37,300)	90.8	94.1 (92.3 - 95.3)
A38	CA-3	8.2 (29,800)	8.8 (32,200)	92.1	95.2 (94.0 - 96.6)
A40	CA-3	8.5 (31,000)	9.2 (33,800)	92.1	95.2 (94.0 - 96.6)
A43	CA-5	8.3 (30,200)	8.8 (32,000)	91.4	95.7 (95.0 - 96.4)
A49	CA-2	8.5 (31,100)	9.2 (33,600)	91.5	95.3 (94.4 - 96.2)
B50	CA-2	8.4 (30,800)	9.5 (34,800)	92.7	96.0 (95.5 - 96.6)

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

**Water immersion density on sampling of approximately 2 percent.

Listed below are the average and median pre-irradiation inside diameters of tubing from the various lots, based on measurements made on samples from these lots. The measurements were within a range of 0.965 to 0.968 cm (0.380 to 0.381 in.).

Tubing Lot	Inside Diameter (cm [in.])	
	Median	Average
CA-1	0.9671 (0.38075)	0.9671 (0.38075)
CA-2	0.9665 (0.3805)	0.9662 (0.3804)
CA-3	0.9658 (0.38025)	0.9660 (0.3803)
CA-4	0.9665 (0.3805)	0.9667 (0.3806)
CA-5	0.9665 (0.3805)	0.9665 (0.3805)

The nominal pre-irradiation pellet diameter was 0.955 ± 0.000 cm (0.376 ± 0.000 in.). The diameter of each pellet in rods B70 and A22 was measured before it was loaded into the tube.

In rod B70, one pellet was 0.947 cm (0.373 in.), 44 pellets were 0.950 cm (0.374 in.), and 17 pellets were 0.952 cm (0.375 in.) in diameter. In rod A22, 4 pellets were 0.945 cm (0.372 in.) to 0.947 cm, 39 were 0.950 cm, and 18 were 0.952 cm (Reference 2).

Table 6
CRUD THICKNESS BY PROFILOMETRY
(Rods That Operated in Dresden through the End of Cycle No. 6)

Rod Number	Circumferential-Average Crud Thickness (cm [in.])		Location(s) of Thickest Crud (cm [in.] from Short End Plug)	Remarks
	Rod-Average	Maximum*		
A7	0.00140 (0.00055)	0.0028 (0.0011)	41 to 51 (16 to 20) 23 to 30 (9 to 12)	Only 0.0008 to 0.001 cm (0.0003 to 0.0004 in.) over most of that part of rod between mid-length and long end plug.
A9	0.00099 (0.00039)	0.0020 (0.0008)	13 to 20 (5 to 8)	Decreases toward long end plug. Only 0.0005 to 0.0008 cm (0.0002 to 0.0003 in.) over most of that part of rod between mid-length and long plug.
A22	0.00127 (0.00050)	0.0018 (0.0007)	58 to 76 (23 to 30)	Fairly uniform thickness over full length with most values between 0.0010 and 0.0015 cm (0.0004 and 0.0006 in.); however, crud is slightly thicker at indicated location than elsewhere on rod.
A37	0.00084 (0.00033)	0.00165 (0.00065)	8 to 18 (3 to 7)	Gradually decreases to 0.00025 to 0.0005 cm (0.0001 to 0.0002 in.) toward long end plug.
A49	0.00112 (0.00044)	0.0020 (0.0008)	—	Ranges from about 0.0013 to 0.0020 cm (0.0005 to 0.0008 in.) in fairly random manner between short plug and mid-length. Drops off to about 0.0005 cm (0.0002 in.) over rest of rod.
B50	0.00173 (0.00068)	0.0024 (0.00095)	10 to 23 (4 to 9)	Tends to decrease somewhat toward long end plug, but thickness is still 0.00165 to 0.0019 cm (0.00065 to 0.00075 in.) in some places near long plug.

* Largest mean value for any 2.5 cm (1 in.) increment along rod.

Table 7
ROD DIAMETER AFTER DECRUDDING

Rod Number	Distance from Short End Plug Shoulder (cm [in.])	Rod Diameter (cm [in.])		
		Post-Irradiation (Average)	Pre-Irradiation	Change
		Initial Phase		
A4	0.95 - 30.5 (0.375 - 12)	1.0765 (0.4238)	1.072 (0.422)	+0.005 (0.002)
	30.5 - 63.5 (12 - 25)	1.0744 (0.4230)	1.072 (0.422)	+0.003 (0.001)
	63.5 - 94.0 (25 - 37)	1.0747 (0.4231)	1.074 (0.423)	0.000 (0.000)
	Average			+0.003 (0.001)
A13	0.95 - 30.5 (0.375 - 12)	1.0838 (0.4267)	1.081 (0.4255)	+0.003 (0.001)
	30.5 - 63.5 (12 - 25)	1.0838 (0.4267)	1.082 (0.426)	+0.001 (0.0005)
	63.5 - 94.0 (25 - 37)	1.0843 (0.4269)	1.082 (0.426)	+0.003 (0.001)
	Average			+0.003 (0.001)
A28	0.95 - 30.5 (0.375 - 12)	1.0866 (0.4278)	1.081 (0.4255)	+0.006 (0.0025)
	30.5 - 63.5 (12 - 25)	1.0846 (0.4270)	1.082 (0.426)	+0.003 (0.001)
	63.5 - 94.0 (25 - 37)	1.0856 (0.4274)	1.082 (0.426)	+0.004 (0.0015)
	Average			+0.004 (0.0015)
A41	0.95 - 30.5 (0.375 - 12)	1.0785 (0.4246)	1.078 (0.4245)	0.000 (0.000)
	30.5 - 63.5 (12 - 25)	1.0772 (0.4241)	1.076 (0.4235)	+0.001 (0.0005)
	63.5 - 94.0 (25 - 37)	1.0775 (0.4242)	1.076 (0.4235)	+0.001 (0.0005)
	Average			+0.001 (0.0005)
B70	0.95 - 30.5 (0.375 - 12)	1.0798 (0.4251)	1.080 (0.425)	0.000 (0.000)
	30.5 - 63.5 (12 - 25)	1.0790 (0.4248)	1.078 (0.4245)	+0.001 (0.0005)
	63.5 - 94.0 (25 - 37)	1.0805 (0.4254)	1.074 (0.423)	+0.006 (0.0025)
	Average			+0.003 (0.001)
B76	0.95 - 30.5 (0.375 - 12)	1.0848 (0.4271)	1.082 (0.426)	+0.003 (0.001)
	30.5 - 63.5 (12 - 25)	1.0841 (0.4268)	1.080 (0.425)	+0.005 (0.002)
	63.5 - 94.0 (25 - 37)	1.0841 (0.4268)	1.080 (0.425)	+0.005 (0.002)
	Average			+0.004 (0.0015)
Final Phase				
A7	0.95 - 30.5 (0.375 - 12)	1.0752 (0.4233)	1.073 (0.4225)	+0.003 (0.001)
	30.5 - 63.5 (12 - 25)	1.0726 (0.4223)	1.072 (0.422)	+0.001 (0.0005)
	63.5 - 94.0 (25 - 37)	1.0744 (0.4230)	1.071 (0.4215)	+0.004 (0.0015)
	Average			+0.003 (0.001)
A9	0.95 - 30.5 (0.375 - 12)	1.0825 (0.4262)	1.080 (0.425)	+0.003 (0.001)
	30.5 - 63.5 (12 - 25)	1.0825 (0.4262)	1.082 (0.426)	0.000 (0.000)
	63.5 - 94.0 (25 - 37)	1.0828 (0.4263)	1.080 (0.425)	+0.004 (0.0015)
	Average			+0.003 (0.001)
A22	0.95 - 30.5 (0.375 - 12)	1.0795 (0.4250)	1.077 (0.424)	+0.003 (0.001)
	30.5 - 63.5 (12 - 25)	1.0787 (0.4247)	1.077 (0.424)	+0.001 (0.0005)
	63.5 - 94.0 (25 - 37)	1.0772 (0.4241)	1.077 (0.424)	0.000 (0.000)
	Average			+0.001 (0.0005)
A37	0.95 - 30.5 (0.375 - 12)	1.0792 (0.4249)	1.078 (0.4245)	+0.001 (0.0005)
	30.5 - 63.5 (12 - 25)	1.0795 (0.4250)	1.080 (0.425)	0.000 (0.000)
	63.5 - 94.0 (25 - 37)	1.0790 (0.4248)	1.077 (0.424)	+0.003 (0.001)
	Average			+0.001 (0.0005)
A49	0.95 - 30.5 (0.375 - 12)	1.0828 (0.4263)	1.080 (0.425)	+0.004 (0.0015)
	30.5 - 63.5 (12 - 25)	1.0803 (0.4253)	1.078 (0.4245)	+0.003 (0.001)
	63.5 - 94.0 (25 - 37)	1.0851 (0.4272)	1.080 (0.425)	+0.005 (0.002)
	Average			+0.004 (0.0015)
B50	0.95 - 30.5 (0.375 - 12)	1.0846 (0.4270)	1.080 (0.425)	+0.005 (0.002)
	30.5 - 63.5 (12 - 25)	1.0823 (0.4261)	1.080 (0.425)	+0.003 (0.001)
	63.5 - 94.0 (25 - 37)	1.0851 (0.4272)	1.080 (0.425)	+0.005 (0.002)
	Average			+0.004 (0.0015)

Figure 47. Diameter Profiles of Fuel Rod A7

Figure 49. Diameter Profiles of Fuel Rod A22

Figure 50. Diameter Profiles of Fuel Rod A37

Figure 51. Diameter Profiles of Fuel Rod A49

Figure 52. Diameter Profiles of Fuel Rod B50

clad with lot CA-4 tubing and had smeared and average pellet densities of 90.6 and 94.3 percent of theoretical, showed diameter increases within the range of 0 to 0.001 cm (0.0005 in.). The other rod, which was clad with lot CA-2 tubing and had smeared and average pellet densities of 90.2 and 93.8 percent of theoretical, showed diameter increases that ranged from 0.003 to 0.004 cm (0.001 to 0.0015 in.), i.e., as large as the overall average increase shown by the twelve rods that received additional irradiation in Dresden.³

The difference between the maximum diameter and the minimum diameter at a given point along the rod axis ($\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$) was as large as 0.0075 or 0.010 cm (0.003 or 0.004 in.) at some locations of some SA-1 rods, both among those that were removed after two cycles of Dresden operation and among those that operated four cycles. The general magnitude of this difference varied considerably among different rods (for example, compare rod B50 in Figure 52 with rod A9 in Figure 48). In general, the rods located at inside positions of the subassemblies showed lower values of $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ than the outside rods measured. The portion of a rod where $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ was greatest varied from rod to rod. For instance, this difference was largest over the short-end-plug, high-power half of rod A22 (Figure 49), but on rod A49 $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ was low between ~25 and 40 cm (~10 and 16 in.) from the short end plug, near the peak burnup location, in comparison with almost any other location. The "A" rods measured in the initial phase of the program did tend to show their largest $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ values either toward the short end plug or near the mid-length. Two of the "B" rods in this group showed the largest values of $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ near the short end plug, but with the other two the magnitude of this difference was greatest near the long end plug.

Chemical removal of the crud generally did not markedly change the amount of or the pattern of this "apparent ovality." However, some portions of rods B50 and A22 between the plenum region and mid-length showed decreases in $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$, up to approximately 0.0025 cm (0.001 in.) on the former rod and about 0.0012 cm (0.0005 in.) on the latter, and in other cases decruding resulted in increases in $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ up to nearly 0.0025 cm over portions of rod A7.

In addition to the general increase in diameter that occurred during operation, local peaks in rod diameter often were present near spacer locations. The SA-1 subassembly spacer springs contacted the rods at approximately 3.8 cm (1-1/2 in.), 35.7 cm (14-1/16 in.), 67.6 cm (26-5/8 in.) and 99.7 cm (39-1/4 in.) from the short end plug shoulder. The VBWR spacer wires were located about 51.4 cm (20-1/4 in.) from the short plug.

All of the rods exhibited local increases in diameter at the 3.8 cm subassembly spacer location and less frequently at the other subassembly spacer locations. These peaks were generally 0.0025 to 0.005 cm (0.001 to 0.002 in.) above the typical rod diameter in the vicinity; however, a few were in the 0.008 to 0.010 cm (0.003 to 0.004 in.) range. Those near the 99.7 cm location were 0.005 to 0.008 cm (0.002 to 0.003 in.), but a force fit between the long end plug and tube may be responsible for at least some of the diameter peaking noted near this location. Chemical removal of the crud from the rods decreased the rod diameter at the spacer peaks in most cases. The 3.8-cm, 35.7-cm, and 67.6-cm locations showed decreases as large as 0.005 to 0.008 cm in about five instances among the twelve decruded rods. Thus, the maximum thickness of crud on some part of a rod might have been as much as 0.008 cm or as little as one-half of this value depending upon the evenness of the crud layer around the rod. The average diameter decrease at these three spacer locations was 0.0018 cm (0.0007 in.) among rods removed at the end of Cycle No. 4 and 0.0030 cm (0.0012 in.) among rods removed at the end of Cycle No. 6. Thus, it appears that on the average the crud was not significantly thicker at spacer locations than elsewhere on the heat transfer surfaces.

Crud removal did not necessarily eliminate a local diameter increase, or even decrease it; some peaks at subassembly spacer locations were relatively more prominent on the profiles that were run after crud removal. Local increases in diameter could still be seen on these profiles at most of the 3.8-cm spacer locations and at some of the other subassembly spacer locations as well. The differences between diameters at the spacer peaks and those of the corresponding adjoining regions on these profiles were as large as 0.005 to 0.008 cm at five spacer locations on rods removed at the end of Cycle No. 4 and at the 3.8-cm location on rod A7 (Figure 47).

All rods showed peaks in their diameter profiles at the VBWR spacer locations. Such peaks were 0.005 to 0.008 cm high on the diameter on most of the rods in each exposure group. Decruding the rods somewhat increased the prominence of the VBWR spacer peak more often than not; hence, the crud was usually thinner at the spacer location than it was on either side of that location.

The stationary, "decruded" diameter profiles of some rods in both groups showed peaks at pellet-length intervals. The profiles of rod A37 show such peaks ~2.2 cm (~7/8 in.) apart between 28 and 38 cm (11 and 15 in.) from the short end plug shoulder and between the 56- and 61-cm (22- and 24-in.) locations (Figure 50). The difference in diameter between these peaks and the corresponding troughs is typically 0.0012 cm (0.0005 in.) to 0.0019 cm (0.00075 in.) and has a maximum value of about 0.0025 cm (0.001 in.). The profiles of rod A22 showed some similar peaks at pellet-length intervals of about 1.5 cm (0.6 in.) between the short end plug and mid-length and also between

the ~69- and 74-cm (27- and 29-in.) locations (Figure 49). The average height of such peaks on this rod are somewhat greater than 0.0012 cm, and the maximum is 0.0019 cm. A few scattered and rather ill-defined peaks are shown by the profiles of rod A9 over the short end plug half of the rod (Figure 48), and a few small peaks are barely discernible within the same region of rod A7 (Figure 47). The length of the pellets in the former rod is ~2.2 cm and in the latter ~ 1.5 cm. The 0 - 180-degree and 90 - 270-degree profiles of rods A49 and B50 are so jagged that it is difficult to tell whether or not there is any particular diameter peaking at pellet-length intervals on these rods. The profiles of rod A41, which was one of the rods removed after two cycles in Dresden, showed peaks at pellet-length intervals between the 8-cm (3-inch) and 36-cm (14-inch) locations and between the 56-cm (22-in.) and 61-cm (24-in.) locations. The magnitude of the peaking was comparable to that shown by rod A37, discussed above. The profiles of most of the other rods in the initial group 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 these rods may have decreased the definition of some peaks.

The rod A49 traces show some sharp and easily discernible troughs at pellet-length intervals, particularly between the 84- and 91-cm (33- and 36-in.) locations (Figure 51). Some of these troughs are as deep as 0.004 to 0.005 cm (~0.0015 to 0.002 in.). Other troughs that are somewhat less well defined can be observed between the 74- and 84-cm (29- and 33-in.) locations and between the 14- and 24-cm (5-1/2- and 9-1/2-in.) locations. The troughs between the 84- and 91-cm locations correspond with the locations of the smooth circumferential rings observed on this rod. This correspondence suggests that the rings may be localized areas of relatively low cladding corrosion. It should be pointed out, however, that no rings were noted on rod A49 at other trough locations, and no well-defined troughs can be detected on the diameter profiles of rods A7, A22, and B50 where rings were observed during the visual examinations.

Rather pronounced local decreases in diameter can be seen on the as-received profile traces of rods A7 and A49 near some of the points of contact with the subassembly corner angle recesses. These recesses were centered at 3.8, 11.7, 19.7, 27.6, 35.8, 43.7, 51.6, 59.5, 67.7, 75.6, 83.5, and 91.4 cm (1-1/2, 4-5/8, 7-3/4, 10-7/8, 14-3/32, 17-3/16, 20-5/16, 23-7/16, 26-21/32, 29-3/4, 32-7/8, and 36 in.) from the short end plug shoulders. The profile traces run after the rods were decrudded presented no evidence of depressions of this sort on rod A7, and only a few of relatively lower prominence could be seen on rod A49.

The diameter profiles of rod A9 appeared quite normal at the location of the pit observed visually (Figure 44) and at the location of the dark gray spot noted on the neutrograph of the rod (Figure 45).

During the visual examinations of rods A40, A43, A38, and A11, areas were noted that were believed to be possibly 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. These rods were not decrudded before profiling.

Rod A40 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 53) 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 54). 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 (see Figure 32c). A 0.6-cm (1/4-in.) X 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 55). The surface appearance suggested that some cladding penetration might have taken place. As mentioned in the preceding section, however, a neutrograph taken of this rod did not show anything indicative of a defect. Rod A38 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 an ~0.3-cm (1/8-in.) diameter discolored area at the 63.5-cm (25-in.) location (Figure 56).

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 (see Figure 30). 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. On the other hand, nothing was observed on the neutrograph of this rod to suggest that it might be defective.

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.

Diameter profiles of rod A11 run with the rod held in the 0- to 180-degree and 90- to 270-degree orientations are shown in Figure 57. 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

Figure 53. Gouge or Possible Crack in Rod A40

*Figure 54. Group of Fine Cracks 92.7 cm (36-1/2 in.)
from Short End Plug Shoulder of Rod A40*

Figure 55. Crack in the Surface of Rod A43 Near Spacer Spring Contact Point 3.8 cm (1-1/2 in.) from Short End Plug

Figure 56. Small Pit or Gouge and Discolored Area Located about 64 cm (25 in.) from Short End Plug of Rod A38

Figure 57. Diameter Profiles of Fuel Rod A11.

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. Although at least some of the surface discolorations observed may have been due to differences in crud deposition associated with variations in diameter, these variations did not appear to be indicative of a defective rod.

The 90 - 270-degree 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 peaks at 35 cm and 52 cm are typical of those frequently seen on other rods at subassembly and VBWR spacer locations. The other two peaks, however, are more unusual. 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.

5.1.3.2 Length

5.1.3.2.1 Procedure and Scope

The distance between the two end plug shoulders (i.e., the overall rod length) was measured on each of the ten rods removed after two cycles of operation in Dresden and on twelve rods that operated four cycles. The lengths of the rods in the initial group were measured to ± 0.04 cm ($\pm 1/64$ in.) with a steel rule. The lengths of those in the second group were measured 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 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.

The fast fluence exposures of the rods in both groups were estimated on the basis of analyses of cladding and fuel samples from rods that operated to the end of Cycle No. 6. These analyses are described in Section 5.1.10.

5.1.3.2.2 Results

The results of the above measurements are given in Table 8. The lengths of the rods that were removed from SA-1 at the end of Cycle No. 4 showed increases over the pre-irradiation lengths of 0.08 to 0.24 cm (1/32 to 3/32 in.). The average increase in length was 0.16 cm (1/16 in.) or 0.16 percent, based on the 100.23-cm (39.462-in.) nominal tube length. The increases in length shown by the rods that operated to the end of Cycle No. 6 ranged from 0.15 to 0.33 cm (0.06 to 0.13 in.) and averaged 0.23 cm (0.09 in.). The estimated rod-average fast fluence exposures ($E > 1$ MeV) were approximately 4×10^{21} nvt for the first group of rods and 5.5×10^{21} to 6×10^{21} nvt for the second. 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. The rods were estimated to have been exposed to fast fluences of about 1×10^{21} and 0.6×10^{21} nvt. The accuracy of the length increase reported for any individual rod is, of course, in doubt because of the uncertainties in the pre-irradiation data.

In addition, a feature of the SA-1 fuel rod design may have had an effect on some of the post-irradiation lengths. The fission gas plenum of each rod contains a stainless steel support tube with a 0.076 cm (0.030 in.) thick wall. With a support tube 4.42 cm (1.74 in.) long, the design length of fuel column (93.98 cm or 37 in.) plus support tube plus interjacent Zircaloy wafer is only 0.41 cm (0.16 in.) less than the design distance between the internal faces of the two end plugs. If the tube is 4.83 cm (1.90 in.) long these two dimensions are equal. 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.

The lengths of the fuel columns were measured during rod fabrication,² and the lengths of the plenum support tubes in most of the rods listed in Table 8 were measured either directly or from neutrographs after irradiation. By applying these lengths to the nominal design dimensions for the plug-to-plug distance, the unirradiated room temperature clearance was calculated for each rod (Table 9). For comparison, the total axial gaps after irradiation were estimated for those rods that had been neutrographed. These total gap values, in general, are probably on the low side since only the relatively larger individual gaps were taken into account. However, in the case of rod B97, the total gap shown by the neutrograph is larger than the calculated gap.

The magnitude of interference was calculated for each rod during operation at its estimated maximum heat flux. The values range from negative quantities (clearances) to nearly 0.5 cm (0.2 in.), which amounts to 0.5 percent of the tube length. The length increases and interference values do not show a clear relationship. For example, three rods that operated to the end of Cycle No. 6 and showed an average increase in length for that group (0.23 cm or 0.09 in.) had

Table 8
POST-IRRADIATION ROD LENGTH

Rod Number	Estimated Fast Fluence Exposure of Cladding ($E > 1$ MeV) nvt X 10^{-21}	Post-Irradiation Length (cm [in.])	Pre-Irradiation Length (cm [in.])	Change (cm [in.])
<u>Initial Phase</u>				
A4	3.5	103.46 (40-47/64)	103.35 (40-11/16) ↓	+0.12 (3/64)
A13	4	103.46 (40-47/64)		+0.12 (3/64)
A28	4	103.43 (40-23/32)		+0.08 (1/32)
A41	4	103.50 (40-3/4)		+0.16 (1/16)
A45	4	103.50 (40-3/4)		+0.16 (1/16)
A46	4	103.50 (40-3/4)		+0.16 (1/16)
B70	4	103.50 (40-3/4)		+0.16 (1/16)
B76	4	103.55 (40-49/64)		+0.20 (5/64)
B88	4	103.58 (40-25/32)		+0.24 (3/32)
B97	4	103.50 (40-3/4)	↓	+0.16 (1/16)
<u>Final Phase</u>				
A1	6	103.49 (40.745)	103.35 (40.688) ↓	+0.15 (0.06)
A7	6	103.54 (40.765)		+0.20 (0.08)
A9	5.5	103.61 (40.790)		+0.25 (0.10)
A11	5.5	103.59 (40.785)		+0.25 (0.10)
A22	5.5	103.52 (40.755)		+0.18 (0.07)
A37	5.5	103.59 (40.785)		+0.25 (0.10)
A40	5.5	103.57 (40.775)		+0.23 (0.09)
A43	5.5	103.61 (40.790)		+0.25 (0.10)
A49	5.5	103.57 (40.775)		+0.23 (0.09)
B50	6	103.50 (40.750)		+0.15 (0.06)
B52	6	103.57 (40.775)		+0.23 (0.09)
B62	6	103.67 (40.815)		↓

Table 9
CALCULATED AXIAL INTERFERENCE IN SA-1 RODS

Rod Number	Calculated Axial Fuel Column Gap, Pre-Irradiation at Room Temperature (cm [in.])	Approximate Axial Fuel Column Gap, Post-Irradiation from Neutrographs (cm [in.])	Interference at Maximum Rod-Average Heat Flux (cm [in.])
A4	(a)		
A13	0.33 (0.13)	0.30 (0.12)	+0.30 (0.12)
A28	0.41 (0.16)	0.10—0.20 (0.04—0.08)	+0.10 (0.04)
A41	0.48 (0.19)	0.41 (0.16)	+0.15 (0.06)
A45	0.33 (0.13)(b)		+0.15 (0.06)
A46	0.33 (0.13)(b)		+0.15 (0.06)
B70	0.25 (0.10)	0.20 (0.08)	+0.23 (0.09)
B76	0.48 (0.19)	0.30 (0.12)	+0.18 (0.07)
B88	0.33 (0.13)(b)		+0.33 (0.13)
B97	0.00 (0.00)	0.20 (0.08)	+0.36 (0.14)(c)
A1	0.64 (0.25)	0.51 (0.20)	-0.20 (0.08)
A7	0.25 (0.10)		+0.23 (0.09)
A9	0.41 (0.16)	0.10—0.20 (0.04—0.08)	+0.25 (0.10)
A11	0.25 (0.10)	0.20 (0.08)	+0.41 (0.16)
A22	(a)		
A37	0.48 (0.19)		+0.15 (0.06)
A40	0.64 (0.25)		-0.15 (0.06)
A43	0.33 (0.13)	0.30 (0.12)	+0.15 (0.06)
A49	0.08 (0.03)		+0.48 (0.19)
B50	0.33 (0.13)		+0.10 (0.04)
B52	0.25 (0.10)	0.10 (0.04)	+0.15 (0.06)
B62	0.25 (0.10)		+0.36 (0.14)

(a) Not determined.

(b) Assumed to have 4.42 cm (1.74 in.) plenum support tube since fuel column was greater than 93.98 cm (37 in.) long.

(c) Value based on axial gap shown by neutrograph.

calculated interferences ranging from -0.15 cm (-0.06 in.) to $+0.48$ cm ($+0.19$ in.). The interference values in Table 9 do not take into account the possible additional effect of UO_2 swelling from fission products, although any contribution to axial interference by an increasing volume of fission products would have been counteracted to some extent by the rather continuous decrease in power at which the rods operated in Dresden.

5.1.3.3 Bow

5.1.3.3.1 Procedure and Scope

The maximum deviation from straightness, or bow, was measured on the ten rods that were removed from SA-1 after two cycles of operation. The measurements were made by supporting the rod at the ends in a horizontal position and determining the largest positive and negative deflections with a dial indicator as the rod was rotated.

5.1.3.3.2 Results

The maximum bow is given for each of the ten rods in Table 10. The measurements range from 0.020 to 0.056 cm (0.008 to 0.022 in.) and have an average value of 0.033 cm (0.013 in.).

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

5.1.4.1 Procedure and Scope

A gas sample was taken from a fuel rod by vacuum sealing a drilling fixture to the rod, drilling a hole into the plenum region, and allowing the released gas to expand into the pre-evacuated gas measurement and sampling system. Total gas volumes in each rod were determined by measuring the gas system equilibrium pressure after the rod puncture with a Zimmerli vacuum gauge, and calculating the gas volume (at STP) from the measured pressure and pre-calibrated vacuum system-sample container volumes.

To measure the internal void volume, the drilled and evacuated rod was back purged with argon to a positive pressure in the rod. The rod was allowed to achieve equilibrium at atmospheric pressure. It was rotated 180 degrees from the original position, and the drilling fixture was resealed to it. The system was again evacuated, and the rod was redrilled. The void volume of the rod was then calculated from the initial rod pressure, i.e., atmospheric, and the volume and equilibrium pressure of the system.

Precision aliquots of the gas samples were analyzed by gamma counting, gas chromatography, and mass spectrometry.

With the counting technique, the 0.52 MeV gamma rays associated with Kr-85 decay were counted, and the Kr-85 concentration in terms of atoms/cm³ was calculated. The total number of Kr-85 atoms collected from a fuel rod was then compared with a calculated value of the total atoms of Kr-85 generated during the fuel's exposure to gain an indication of the total fission gas release percentage.

Total composition was determined by gas chromatography techniques. In analyses carried out during the initial phase of the program, the following combinations of column material and carrier gas were employed to determine the amounts of the various components:

- (1) Helium carrier gas—Molecular Sieve column
O₂/Ar, N₂, CO, CH₄, Kr, and Xe
- (2) Argon carrier gas—Molecular Sieve column
He, H₂ and O₂
- (3) Helium carrier gas—Silica gel column
CO₂, ethane, ethylene, and acetylene

In the final phase of the program, most of the components were determined from scans obtained by temperature programming a 6.1 -m (20 -ft) Porapak QS column from -60°C to $+75^\circ\text{C}$, using helium as carrier gas. A molecular sieve column with argon carrier gas was used to analyze for He and H₂.

The isotopic abundances of Xe and Kr and the ratio of Xe to Xe + Kr, as well as a qualitative analysis of total composition, were determined with a time-of-flight mass spectrometer.

The free gas was collected from five fuel rods that operated to the end of Cycle No. 4 and nine rods that operated to the end of Cycle No. 6. The gas from each of the first five rods and that from selected rods in the second group were analyzed by the different techniques. The void volumes of the first five rods also were determined. Rods A1, A9, A11,

Table 10
ROD BOW

Rod Number	Maximum Deviation from Straightness (cm [in.])	Axial Location of Maximum Deviation (cm [in.] from Short End Plug Shoulder)
A4	0.028 (0.011)	84 (33)
A13	0.025 (0.010)	46 (18)
A28	0.020 (0.008)	84 (33)
A41	0.051 (0.020)	38 (15)
A45	0.033 (0.013)	23-30 (9-12)
A46	0.020 (0.008)	23 (9)
B70	0.056 (0.022)	53 (21)
B76	0.023 (0.009)	53 (21)
B88	0.038 (0.015)	46 (18)
B97	0.041 (0.016)	53-61 (21-24)

A18, A35, and B52 from the second group contained what were believed to be possible defects based on visual examination of their external surfaces, neutron radiographic examination, or irregularities in a diameter profile, and the gas collection operation afforded an additional method of determining whether or not these rods were sound.

5.1.4.2 Results

No difficulties were encountered in maintaining a vacuum on any of the rods, which fact tends to indicate that they contained no full-wall cladding penetrations. The total free gas contents of the different rods ranged from 4.7 to 12.5 cm³ (0.29 to 0.76 in.³), and the void volumes of the five rods on which these measurements were made were between 3.4 and 3.8 cm³ (0.21 and 0.23 in.³).

The compositions of the eight samples analyzed by chromatography, in general, appear fairly normal (Table 11). Some of the rods in the initial group show rather high N₂ and O₂ contents, which may have resulted from leakage of air into the system. The normal compositions of the samples from rods A9 and A11 provide additional evidence that these rods were sound. The compositions of the gas from the five rods removed after two cycles of Dresden operation and from rods A9 and B90 of the second group also were qualitatively determined by mass spectrometric analysis. Additional constituents detected in the earlier samples were Ar in all five samples, CO₂ in samples from rods A41 and B70, and H₂O in all samples except that from rod A13. Analyses for CO₂ were performed by chromatography only on the samples from A13 and A46 in the initial phase of the program. No species were detected in the samples from rods A9 and B90 in addition to those listed in Table 11.

The percentage of fission-generated Kr-85 that was released from the UO₂ matrix to the internal void volume is given for ten rods in Table 11. The values range from 0.06 to 0.93 percent. On the average, there is little difference between the two groups of rods with respect to release percentages. The highest percentage was shown by rod A41 in the lower exposure group. Rods A1, A18, A35, and B52 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, most of these same rods also contained pellets of medium to low density. The pellets in rods A1, A7, A35, A46, B52, and B70 (average density 95.1 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 94.8 percent of theoretical) were ~2.3 cm (0.9 in.) long.

The isotopic compositions of the krypton and xenon released from seven rods and the Xe/(Xe + Kr) ratios, determined by mass spectrometry, are given in Table 12.

Table 11
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)	Rod Void Volume 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	
									Initial Phase											
A13	611	7.0 (25,600)	45.1 (143,000)	132 (418,000)	JO1DD/JO2DD	94.4	7.7 (0.47)	3.8 (0.23)	6.49	32.7	59.9	NA ^(c)	ND	2.59	1.61	ND ^(d)	ND	0.11	ND	0.58
A41	607	6.6 (24,000)	41.9 (133,000)	132 (418,000)	JO1DD	94.8	9.5 (0.58)	3.7 (0.23)	5.59	41.9	49.7	NA	ND	0.88	0.40	ND	ND	NA	ND	0.93
A46	619	6.0 (22,000)	38.8 (123,000)	101 (319,000)	JO5HB	96.0	4.7 (0.29)	3.7 (0.23)	0.69	6.56	92.5	NA	ND	4.24	2.89	ND	ND	0.11	ND	0.06
B70	612	5.5 (20,200)	35.0 (111,000)	111 (351,000)	JO3HB	95.1	4.7 (0.29)	3.7 (0.23)	0.93	6.94	91.6	NA	ND	1.14	0.93	ND	ND	NA	ND	0.08
B76	608	6.1 ^(a) (22,400)	39.1 (124,000)	137 (435,000)	JO1DD/JO2DD	94.4	7.1 (0.43)	3.4 (0.21)	3.93	30.8	63.7	NA	ND	0.97	0.77	ND	ND	NA	ND	0.50
Final Phase																				
A1	611	8.8 ^(a) (32,200)	36.9 (117,000)	90 (284,000)	JO3HB	95.4	5.3 (0.32)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A7	611	9.0 ^(a) (32,900)	38.8 (123,000)	111 (351,000)	JO3HB	95.7	5.5 (0.34)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.10
A9	610	8.8 (32,200)	37.2 (118,000)	137 (435,000)	JO1DD/JO2DD	94.7	7.6 (0.46)	NA	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	9.1 (33,300)	38.2 (121,000)	127 (402,000)	JO1DD	94.0	9.8 (0.60)	NA	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	8.7 ^(a) (31,900)	36.6 (116,000)	125 (396,000)	JO1DD/JO2DD	94.2	8.9 (0.54)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A35	611	7.9 ^(a) (28,800)	33.1 (105,000)	103 (328,000)	JO3HB	95.4	5.3 (0.32)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A37	603	9.3 (33,900)	38.8 (123,000)	132 (418,000)	122360-6/JO1DD	94.1	11.5 (0.70)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.51
B52	621	8.2 ^(a) (29,800)	34.7 (110,000)	86 (272,000)	JO5HB	96.0	5.1 (0.31)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B90	600	9.1 ^(a) (33,200)	37.8 (120,000)	132 (418,000)	122360-6/JO1DD	93.8	12.5 (0.76)	NA	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.
(b) To obtain linear power in kW/ft of rod length, multiply W/cm² by 0.103.
(c) NA = not analyzed.
(d) ND = Below the limits of detection (<0.05%). Furthermore, C₂H₆, C₂H₄, and C₂H₂ were not detected in any of the samples.

Table 12
ISOTOPIC ANALYSIS OF KRYPTON AND XENON BY MASS SPECTROMETRY

Rod	Krypton (Atom Percent)				Xenon (Atom Percent)				Atoms Xe
	83	84	85	86	131	132	134	136	Atoms Kr + Xe
Initial Phase									
A13	9.62 ±0.59	33.26 ±1.08	5.15 ±0.33	51.97 ±0.92	7.43 ±0.10	21.44 ±0.32	29.61 ±0.38	41.53 ±0.31	0.882
A41	9.12 ±0.30	33.48 ±0.70	5.54 ±0.27	51.85 ±0.67	7.37 ±0.13	21.53 ±0.10	29.48 ±0.28	41.62 ±0.32	0.871
A46	12.05 ±0.95	30.46 ±1.18	6.68 ±0.70	50.61 ±1.08	8.80 ±0.42	20.66 ±0.49	28.90 ±0.65	41.63 ±0.67	0.893
B70	11.80 ±1.06	31.63 ±1.58	5.47 ±0.41	51.10 ±1.26	9.01 ±0.22	20.58 ±0.42	28.76 ±0.36	41.64 ±0.36	0.893
B76	10.93 ±0.23	32.00 ±0.74	5.60 ±0.41	51.47 ±0.75	8.18 ±0.12	21.05 ±0.12	29.20 ±0.29	41.57 ±0.18	0.875
Final Phase									
A9	8.16 ±0.26	34.69 ±0.41	4.74 ±0.12	52.41 ±0.47	6.67 ±0.08	22.51 ±0.12	29.14 ±0.16	41.68 ±0.18	0.893
B90	8.80 ±0.24	34.25 ±0.25	4.96 ±0.12	51.99 ±0.42	7.21 ±0.11	22.19 ±0.14	28.91 ±0.14	41.69 ±0.21	0.881

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

5.1.5.1 Procedure and Scope

Sections of the irradiated SA-1 fuel rods were examined during both phases of the examination program. The metallographic procedures used in the final phase examinations were as follows. Fuel rod sections between ~1.3 and ~2.5 cm (~1/2 and ~1 in.) long were obtained from selected locations by transversely cutting the rods with a silicon carbide cut-off wheel. Care was taken to retain both the axial and radial orientations of a specimen with respect to those of the rod from which it came. The specimens were inserted into hollow Bakelite mounts and vacuum potted with epoxy resin to fill the cracks and voids. The mounted specimens were placed in an oven (49°C [120°F] for 24 hours) to cure the resin. A Buehler automet was employed to grind the specimens on 240-grit silicon carbide papers until a full cross section was obtained. The grinding was then continued on 400- and 600-grit papers. Each specimen was macrographed at 5X. The rough polishing was accomplished in two steps by rotating the specimens on nylon cloths charged with 9- and 6-micrometer diamond compounds using a Buehler Whirlimet polisher. The final polishing was accomplished with 0.5-micrometer diamond compound on a short-nap cloth attached to a Syntron vibratory polisher. Kerosene was used to lubricate the specimens during the grinding and polishing operation. The specimens were cleaned ultrasonically in xylene between each grinding and polishing operation.

Longitudinal specimens were prepared by mounting a full cross-section sample and grinding parallel to its axis until the desired surface was attained.

The specimens were examined at magnifications up to 500X. All specimens were examined in the final polished condition. The thicknesses of the deposited crud (if it had not been removed) and of the ZrO_2 on the outside and inside tubing surfaces were measured by means of a filar eyepiece with the specimens in the as-polished condition. In making these measurements on a transverse specimen, the prepared face was divided into octants and an average thickness determined for each octant. Since the external corrosion layers consisted of even films and intermittent thicker patches of oxide, the average thicknesses and proportions of each oxide form were determined for each octant. This allowed the calculation of an overall circumferential-average ZrO_2 thickness for a specimen by taking a weighted average of the two forms for each octant, summing these values, and dividing by eight.

The etched UO_2 microstructures of selected specimens were examined after examining them in the as-polished condition. The fuel was etched by swabbing with a solution of 10 ml HNO_3 - 20 ml H_2O_2 (30%) - 70 ml H_2O for 45 seconds. The cladding microstructure and hydride distribution were examined in all specimens. To accomplish this the cladding was etched by swabbing for about 20 seconds with a fresh solution of 45 ml HNO_3 - 45 ml H_2O_2 (30%) - 4 ml HF and viewing the specimens under polarized and normal lighting. Estimates of hydrogen content were made by comparing the specimens with photographic standards.

Some of the procedures used in the initial phase of the program differed to some extent from those just described. In the initial phase:

- a) The radial orientation of a specimen was not always maintained.
- b) Rough polishing was accomplished in a single step with the 6-micrometer diamond compound.
- c) Water was used as the lubricant during grinding and polishing.
- d) In measuring the external corrosion layer on a specimen, the relative amounts of even film- and patch-type ZrO_2 were not determined for each octant. A statistical method was employed to estimate these proportions for the specimen as a whole.
- e) Some of the UO_2 was examined in a light (3-second) etched condition in addition to the standard (45-second) etched condition.

Specimens from five of the fuel rods removed from Assembly SA-1 at the end of reactor Cycle No. 4 and from thirteen rods that operated to the end of reactor Cycle No. 6 were examined. Most of the specimens were transverse sections selected to determine the general form and extent of cladding corrosion and zirconium hydride precipitation, and the natures of the cladding and UO_2 microstructures. To investigate the condition of the cladding, specimens were obtained from various axial and radial locations in the assembly and, to some extent, from rods clad with tubing from the five different lots. Most specimens were obtained from near the peak burnup locations, which gamma scanning indicated were 25 to 30 cm (10 to 12 in.) from the short end plug shoulders of both the "A" and "B" rods (see Section 5.3). While there was some variation in the burnup of the UO_2 examined, the main emphasis was placed on the relatively higher exposure fuel in each group of rods. The form of the crud was examined, and its thickness was determined over the various sectors of the rod periphery on those specimens on which chemical removal had not previously been carried out.

Some specimens were selected to further investigate special features noted in other portions of the examination. Examples of these are an area of unusual crud spalling, contact areas between spacer springs and fuel rods, a dark spot on a neutrograph, and regions that showed peaks in rod diameter profile traces.

5.1.5.2 Results

5.1.5.2.1 Cladding

Examples of the cladding microstructure are shown in Figures 58 through 61. Typical areas of a transversely-oriented specimen (No. 9957) and of a longitudinally-oriented specimen (No. 9956) from rod A41, which was removed from the assembly after two cycles in Dresden, are shown in the first two figures. There is no marked difference between the two orientations with respect to the distribution and concentration of zirconium hydride platelets. The microstructures of specimens from rods that operated through four cycles appeared very similar to those of the specimens examined during the initial phase of the program. Examples of transverse specimens from the more highly exposed rods are shown in Figures 60 and 61. 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. In general, very few hydride platelets were observed, but those that were present appeared to be uniformly distributed. Cladding samples adjacent to some of the metallography specimens were analyzed for hydrogen by the hot vacuum extraction technique (see Section 5.1.7). The highest H_2 concentrations (129 to 146 ppm) were shown by samples adjacent to specimen No. A594 from rod A-49 (Figure 61).

Figure 62 indicates the type of corrosion that typically occurred on the outside surfaces of the SA-1 cladding, i.e., the formation of a relatively thin and even ZrO_2 film in combination with a pitting attack, represented by the intermittent thicker patches of ZrO_2 . These oxide patches, which vary in concentration, length, and thickness, are thus responsible for the roughness observed over various portions of the rod surfaces during the visual examinations. ZrO_2 thickness measurements made on an octant-by-octant basis on the transverse specimens are given in Table 13. In the case of the initial phase specimens obtained from rods that operated between 1175 and 1218 days in the VBWR and Dresden, the selection of Octant No. 1 was arbitrary. With the later specimens, from rods that operated between 1767 and 1846 total days, 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 (see Figure 16). 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 to those made on transverse specimens, ZrO_2 thickness measurements made on two longitudinally-oriented specimens that were examined during the initial phase are given in Table 14.

Among the initial phase specimens, the even film-type oxide typically showed circumferential-average thicknesses between 10μ (0.0004 and 0.0005 in.). The circumferential-average patch-type oxide thicknesses ranged from 26μ to 54μ (0.0010 and 0.0021 in.) and had a mean value of 40μ (0.0016 in.).

The estimated proportion of rod circumference covered by the patch-type ZrO_2 ranged from 0.1 to 0.7 among the different specimens. Among the final phase specimens, the circumferential-average thickness of the even films typically ranged from 8μ to 35μ (0.0003 to 0.0014 in.) and had a mean value of 15μ (0.0006 in.). That of the patches ranged from 23μ to 110μ (0.0009 to 0.0043 in.) and averaged 64μ (0.0025 in.). The proportion of the rod circumference covered by the patch-type ZrO_2 ranged from <0.1 to 0.5 and had an average value of 0.2. 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 and A625), B83 (A611), and B85 (A592), which operated four cycles in Dresden, and from rod A46 (9956), which operated just two cycles. A portion of such a region on specimen No. 611 is shown in Figure 63(b). The corrosion layer on specimen No. A592 reached an octant-average thickness of 119μ (0.0047 in.).

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. This kind of variation is illustrated in Figures 64 and 65. (However, the specimen chosen as an example is somewhat exceptional in that its overall corrosion was comparatively low.) 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

(a) CLADDING ETCHED
PHOTOGRAPHED UNDER NORMAL LIGHT

250X

(b) CLADDING ETCHED
PHOTOGRAPHED UNDER POLARIZED LIGHT

250X

*Figure 58. Cladding Microstructure of Transversely-Oriented
Specimen No. 9957 from Fuel Rod A41*

(a) CLADDING ETCHED
PHOTOGRAPHED UNDER NORMAL LIGHT

250X

(b) CLADDING ETCHED
PHOTOGRAPHED UNDER POLARIZED LIGHT

250X

Figure 59. Cladding Microstructure of Longitudinally-Oriented Specimen No. 9956 from Fuel Rod A41.

(a)

CLADDING ETCHED

250X

PHOTOGRAPHED UNDER NORMAL LIGHT

(b)

CLADDING ETCHED

250X

PHOTOGRAPHED UNDER POLARIZED LIGHT

Figure 60. Cladding Microstructure of Transversely-Oriented Specimen No. A580 from Rod A37

(a) CLADDING ETCHED
PHOTOGRAPHED UNDER NORMAL LIGHT

250X

(b) CLADDING ETCHED
PHOTOGRAPHED UNDER POLARIZED LIGHT

250X

*Figure 61. Cladding Microstructure of Transversely-Oriented
Specimen No. A594 from Rod A49*

(a)

AS-POLISHED

100X

(b)

AS-POLISHED

500X

Figure 62. Example of Corrosion of Outside Cladding Surface,
(a) Rod B50 (Specimen No. A609), (b) Rod B57 (Specimen A613)

(a)

AS-POLISHED

100X

(b)

AS-POLISHED

100X

Figure 63. ZrO_2 Layer on Outside Cladding Surface of Specimen No. A611 of Rod B83, (a) Octant No. 8, (b) Octant No. 4

(a)
AS-POLISHED

(b)
AS-POLISHED

(c)
AS-POLISHED

Figure 64. External ZrO₂ at Different Locations of Specimen No. 9954 (See Figure 65)

Figure 65. Macrograph of Specimen No. 9954 from Rod A13 (As-Ground—~6X Magnification). Locations of Micrographs and Octants (Listed in Table 13) are Indicated.

Table 13

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

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*		Initial Phase						Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		ZrO ₂ on Outside Surface							
		Even Film Average Thickness (microns)	Patches		Overall				
			Average Thickness (microns)	Relative Amount	Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**			
		Octant							
A13	9954	1	13	55					
a)	27.9 (11)	2	14	35					
b)	126.0 (49-5/8)	3	11	19					
c)	1204	4	10	15					
d)	8.1 (29,700)	5	10	20				Crud	
e)	52 (166,000)	6	10	22				chemically	Not
f)	129 (410,000)	7	11	37				removed	measured
g)	CA-2	8	16	79					
		1 through							
		8	12	35	0.1	14	220		
A41	9957	1	10	16					2
a)	48.3 (19)	2	11	11					4
b)	105.7 (41-5/8)	3	11	14					3
c)	1204	4	10	43				Crud	3
d)	7.2 (26,400)	5	10	41				chemically	3
e)	46 (147,000)	6	9	36				removed	3
f)	117 (370,000)	7	10	26					4
g)	CA-4	8	10	20					3
		1 through							
		8	10	26	0.4	16	250		3

Crud
chemically
removedNot
measuredCrud
chemically
removed

Table 13 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*		Initial Phase						Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		ZrO ₂ or Outside Surface							
		Even Film Average Thickness (microns)	Patches		Overall		Weight Gain (mg/dm ² O ₂)**		
			Average Thickness (microns)	Relative Amount	Average Thickness (microns)				
A46	9958	1	10	27			8	1	
a)	25.1 (9-7'8)	2	10	20			8	1	
b)	128.9 (5C-3/4)	3	11	44			8	2	
c)	1218	4	12	75			9	1	
d)	6.9 (25,300)	5	12	54			6	1	
e)	44 (141,000)	6	14	85			8	1	
f)	91 (290,000)	7	12	76			6	1	
g)	CA-2	8	10	53			7	1	
	1 through								
	8	11	54	0.3	24	370	8	1	
A46	9959	1	9	46			3	1/2 to 1	
a)	92.1 (36-1/4)	2	8	36			3	↓	
b)	61.9 (24-3/8)	3	8	26			3		
c)	1218	4	31	53			3		
d)	4.6 (16,900)	5	64	72			3		
e)	30 (94,000)	6	41	59			2		
f)	54 (170,000)	7	8	42			2		
g)	CA-2	8	7	33			3		
	1 through								
	8	22	46	0.7	39	610	3	<1	

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Table 13 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*		Initial Phase					Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		ZrO ₂ on Outside Surface						
		Even Film Average Thickness (microns)	Patches		Overall			
			Average Thickness (microns)	Relative Amount	Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**		
		Octant						
B70	9960	1	10	50				4
a) 35.6 (14)		2	9	34				3
b) 190.8 (75-1/8)		3	10	49				5
c) 1175		4	10	40			Crud chemically removed	3
d) 6.5 (23,900)		5	10	46				3
e) 42 (132,000)		6	10	45				4
f) 107 (340,000)		7	9	46				3
g) CA-5		8	9	55				3
		1 through 8	10	46	0.1	14	220	4
B97	9962	1	10	31			10	3
a) 23.5 (9-1/4)		2	10	22			11	5
b) 178.8 (70-3/8)		3	10	20			9	1
c) 1218		4	11	24			10	6
d) 7.3 (26,600)		5	11	32			10	4
e) 46 (147,000)		6	11	39			10	3
f) 117 (370,000)		7	10	55			10	2
g) CA-2		8	10	46			11	4
		1 through 8	10	34	0.4	20	310	4
B97	9963	1	13	34			10	2
a) 73.7 (29)		2	18	44			10	3
b) 228.9 (90-1/8)		3	14	54			10	5
c) 1218		4	7	50			10	7
d) 5.1 (18,500)		5	11	59			10	5
e) 32 (102,000)		6	8	56			11	2
f) 57 (180,000)		7	9	59			10	1
g) CA-2		8	10	36			10	1
		1 through 8	11	49	0.6	34	530	3

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Table 13 (Continued)

Final Phase

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant	ZrO ₂ on Outside Surface				Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		Even Film Average Thickness (microns)	Patches Average Thickness (microns)	Relative Amount	Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**	
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) 1832	4	11	63	0.53	39	25	9
d) 9.9 (36,20C)	5	10	34	0.10	12	17	10
e) 41 (31,000)	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	330	9
A15 A590	1(0°)	13	106	1.00	106	18	12μ to 1/2μ spots -to-trace
a) 25.7 (10-1/3)	2	11	68	0.15	20	12	↓
b) 128.3 (50-1/2)	3	11	41	0.02	12	10	8
c) 1767	4	11	36	0.08	13	9	↑
d) 9.1 (33,100)	5	11	40	0.17	16	8	trace with scattered spots
e) 40 (127,000)	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	440	low
A15 A591	1(0°)	8	29	0.05	9	3	4
a) 89.9 (35-3/8)	2	7	29	0.12	10	4	5
b) 64.1 (25-1/4)	3	8	42	0.08	11	4	↑
c) 1767	4	8	30	0.12	11	3	scattered spots
d) 6.8 (24,900)	5	7	39	0.18	13	3	↓
e) 30 (95,000)	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	180	4(0.25)***

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Table 13 (Continued)

			Final Phase						
			ZrO ₂ on Outside Surface					Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Octant		Even Film Average Thickness (microns)	Patches Average Thickness (microns)	Relative Amount	Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**		
A32 A610	1(0°)		11	23	0.02	11		8	7
a) 26.7 (10-1/2)	2		10	24	0.03	10		8	8
b) 127.3 (50-1/8)	3		10	24	0.03	10		8	8
c) 1832	4		10	24	0.05	11		8	7
d) 9.3 (33,900)	5		10	25	0.05	11		9	10
e) 39 (123,000)	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	170	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) 1832	4		10	21	0.05	11			7
d) 10.1 (37,000)	5		8	21	0.05	9			8
e) 42 (134,000)	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	200		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	39		9	7(0.2)
c) 1846	4		12	72	0.40	36		13	8(0.5)
d) 9.1 (33,100)	5		11	58	0.26	23		12	7(0.3)
e) 38 (121,000)	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 13 (Continued)

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*		Octant	Final Phase ZrO ₂ on Outside Surface					Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
			Even Film Average Thickness (microns)	Patches		Overall			
				Average Thickness (microns)	Relative Amount	Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**		
A49	A534	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) 1846		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) 32 (102,000)		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	8	10	105	0.4E	56	870		6(0.4)
									0(0.5)
									7(0.5)
									6
B50	A609	1(0°)	10	61	0.2E	23			
a) 74.9 (29-1/2)		2	11	64	0.51	38			↑ trace to
b) 230.2 (90-5/8)		3	12	69	0.4E	38			6μ spots
c) 1846		4	13	88	0.3E	42			↓
d) 7.4 (27,100)		5	94	89	0.37	92		Crud chemically removed	5(0.6)
e) 31 (99,000)		6	105	—	0.0C	105			7(0.5)
f) 47 (150,000)		7	78(0.1) 14(0.5)	—(0.1) 78(0.9)	0.0C (0.1) 0.37 (0.9)	43			5(0.2)
g) CA-2		8	11	68	0.39	33			
	1 through	8	40	74	0.34	52	810		spotty
									6(0.16)***
B57	A613	1(0°)	12	81	0.3E	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) 1846		4	12	73	0.38	35		18	9μ
d) 8.8 (32,000)		5	12	48	0.22	20		17	8(0.5)
e) 37 (117,000)		6	12	45	0.12	16		17	7(0.6)
f) 82 (260,000)		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)***

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Table 13 (Continued)

Final Phase

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*		Octant	ZrO ₂ on Outside Surface					Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
			Even Film Average Thickness (microns)	Patches		Overall			
				Average Thickness (microns)	Relative Amount	Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**		
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)	1832	4	12	28	0.06	13		16	8
d)	10.2 (37,400)	5	12	20	0.01	12		16	10
e)	43 (136,000)	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	200	16	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(0.8)	0.26(0.8)	37		19	7
			61(0.2)	—(0.2)	0.00(0.2)				
c)	1846	4	99	—	0.00	99		20	8
d)	8.5 (31,100)	5	87	—	0.00	87		20	8
e)	36 (113,000)	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	730	18	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)	1803	4	33	124	0.43	72		20	7
d)	9.0 (33,000)	5	30	98	0.20	44		18	trace-to-spotty
e)	39 (123,000)	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(0.5)	100(0.5)	0.70(0.5)	92		17	7
			108(0.5)	—(0.5)	0.00(0.5)				
	1 through								
	8		49	110	0.34	71	1110	17	7(0.82)***

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Table 13 (Continued)

Final Phase

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*			ZrO ₂ on Outside Surface					Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
			Even Film Average Thickness (microns)	Patches		Overall			
				Average Thickness (microns)	Relative Amount	Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**		
Octant									
B85	A593	1(0°)	21	39	0.36	27		0(0.5) 16(0.5) 18	↑ trace and scattered spots up to 8μ
a)	89.9 (35-3,8)	2	35	73	0.40	50		16	
b)	245.1 (96- /2)	3	44	105	0.40	68		17	
c)	1803	4	37	66	0.37	48		16	
d)	5.7 (20,700)	5	29	48	0.01	29		19(0.1) 0(0.9) 0	
e)	24 (77,000)	6	19	45	0.05	20		0(0.5) 15(0.5)	
f)	38 (120,000)	7	17	—	0.00	17			↓
g)	CA-5	8	21	58	0.03	22			
		1 through 8	26	70	0.20	35	550	17(0.64)***	low

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Table 13 (Continued)
Final Phase

Rod Designation Specimen Number Location, Operation, and Tubing Lot Number*	Octant	ZrO ₂ on Outside Surface				Crud Average Thickness (microns)	ZrO ₂ on Inside Surface Average Thickness (microns)
		Even Film Average Thickness (microns)	Patches Average Thickness (microns)	Relative Amount	Overall Average Thickness (microns)	Weight Gain (mg/dm ² O ₂)**	
A9 A626	1(0°)	8	23	0.11	10		8
a) 29.4 (11-9/16)	2	8	15	0.04	8		9
b) 124.6 (49-1/16)	3	10	19	0.06	11		9
c) 1832	4	9	15	0.06	9		9
d) 9.6 (35,100)	5	10	26	0.09	11	Crud chemically removed	8
e) 41 (129,000)	6	10	25	0.16	12		9
f) 140 (440,000)	7	11	49	0.34	24		8
g) CA-2	8	10	35	0.20	15		9
	1 through 8	9	33	0.13	12		9
B50 A625	1(0°)	16	84	0.44	46		
a) 68.3 (26-7/8)	2	13(0.8)	83 (0.8)	0.50(0.8)	58		
		97(0.2)	— (0.2)	0.00 (0.2)			
b) 223.5 (88)	3	89	—	0.00	89	crud chemically removed	
c) 1846	4	16	83	0.60	56		
d) 7.4 (27,200)	5	16	98	0.66	70		
e) 32 (100,000)	6	14	87	0.30	36		
f) 50 (160,000)	7	14	73	0.37	36		
g) CA-2	8	14	75	0.27	30		
	1 through 8	33	85	0.38	53		
						830	
B56 A624	1(0°)	29	61	0.40	42	34	10
a) 36.5 (14-3/8)	2	41	73	0.35	52	29	10
b) 191.8 (75-1/2)	3	30	56	0.29	38	29	8
c) 1846	4	26	66	0.46	44	31	8
d) 9.4 (34,300)	5	22	56	0.33	33	34	8
e) 39 (125,000)	6	34	107	0.35	60	22	9
f) 117 (370,000)	7	46	81	0.13	51	21	9
g) CA-2	8	43	141	0.20	63	20	9
	1 through 8	35	76	0.31	48	750	9
						28	

*[a] Distance from prepared surface 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 VBWR 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.

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Table 14

**THICKNESS OF ZrO_2 ON THE CLADDING
OF LONGITUDINAL METALLOGRAPHY SPECIMENS**

Rod Designation Specimen Number, Location, Operation, and Tubing Lot Number*	Orientation (degrees)	ZrO ₂ on Outside Surface			ZrO ₂ on Inside Surface Average Thickness (microns)
		Even Film Average Thickness (microns)	Patches	Estimated Overall Weight Gain (mg/dm ² O ₂)**	
A41 9955	90	10	17		4
a) 21.6--25.1 (8-1/2--9-7/8)	270	11	43		6
b) 128.9--132.4 (50-3/4--52-1/8)				210	
c) 1204					
d) 7.7 (28,300)					
e) 50 (157,000)					
f) 123 (390,000)					
g) CA-4					
B70 9961	90	21	65		4
a) 50.8--54.3 (20--21-3/8)	270	15	57		~1-1/2
b) 206.1--209.6 (81-1/8--82-1/2)				330	
c) 1175					
d) 6.0 (22,100)					
e) 38 (121,000)					
f) 98 (310,000)					
g) CA-5					

*(a) Distance from prepared surface 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 [$11-5/16 \pm 1-3/4$ in.] below the top of the reactor active fuel zone.)

(c) Total days of operation (hours VBWR thermal power greater than 5 MW $\div$ 24 + hours of Dresden turbine-generator operation $\div$ 24).

(d) Specimen burnup (fissions/cm³ $\times 10^{-20}$ [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 = $15.6 \times ZrO_2$ thickness in microns.

11 μ 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 ZrO₂ 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 from the direction of the rod vacancy water gap.

The corrosion weight gains, determined by multiplying the overall circumferential-average ZrO₂ thicknesses by 15.6 ranged from 210 to 610 mg/dm² and averaged 340 mg/dm² among initial phase specimens. The weight gains shown by the final phase specimens ranged from 170 to 1110 mg/dm² and had an average value of 510 mg/dm². The weight gain values presented in Table 13 give full weight to all octants of every transverse specimen and thus include those regions which might be considered abnormally corroded.

The post-transition corrosion weight gain of the SA-1 cladding is shown as a function of exposure time in Figure 66. The 365-day data were obtained from like fuel rods irradiated in the VBWR under the AEC Fuel Cycle Program. The average weight gain for these specimens was 125 mg/dm² (Ref. 3). In some cases among those rods that operated in Assembly SA-1, two specimens were prepared from a single rod. In such cases, the average weight gain of the two was plotted as a single value.

Where two specimens were taken from a fuel rod that operated four cycles in Dresden (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. Measurements made on specimens from rods A46 and B97 during the initial phase also indicate that the "corrosion profile" for a given rod does not necessarily correspond to the burnup profile. 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 exceptions of rods B83 and B70, 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 62(b) and 63. The circumferential-average crud thickness measured on metallography specimens from rods that operated in Dresden 840 days ranged from 3 to 10 μ (0.0004 in.) and had a mean value of 9 μ (0.00035 in.). The crud thicknesses measured on specimens from rods that operated in Dresden 1468 days ranged from 4 to 28 μ (0.0002 to 0.0011 in.) and had a mean value of 14 μ . The lowest deposition was measured on specimens 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 lengths of time. It may be recalled that the rod-average crud thicknesses measured by profilometry in the initial phase of the program showed mean and maximum values of 9 μ and 12 μ , while the corresponding values for measurements made in the final phase were 12 μ and 17 μ . The maximum circumferential-average thickness measured with the profilometer at any axial location of any rod that operated to the end of Cycle No. 6 was 28 μ (rod A7), i.e., the same as the maximum measured on any metallography specimen.

Like the corrosion layers, the thickness of the crud deposit also varied considerably about the periphery of some specimens in the final phase group. In such cases, the crud was generally thickest, or at least thicker than average, in the orientation of heaviest corrosion. However, specimen A624 (rod B56) and A592 (rod B85) represent exceptions to this relationship. The crud on these specimens was thinnest over the octants of maximum overall corrosion; however, on the latter specimen it was thickest over the octant with the greatest average *patch-type* ZrO₂ thickness. In other instances, the variation in crud thickness was rather small compared to that in ZrO₂ thickness (e.g., specimen A611 [rod B83])

*Between Cycle Nos. 4 and 5, rod A11 was moved to its final assembly position from the adjacent rod vacancy position (see Figure 16). Its orientation during Cycle Nos. 3 and 4 is unknown. The other final phase rods listed in Table 13 were not removed from their original subassembly locations until their examination at Vallecitos Nuclear Center (VNC).

Figure 66. Oxide Weight Gain for SA-1 Cladding as a Function of Fuel Rod Operating Time

and all of the specimens on which crud measurements were made in the initial phase. The crud on rod B56 had spalled down to a continuous white ZrO_2 surface at several locations (see Figure 26). A portion of the crud and ZrO_2 layers are shown in cross-sectional view in Figure 67. The average thickness of crud on this specimen was 28μ (0.0011 in.); i.e., the maximum measured on any specimen and approximately twice the average thickness measured on the final phase specimens taken as a group. The weight gain shown by specimen No. A624 was 230 mg/dm^2 greater than the average for all 16 specimens, but it was still lower than the weight gains shown by 4 of these specimens.

The reason(s) for the wide variation in corrosion behavior shown by the external surfaces of the specimens is not clear. For each group of specimens, 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.²

During the visual examinations of the fuel rods, markings frequently were noted near points of contact with the SA-1 subassembly spacer springs. Some of the most prominent markings of this type, at least on decruded rods, were observed at 36 cm (14 in.) from the short end plug of rod B70, which was one of those removed from SA-1 after two cycles of operation (see Figure 41). B70 was located in an outside non-corner position in Assembly SA-1; it was in contact at each spacer with three springs and the peripheral spacer band at 90-degree intervals. The band contacted the rod near the top and bottom edges of the 2.5-cm (1-in.) high spacer; spring contact was at the midpoint. The rod was sectioned transversely and ground so that the plane through the center of the spacer spring marks could be examined. These marks can be seen on the macrograph of Figure 68 as regions of increased cladding corrosion. One of these regions showed a layer of ZrO_2 0.14 cm (0.055 in.) across and 70 to 100μ (~ 0.003 to 0.004 in.) thick (Figure 69). In general, as Table 13 indicates, the external ZrO_2 around the circumference of specimen No. 9960 took the form of a 10μ film, with intermittent patches 40 to 50μ (0.0015 to 0.002 in.) thick.

The most prominent spring contact area markings among decruded rods that operated four cycles in Dresden were shown by corner rod B50. In general, the external corrosion layer around specimen No. A625 consisted of an $\sim 15\mu$ -thick film with numerous intermittent oxide patches 60 to 90μ thick. A relative increase in corrosion was noted in the vicinity of the prominent contact area in octant 3 and part of octant 2 (see Table 13). In this region the external ZrO_2 layer was continuous and 90 to 100μ (0.0035 to 0.004 in.) thick. The prepared surface of specimen No. A625 included a second spring-rod contact area 90 degrees from the one just discussed. This second region showed some enhancement of corrosion, but not to the degree shown by the first contact area. Thus, although rod B50 operated 1468 days in Assembly SA-1, compared with 840 days for rod B70, the corrosion shown by rod B50 in the spring contact region was not much greater than that shown by rod B70. No evidence of mechanical wear of the cladding was detected in either of these spring contact regions.

Like most of the other SA-1 fuel rods, rod B70 did show evidence of cladding wear near midlength, which was caused during VBWR operation by contact with the wire-type spacers (see Figure 42(a)). All of the rods that were scanned for diameter profiles exhibited local diameter peaking at the VBWR spacer locations. In the case of B70, this increase in diameter was 0.009 cm (0.0035 in.). A pronounced localized increase in surface roughness occurred in the vicinity of the VBWR spacer location (see Figure 42(a)). A longitudinal section that passed through a wear groove in the cladding of rod B70 was examined metallographically. The 0.005- to 0.008-cm (0.002 - to 0.003 -in.)-deep groove is shown in Figure 70 (where it is barely discernible) and in Figure 71. A buildup of ZrO_2 50 to 100μ (0.002 to 0.004 in.) thick was observed within the groove and for a distance of about 0.3 cm ($1/8$ in.) on either side of it ("a" in Figure 70). Elsewhere on the "groove side" of specimen No. 9961, the external oxide consisted of an even ~ 9 -micron film with a few intermittent patches 14 to 75 microns (0.0006 to 0.003 in.) thick. On the opposite (270-degree) side of the specimen, the external ZrO_2 generally consisted of an ~ 10 -micron film with intermittent patches 28 to 103 microns (~ 0.001 to 0.004 in.) thick distributed over the entire length. Over that portion designated "d" in Figure 70, however, a fairly continuous layer of oxide that built up to a maximum thickness of 75 microns (0.003 in.) was noted. A part of region "d" is shown at a higher magnification in Figure 72. This particular region may have been close to another spacer wire contact point, although no evidence of wear was observed in the plane examined. The gap

between the two pellets of specimen No. 9961 probably did not exist during the irradiation of rod B70, but was formed during specimen preparation. The neutron radiograph taken of the rod did not show such a gap at this location.

As was mentioned earlier, the stationary, "decrudded" diameter profiles of some rods showed peaks at pellet-length intervals during both the initial and final phases of the examination program. In an attempt to learn more about the mechanism(s) responsible for diameter increases of this type, a longitudinal specimen was taken from rod A41 at the location indicated in Figure 73. A macrograph of the specimen is shown in Figure 74. The distribution of the external ZrO_2 along the two sides of the specimen is shown.

It will be noted that the degree of corrosion is significantly different at different locations on the specimen. The patch-type oxide and, to a lesser degree, the even film-type are thicker on one side (270-degree) than on the other. On both sides, the patch-type ZrO_2 is thicker over the whole pellet portion of the specimen than over the ends. In fact, essentially no pitting corrosion took place over the ends of the 90-degree side. (This observation suggests a possible explanation for the "smooth rings" noted at pellet length intervals on the surfaces of some rods (see Figure 40). The variations in diameter along the specimen that one might expect from differences in ZrO_2 thickness are of about the same magnitude as the variations over the corresponding portion of the profile scan, but the relationship in regard to distribution is not well defined. It is difficult to say whether or not cladding deformation has occurred at locations of local diameter increase.

It was of interest to consider the possible contribution made by the external corrosion layers to diameter increases and to values of $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$. For this purpose the layers of ZrO_2 and crud (when present) on five specimens from initial phase rods (Nos. 9954 [Rod A13], 9957 [Rod A41], 9958 [Rod A46], 9962 and 9963 [rod B97]) and six specimens from final phase rods (Nos. A626 [Rod A9], A582 [Rod A11], A580 [Rod A37], A594 [Rod A49], A609 and A625 [Rod B50]) were compared with the diameter profiles of these rods at the specimen locations. Reactor exposure effected a diameter increase that ranged from 0.0013 to 0.0038 cm (0.0005 to 0.0015 in.) and averaged 0.0025 cm (0.001 in.) among the initial phase specimens and that ranged from less than 0.0013 cm to 0.0076 cm (0.003 in.) and averaged 0.0051 cm (0.002 in.) among the final phase specimens. The values of $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ ranged from 0.0025 to 0.0051 cm for both groups. The average values were approximately 0.0051 cm for the first group and 0.0038 cm for the second.

100X

Figure 67. Portion of Rod B56 Cladding Showing Thick Crud and External ZrO_2 (Specimen No. A624)

- a. HIGH CORROSION REGIONS ARE INDICATED BY ARROWS.
- b. LOCATIONS OF OCTANTS LISTED IN TABLE 13 ARE INDICATED BY NUMBERS ABOUT CIRCUMFERENCE.

Figure 68. Macrograph of Specimen No. 9960 (As-Ground—10X Magnification)

Figure 69. Thick ZrO_2 Layer on Cladding in Spacer Spring Contact Area (Rod B70, Specimen No. 9960)

REGIONS	EXTERNAL ZrO ₂ THICKNESS IN MICRONS	
	CONTINUOUS FILM AVERAGE (RANGE)	INTERMITTENT PATCHES AVERAGE (RANGE)
a	60 (56-66)	84 (75-94)
b	} 9 (4-11)	50 (14-75)
c		NONE
d	46 (19-75)	—
e	10 (8-14) *	57 (28-103)

* DOES NOT INCLUDE REGION d

Figure 70. Macrograph of Specimen No. 9961 (As-Ground~4X Magnification).
External ZrO₂ Thickness in Various Locations is Shown.

Figure 71. Highly Corroded Groove Worn into Cladding of Rod B70 by VBWR Spacer Wire (Specimen No. 9961)

Figure 72. Thick External ZrO₂ Layer in Region d of Specimen No. 9961. (See Figure 70)

Figure 73. Diameter Profile Traces Over-Part of Rod A41 at 0-180-degree and 90-270-degree Orientations. The Location of Metallography Specimen No. 9956 is Indicated.

Figure 74. Macrograph of Specimen No. 9956 (As-Ground—5X Magnification). Thickness of Patch-Type and Even-Film-Type ZrO₂ on External Cladding Surface is Shown in Microns.

Subtracting out the estimated contribution of the ZrO_2 reduced the diameter increases by as much as 0.0038 to 0.0051 cm in some instances. With the effects of the corrosion and crud layers taken into account, the diameter changes with respect to pre-irradiation ranged from 0 to +0.0012 cm (0.0005 in.) for the initial group and from 0 to +0.0038 cm (0.0015 in.) for the second. The rods that operated four cycles in Dresden showed an average increase in diameter of ~ 0.0025 cm (0.001 in.) at the specimen locations. Specimen Nos. A594 and A609 were chosen specifically because of the large diameter increases shown by the A49 and B50 profiles at their respective locations (0.0076 cm or 0.003 in.). After subtracting out the estimated contribution of the ZrO_2 , both specimens showed increases between 0.0025 and 0.0038 cm (0.001 to 0.0015 in.).

The average values of $\text{o.d.}_{\text{max}} - \text{o.d.}_{\text{min}}$ were decreased to ~ 0.0025 cm for both groups of specimens. The range was 0.0013 to 0.0038 cm for the initial group and 0 to 0.0038 cm for the second.

The ZrO_2 films on the internal cladding surfaces were quite even and continuous in some cases (Figures 75 and 77) and were spotty in others (Figure 76). It is possible that portions of some of these films were lost during sample preparation. Where the films were continuous, the average thicknesses ranged from less than 1 to 5μ among specimens from rods that were removed from the assembly at the end of Cycle No. 4 and had a mean value of 3 to 4μ . The thinnest continuous films were shown by the two specimens from rod A46. The internal films on the specimens from rods that operated to the end of Cycle No. 6 were generally thicker than the films on those in the initial group. Those with the longer exposure showed circumferential-average thicknesses that ranged from 4 to 9μ and had a mean value of 8μ . In some areas of specimens from both groups, fuel, either in the form of individual "globules," as shown in Figure 75, or in the form of rather extensive layers (Figures 77 and 78), was bonded to the ZrO_2 film. Particularly where the layers of fuel existed, a layer of a darker material, perhaps a reaction product, was observed between the ZrO_2 and fuel layers. A similar phenomenon was noted during the destructive examinations of Fuel Cycle Program fuel rods conducted at the conclusion of VBWR operation.³ The thicknesses of the internal and external ZrO_2 were not related in any particular way.

Specimen No. A626 from rod A9 was prepared, to examine a possibly defective area in the cladding of the rod. The area showed on a neutron radiograph print as an ~ 0.1 -cm (~ 0.04 -in.)-long spot slightly darker than the surrounding background (see Figure 45). Metallographic examination failed to reveal any reason for the spot. As was mentioned earlier, nothing unusual was noted during the earlier visual examinations of the rod surface or on the diameter profile traces, and analyses of the contained gases indicated that the rod was sound.

5.1.5.2.2 Fuel

The UO_2 of the following specimens was examined in the etched condition by light microscopy: No. 9954 (rod A13), Nos. 9956 and 9957 (rod A41), Nos. 9958 and 9959 (rod A46), No. 9960 (rod B70) from the initial group and No. A580 (rod A37), No. A581 (rod B62), and No. A582 (rod A11) from the final group.

Most of the specimens showed no significant radial variation in grain size. However, specimen No. 9956 from the initial group and specimen Nos. A581 (Figure 79(b)) and A582 (Figure 80) from the final group did show evidence of equiaxed central grain growth to varying degrees.

Precipitates were observed within the UO_2 grains near the outside surfaces of the pellets in all specimens (Figures 79, 80, 81, and 82). The lowest concentration of these precipitates was shown by that specimen with the lowest burnup and power rating (No. 9959). With the exception of the three specimens with the lowest exposures (Nos. 9958, 9959, and 9960), intragranular precipitates could be seen at interior locations of the etched fuel as well. With specimen No. 9957 of the initial group and No. A581 of the final group, these interior precipitates were most pronounced at the pellet center as illustrated in Figures 79(b) and 82(a). With the remaining specimens that showed interior precipitates, the maximum concentrations were attained at mid-radial locations (Figures 79(a), 80, and 81).

Differences with respect to the distribution of precipitates within the central grains also were noted. In those cases where the precipitates were concentrated at the center, distribution over the grains was quite even as indicated in Figures 79(b) and 82(a). In most cases where the maximum concentration occurred at mid-radial locations, the central grains showed precipitate-free bands extending inward from the boundaries as shown in Figure 79(a). However, in the case of specimen No. A582 from rod A11, the precipitates in the central grains are more highly concentrated next to the boundaries than in the grain centers (Figure 80).

Figure 75. Fuel Particles Attached to Thick Interior ZrO_2 Film—Specimen No. 9954

Figure 76. Fuel Particles Attached to Inside Cladding Surface and/or Thin Interior ZrO_2 Film—Specimen No. 9958

Figure 77. Layer of Fuel Attached to Thick Interior ZrO₂ Film and Intermediate Darker Phase

Figure 78. Area Shown in Figure 77 with Fuel in Etched Condition

OUTSIDE OF PELLETT

500X

MID-RADIUS OF PELLETT

500X

CENTER OF PELLETT

500X

(a)

OUTSIDE

500X

MID-RADIUS

500X

CENTER

500X

(b)

Figure 79. UO_2 Microstructures of (a) Specimen No. A580 (Rod A37) and (b) Specimen No. A581 (Rod B62) (Fuel Etched).

Figure 80. UO₂ Microstructure of Specimen No. A582 from Rod A11 (Fuel Etched)

Figure 81. UO_2 Microstructure of Specimen No. 9954 from Rod A13 (Fuel Etched).
Area Later Examined by Replication Electron Microscopy Is Outlined (See Subsection 5.2.1).

Figure 82. UO_2 Microstructures of (a) Specimen No. 9957 and (b) Specimen No. 9958—Fuel Etched 45 seconds

5.1.6 Electron Microscopic Examination of SA-1 Cladding Samples (H. S. Rosenbaum, U. E. Wolff, W. H. Kimball)

5.1.6.1 Procedure and Scope

Thin foils of unirradiated archive cladding were prepared for transmission electron microscopic examination by first slitting a tube section longitudinally and flattening the resulting half rings. The pieces were ground on both sides to remove the oxide and then prethinned chemically to a thickness of about 0.013 to 0.025 cm (0.005 to 0.010 in.). Discs 3 mm in diameter were punched from these pieces. Finally, the centers of the discs were thinned electrolytically in a twin-jet electro-polisher.

Samples of SA-1 cladding that had been exposed to a fast neutron fluence of approximately 5×10^{21} nvt > 1 MeV in 1204 days of VBWR and Dresden operation were prepared by first slitting and straightening sections of tubing from fuel rod A13 and punching 3 mm diameter discs from these sections in a hot cell. The discs then were prethinned by hand grinding and finally thinned with the twin-jet electro polisher.

Examinations of the thinned material were performed with a 100 kV electron microscope.

5.1.6.2 Results

Structures typical of the unirradiated Zircaloy are shown in Figure 83, and representative areas of the irradiated material are shown in Figure 84. Evidence of long dislocations can be seen in both the unirradiated and irradiated material. No evidence of radiation-induced voids was observed.

5.1.7 Analysis of Cladding Samples for Total Hydrogen and for Tritium (D. E. Rey)

5.1.7.1 Procedure and Scope

Samples of the SA-1 cladding, both from fuel rods that were removed from the assembly at the end of reactor Cycle No. 4 and from rods that operated to the end of Cycle No. 6, were analyzed for total hydrogen and other gaseous species. In addition, some of the samples from the first group of rods were analyzed for tritium content. Tritium, which is produced by the ternary fission of uranium and plutonium, decays by beta emission to ^3He . The degree to which it enters and is trapped by the Zircaloy cladding is of interest from the standpoint of both reactor operation and spent fuel reprocessing.*

Sample Preparation. Fuel rod segments, each 0.95 cm (3/8 in.) wide, were sectioned in duplicate from the desired axial locations in a hot cell of the Radioactive Materials Laboratory. Most of the segments came from the peak burnup regions of the rods; however, some were taken from locations near the top and bottom of the SA-1 fuel column. The bulk fuel was removed, and the cladding segments were leached with nitric acid and then rinsed thoroughly with distilled water. After drying, a cladding segment was split longitudinally into three pieces of equal length. These pieces were placed in appropriately labeled screw-cap glass vials and were shipped to Chemistry in a 110-kg (250-lb) cask.

In the lead fort of the Physical Chemistry Laboratory, the pieces of cladding were removed from the vials, visually inspected with mirrors, and then weighed. Each weighed piece of cladding was carried in a lead pig to the shielded vacuum outgassing apparatus and inserted into the loading arm.**

Outgassing. The vacuum system was pumped down overnight. The tungsten crucible then was degassed at a temperature between 1800°C and 1900°C. (The crucible was heated by induction with a 10 KVA LEPEL RF generator.) With the system at a final base pressure of less than 10^{-7} torr, each cladding piece was dropped into the crucible and heated for a period of 30 minutes at 1300°C. Evolved gases were moved rapidly from the furnace area by two mercury diffusion pumps working in tandem. The transfer of gases to the measuring section was completed by an automatic toepler pump. At the end of a run, the sample was dumped into the spent sample reservoir by lifting the crucible bail with a magnet. Blanks were run by heating the empty crucible for 30 minutes at 1300°C.

*The investigation of tritium in fuel rods was carried further in a separate program under Project Agreement 41, "Tritium Distribution in Zircaloy-Clad Fuel Rods."⁵

**Some of the first samples prepared went through degreasing steps with an organic solvent both immediately before the weighing and after the distilled water rinse in the hot cell.

(a)

10,500x

(b)

30,000x

*Figure 83. Unirradiated SA-1 (Fuel Cycle Program)
Archive Cladding Material*

(a)

30,000x

(b)

30,000x

Figure 84. SA-1 Fuel Rod Cladding Exposed to
Approximately 5×10^{21} nvt > 1 MeV

Analysis. The total gas release from each sample of cladding was measured by means of a multirange McLeod gage. Constituent analysis was performed by gas chromatography. Some of the earlier analyses were carried out with a molecular sieve column. Later, the gas chromatographic scans were obtained by temperature programming a 6.1-m (20-ft) Porapak QS column from -60°C to $+75^{\circ}\text{C}$, using helium as carrier gas.

When a sample was to be analyzed for tritium as well as total composition, the gas was aliquoted after volume determination so that about one-third of the total collected was available for tritium analysis. The aliquot was first scanned for Kr-85 by gamma spectrometry (primarily to qualitatively determine the detectability of this isotope in cladding samples), and then sent to the Metallurgy Mass Spectrometry Laboratory for conversion of hydrogen/tritium to water products (H_2O , HTO , T_2O) and residual gas analysis. The conversion was done by addition of a carefully measured amount of oxygen and subsequent combustion with a heated filament. The products of combustion were frozen out with a dry-ice acetone bath and then taken up with scintillator fluid for tritium counting.

Samples from seven locations of five rods were analyzed by chromatography during the initial phase of the program. Two pieces from the first set of seven cladding segments were analyzed. Then, at a later date, one piece from each corresponding adjacent segment was analyzed. The tritium analyses were performed on aliquots of gas extracted from the pieces of cladding from this second set of segments.

During the final phase of the program, samples from six locations of four rods were analyzed by chromatography for total composition only.

5.1.7.2 Results

5.1.7.2.1 Chromatographic Analyses

The results of the analyses performed on samples from rods that operated between 1175 and 1218 days in the VBWR and Dresden are given in Table 15, and Table 16 gives the results on samples from rods that operated between 1767 and 1846 days.

For the first group of samples, the total volumes of gas collected ranged from approximately 500 to 1100 microliters per gram of sample and averaged about 800. For a given pair of samples, these volumes generally were within ~ 100 microliters per gram of each other, and the total volumes collected from the samples of one set were neither predominately larger nor smaller than the volumes collected from the corresponding duplicates. Sample B70F, however, contained 250 to 275 microliters per gram, or approximately one-third, more gas than sample B70E.

The chromatographic analyses showed total hydrogen contents of 84 to 95 percent, carbon monoxide contents of 1 to 12 percent, and carbon dioxide contents of 0.3 to 6 percent. The samples also contained up to 3.4 percent nitrogen, up to 0.6 percent oxygen, and up to 0.2 percent methane. In terms of parts per million, the total hydrogen contents ranged from 45 to 89. The absorption of corrosion-generated hydrogen ranged from 1 to 7 percent and averaged 4 percent.

With the exception of the sample pair, B97C and B97D, the corresponding percentages of total hydrogen were within ~ 5 points of each other. The combined differences in total gas volumes and percentages of hydrogen then resulted in differences in cladding hydrogen contents that ranged from about 3 to 11 parts per million in six of the seven pairs of samples. The total hydrogen content of B70F was 21 to 22 ppm greater than that of B70E.

In the first set of samples no oxygen and generally low-amounts of nitrogen were measured. The presence of oxygen and the correspondingly higher quantities of nitrogen measured in pieces from the adjacent cladding segments suggest that air contamination occurred during the extra manipulations required in taking aliquots for the tritium determinations.

For the final phase samples, the total volumes of gas collected ranged from a minimum of approximately 700 microliters per gram to a maximum of approximately 2200, twice the content of any initial phase sample. The average gas content of the samples from rods that operated to the end of reactor Cycle No. 6 was 1200 microliters per gram.

The analyses showed total hydrogen contents of 72 to 96 percent, carbon monoxide contents of 5 to 24 percent, and carbon dioxide contents of 0.3 to 2 percent. The samples also contained up to 0.6 percent nitrogen and oxygen, and up to 0.05 percent methane. The total hydrogen contents in parts per million ranged from 46 to 146 and were somewhat higher, in general, than the hydrogen contents of samples from rods that were removed from SA-1 at the end of Cycle No. 4. The maximum percent absorption did not increase, however. Cladding samples from fuel rods of the same type as the SA-1 rods showed a maximum hydrogen content of about 60 ppm and a maximum absorption of somewhat less than 7 percent after 365 days of operation.³

Table 15
CHROMATOGRAPHIC ANALYSIS OF GASES EVOLVED FROM FUEL ROD CLADDING SAMPLES

Sample Number and Location*	Total Gas Volume (Microliters per Gram at STP)	Initial Phase												Hydrogen Content (ppm)		Weight Gain (mg/dm ² O ₂)***	Hydrogen Absorption (percent)
		Composition (percent by volume)						Volume of Constituents (microliters per gram at STP)						Terminal	Preirradiation**		
		H ₂	O ₂	N ₂	CH ₄	CO	CO ₂	H ₂	O ₂	N ₂	CH ₄	CO	CO ₂				
B70E (a)	750	88.3	ND	0.9	ND	10.80	—	662	≤1	7	≤1	81	—	60	28	220 (No. 9960)	4.2****
(b)	776	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	760	90.0	ND	0.7	ND	9.00	0.30	684	≤1	5	≤1	68	2	61	—	—	—
B70F																	
1) 34.6 cm (13-5/8 in.)	1025.2	89.99	0.40	1.68	0.03	6.36	1.54	922.6	4.1	17.2	0.3	65.2	15.8	82	—	—	7.1
2) 189.9 cm (74-3/4 in.)																	
A13F (a)	703	89.7	ND	ND	T	10.30	—	631	≤1	≤1	<1	72	—	57	27	220 (No. 9954)	3.7****
(b)	730	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	698	87.2	ND	ND	T	10.60	2.20	609	≤1	≤1	<1	74	15	54	—	—	—
A13G																	
1) 30.8 cm (12-1/8 in.)	844.0	84.92	0.13	2.16	ND	10.32	2.47	716.7	1.1	18.2	<0.1	87.1	20.8	64	—	—	4.8
2) 123.2 cm (48-1/2 in.)																	
A41D (a)	622	89.9	ND	ND	T	10.10	—	559	≤1	≤1	<1	63	—	50	35	210 (No. 9955)	2.2****
(b)	615	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	650	89.6	ND	ND	T	5.20	3.40	582	≤1	≤1	<1	34	22	52	—	—	—
A41E																	
1) 26.0 cm (10-1/4 in.)	528.5	94.81	0.02	3.44	0.01	1.21	0.51	501.1	0.1	18.2	0.1	6.4	2.7	45	—	—	1.4
2) 128.0 cm (50-3/8 in.)																	
A46T (a)	745	88.0	ND	ND	T	12.00	—	656	≤1	≤1	<1	89	—	59	27	610 (No. 9959)	1.5****
(b)	749	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	784	85.7	ND	ND	T	10.3	5.70	672	≤1	≤1	<1	81	45	60	—	—	—
A46U																	
1) 91.1 cm (35-7/8 in.)	836.9	86.86	0.42	1.79	0.19	7.66	3.06	726.9	3.5	15.0	1.6	64.1	25.6	65	—	—	1.8
2) 62.9 cm (24-3/4 in.)																	
A46F (a)	960	87.4	ND	1.0	T	11.60	—	839	≤1	10	<1	111	—	75	27	380 (No. 9958)	3.5****
(b)	986	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	886	88.2	ND	0.2	T	7.40	4.20	781	≤1	2	<1	66	37	70	—	—	—
A46G																	
1) 24.1 cm (9-1/2 in.)	870.2	85.60	0.58	2.30	ND	10.03	1.49	744.9	5.0	20.0	<0.1	87.3	13.0	66	—	—	3.0
2) 129.9 cm (51-1/8 in.)																	
B97C (a)	894	90.5	ND	ND	T	9.50	—	809	≤1	≤1	<1	85	—	73	27	310 (No. 9962)	4.4****
(b)	890	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	933	89.4	ND	ND	T	7.30	3.30	834	≤1	≤1	<1	68	31	74	—	—	—
B97D																	
1) 26.4 cm (10-3/8 in.)	924.4	83.73	0.48	1.88	0.04	11.69	2.19	774.0	4.4	17.4	0.4	108.1	20.2	69	—	—	3.9
2) 181.6 cm (71-1/2 in.)																	
B97J (a)	1095	90.0	ND	0.8	T	9.20	—	986	≤1	9	<1	101	—	89	27	530 (No. 9963)	3.2****
(b)	1095	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
(c)	1081	87.1	ND	1.5	T	7.00	4.40	924	≤1	16	<1	74	47	82	—	—	—
B97K																	
1) 76.8 cm (30-1/8 in.)	969.6	89.73	0.33	1.50	0.12	6.69	2.54	870.0	3.2	15.4	1.2	55.2	24.6	78	—	—	2.8
2) 231.8 cm (91-1/4 in.)																	

— = Not Analyzed

T = Trace (<0.03%)

ND = Not Detected (<0.01%)

*1) Distance from center of sample pairs to shoulder of short end plug (cm [in.]).

2) Distance from bottom of Dresden Reactor active fuel zone (cm [in.]).

** Determined by General Electric Company under the AEC Fuel Cycle Program on samples of tubing from corresponding lots.

*** Weight gain in mg/dm² = 15.6 X circumferential average ZrO₂ thickness in microns measured on adjacent metallography specimens identified in parentheses (see Tables 13 and 14).

**** Based on average hydrogen content of corresponding "a" and "c" pieces.

Table 16
CHROMATOGRAPHIC ANALYSIS OF GASES EVOLVED FROM FUEL ROD CLADDING SAMPLES

Sample Number and Location*	Total Gas Volume (Microliters per Gram at STP)	Final Phase												Hydrogen Content (ppm)		Weight Gain (mg/dm ² O ₂)***	Hydrogen Absorption**** (percent)
		Composition (percent by volume) (Normalized to Total 100 Percent)						Volumes of Constituents (microliters per gram at STP)						Terminal	Preirradiation**		
		H ₂	O ₂	N ₂	CH ₄	CO	CO ₂	H ₂	O ₂	N ₂	CH ₄	CO	CO ₂				
A15F(a)	659.7	77.57	ND	0.03	ND	21.34	0.79	511.7	<0.1	2.0	<0.1	140.8	5.2	46	28	180 (No. A591)	3.4
(b)	738.9	78.47	0.09	0.60	0.01	20.08	0.75	579.8	0.7	4.4	0.1	148.4	5.5	52			
1) 88.4(34-13/16)																	
2) 65.6(25-13/16)																	
A15B(a)	1344.4	91.15	0.26	0.42	0.05	7.41	0.70	1225.4	3.5	5.6	0.7	99.6	9.4	109	28	440 (No. A590)	4.5
(b)	988.4	93.49	0.13	0.51	0.03	5.33	0.50	924.1	1.3	5.0	0.3	52.7	4.9	83			
1) 24.3(9-9/16)																	
2) 129.7(51-1/16)																	
A49D(a)	2240.7	73.11	0.65	ND	0.05	23.99	2.20	1638.1	14.6	≤0.2	1.1	537.5	49.3	146	27	870 (No. A594)	3.7
(b)	1678.2	85.88	0.19	ND	0.05	12.71	1.17	1441.2	3.2	<0.2	0.8	213.3	19.6	129			
1) 75.4(29-11/16)																	
2) 78.6(30-15/16)																	
B50D(a)	1029.7	94.75	0.01	0.44	ND	4.47	0.33	975.6	0.1	4.5	≤0.1	46.0	3.4	87	27	800 (No. A609)	2.7
(b)	1380.3	93.51	0.21	0.26	0.01	5.59	0.41	1290.7	2.9	3.6	0.1	77.2	5.7	115			
1) 73.5(28-15/16)																	
2) 228.8(90-1/16)																	
B85B(a)	1290.5	89.17	0.49	0.63	0.04	9.01	0.66	1150.7	6.3	8.1	0.5	116.3	8.5	103	28	1090 (No. A592)	1.9
(b)	1135.3	93.70	0.04	0.38	0.02	5.46	0.41	1063.8	0.5	4.3	0.2	62.0	4.7	95			
1) 24.3(9-9/16)																	
2) 179.5(70-11/16)																	
B85F(a)	983.4	79.94	0.29	0.33	0.03	18.55	0.85	786.1	2.9	3.2	0.3	182.4	8.4	70	28	550 (No. A593)	2.2
(b)	900.2	85.85	ND	0.58	0.02	12.95	0.59	772.8	<0.1	5.2	0.2	116.6	5.3	69			
1) 88.4(34-13/16)																	
2) 243.7(95.15/16)																	

ND= Not Detected (<0.01%)
*1) Distance from center of sample to shoulder of short end plug (cm[in.]).
2) Distance from bottom of Dresden Reactor active fuel zone (cm[in.]).
** Determined by General Electric Company under the AEC Fuel Cycle Program on samples of tubing from corresponding lots
*** Weight gain in mg/dm² = 15.6 X circumferential average ZrO₂ thickness in microns measured on adjacent metallography specimens identified in parentheses (see Table 13).
**** Based on average hydrogen content of corresponding "a" and "b" samples.

The maximum percent CO value was about twice the maximum value determined on any of the initial phase specimens, but it was no greater than some of those obtained in the analysis of samples from rods that saw only VBWR operation. Investigators under the Fuel Cycle Program suggested that the UO_2 may have been the source of the CO and CO_2 in the irradiated cladding.³ However, the wide variation in the CO content of the SA-1 cladding samples—even between two pieces from the same segment [A49D (a) and (b), for example]—seems difficult to explain. It is possible that contamination from some unknown source was at least partly responsible for the evolution of CO and CO_2 .

The source of the oxygen in the final phase samples is also uncertain. The low nitrogen contents of some of these samples indicate that air contamination was not responsible for the oxygen evolved in these cases.

5.1.7.2.2 Tritium Analysis

The tritium analyses are presented in Table 17, and data on the operation of the different rods in the two reactors are given in Table 18. The tritium content of the cladding ranged from approximately 5 to 58 parts per billion, equivalent to about 2 to 16 percent of the tritium generated during operation. The burnup of the fuel corresponding to the cladding samples analyzed for tritium ranged from 5×10^{20} to 8×10^{20} fissions/cm³ (17,000 to 30,000 MWd/t), and the time-averaged power values ranged from about 30 to 50 W/cm² (100,000 to 160,000 Btu/-ft²). The maximum power of any rod at a sample location while in Dresden is estimated to have been 98 W/cm² or 310,000 Btu/h-ft². This power was attained relatively early in Dresden operation. The cladding tritium content correlates quite well with the fuel burnup or average power rating over the total operating time. It will be noted that the ratio of cladding tritium content to burnup and time-averaged power increased rather markedly with increasing burnup and power both among samples from different rods and between two samples from an individual rod.

The values of tritium generation were approximated as follows: The distribution of fissions among U-235, Pu-239, Pu-241, and U-238 were obtained from chemical isotopic analyses. This information was directly obtainable for samples A13G, A41E, and A46G from analysis of adjacent fuel samples (see subsection 5.3). Fission distributions for the other four samples were estimated from curves of atom percent fission versus burnup generated from the SA-1 data and other chemically determined isotopic data. Yield values of 1.3×10^{-4} for U-235 and U-238 and 2.3×10^{-4} for Pu-239 and Pu-241 were then applied to estimate the production of tritium.

5.1.8 Cladding Mechanical Properties Testing (G. P. Ferguson)

The tests and measurements performed to determine the mechanical properties of the irradiated SA-1 fuel rod cladding included the following:

- a. Tensile tests on longitudinally-oriented miniature coupon specimens
- b. "Ring-on-mandrel" tensile tests on transverse cladding sections
- c. Burst tests on rod sections
- d. Microhardness measurements on the cladding wall of transversely and longitudinally-oriented metallography specimens

The burst tests were carried out only on cladding samples from rods that operated in Dresden to the end of Cycle No. 6. The other tests and measurements were performed only on samples from rods that operated to the end of Cycle No. 4.

5.1.8.1 Tensile Tests on Longitudinal Coupon Specimens

5.1.8.1.1 Procedure and Scope

Longitudinally-oriented tensile coupon specimens were obtained from the cladding of four irradiated fuel rods (A13, A41, A46, and B97). To prepare a specimen, the fuel rod was sectioned transversely to the desired length with a thin, abrasive cutting wheel. This section was then slit longitudinally to obtain two tensile coupon blanks. A hot cell-adapted Tensilkut machine and special holding fixtures were used to machine a reduced gauge length region on each coupon blank. A sketch of a tensile specimen is shown in Figure 85. The gauge width and cladding thickness of each specimen were measured with a micrometer.

Similar specimens were prepared from unirradiated archive tubing to provide comparative data. Some of these specimens were prepared remotely, while others were prepared out-of-cell with either a Tensilkut machine or milling machine.

Table 17
TRITIUM CONTENT OF CLADDING SAMPLES

Sample Number and Location ^a	Gas Volume (Microliters per Gram at STP)	Tritium Content ^c			Approximate	Percent Tritium in Cladding	Krypton-85 $\frac{\text{dpm}}{\text{gm}} \times 10^{-6}$ ^b
		$\frac{\mu\text{Ci}}{\text{gm Cladding}}$	ppb Cladding	$\frac{\text{gm in Cladding}}{\text{gm UO}_2}$	$\frac{\text{gm}^3 \text{H}_2}{\text{gm UO}_2}$		
				($\times 10^9$)	generated ($\times 10^9$)		
B70E							
1) 35.1 cm (13-13/16 in.)	1025.2	242.4	24.9	3.99	50	8	12
2) 190.3 cm (74-15/16 in.)							
A13G							
1) 31.3 cm (12-5/16 in.)	844.0	561.4	57.8	9.25	61	15	16
2) 122.7 cm (48-5/16 in.)							
A41E							
1) 26.5 cm (10-7/16 in.)	528.5	553.4	56.9	9.14	57	16	NA
2) 127.5 cm (50-3/16 in.)							
A46U							
1) 91.6 cm (36-1/16 in.)	836.9	43.3	4.5	0.71	33	2	0.75
2) 62.4 cm (24-9/16 in.)							
A46G							
1) 24.6 cm (9-11/16 in.)	870.2	246.4	25.4	4.02	53	8	6.9
2) 129.4 cm (50-15/16 in.)							
B97D							
1) 26.8 cm (10-9/16 in.)	924.4	311.6	32.1	5.14	57	9	8.9
2) 182.1 cm (71-11/16 in.)							
B97K							
1) 77.0 cm (30-5/16 in.)	969.6	92.7	9.5	1.53	36	4	1.1
2) 232.3 cm (91-7/16 in.)							

NA = Not Analyzed.

(a) 1) Distance from center of sample to shoulder of short end plug (cm[in.]).

2) Distance from bottom of Dresden Reactor active fuel zone (cm[in.]).

(b) Not corrected for either counting efficiency or decay. Analyzed in July 1970.

(c) Corrected to date of discharge (January 13, 1967).

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Table 18
ROD OPERATING DATA

Rod or Sample	Initial Enrichment (weight percent U-235)	Burnup Rod-Average, or Sample		Days of Operation ^a	Time-Averaged VBWR + Dresden	Estimated Heat Flux in W/cm ² (Btu/h-ft ² X 10 ⁻³) ^b					
						VBWR Operation		Dresden Operation			
						At Maximum Reactor Power Rod-Average or Sample	Time-Averaged Cycles 3 and 4 Rod-Average or Sample	At Maximum Reactor Power Average for Rod or Sample			
		Fissions/cm ³ X 10 ⁻²⁰	MWD/tU					BOC 3 ^c	EOC 3 ^c	BOC 4	EOC 4
B70	2.76	5.5	20,200	1,175	35.1 (111)	74 (230)	34 (110)	69 (220)			
B70F		6.5	23,900		41.5 (132)	—	40 (130)	73 (230)	48 (150)	55 (170)	41 (130)
A13	3.49	7.0	25,600	1,204	45.1 (143)	88 (280)	41 (130)	79 (250)	—	—	—
A13G		8.1	29,700		52.1 (166)	129 (410)	47 (150)	82 (260)	53 (170)	61 (190)	46 (150)
A41	3.49	6.6	24,000	1,204	42.0 (133)	88 (280)	36 (110)	82 (260)	—	—	—
A41E		7.7	28,300		49.5 (157)	123 (390)	43 (140)	98 (310)	64 (200)	73 (230)	55 (170)
A46	2.76	6.0	22,000	1,218	38.7 (123)	63 (200)	40 (130)	73 (230)	—	—	—
A46U		4.6	16,900		29.7 (94)	—	30 (100)	54 (170)	35 (110)	41 (130)	30 (90)
A46G		6.9	25,300		44.5 (141)	91 (290)	46 (150)	88 (280)	57 (180)	66 (210)	49 (150)
B97	2.76	6.1	22,200	1,218	38.6 (122)	82 (260)	36 (110)	76 (240)	—	—	—
B97D		7.3	26,600		46.3 (147)	117 (370)	43 (140)	88 (280)	57 (180)	66 (210)	49 (150)
B97K		5.1	18,500		32.2 (102)	—	30 (100)	57 (180)	37 (120)	43 (140)	32 (100)

(a) Total days of operation, 840 days of which were in Dresden in all cases.
Days of operation in the VBWR is defined as hours at temperature (reactor thermal power > 5 MW) divided by 24.
Days of operation in Dresden is defined as hours of turbine-generator operation divided by 24.

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

(c) BOC = Beginning of Cycle. EOC = End of Cycle.

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Figure 85. Schematic Diagram of Tensile Specimens Obtained from SA-1 Fuel Cladding

All of the irradiated specimens and some of the unirradiated specimens were tested with an Instron Model TT-C-L hot cell tensile testing machine. All specimens were pulled at a strain rate of either 0.02 or 0.025 cm/cm/min. The uniform and total extension values on the remotely tested specimens were determined from traces of load versus time and the crosshead speed of the testing machine.

Specimens were tested at room temperature, 343°C (650°F), 399°C (750°F), and 454°C (850°F). The specimens were normally held at the testing temperature 15 minutes before tension was applied. However, several specimens were held at temperature for longer periods, up to 16-1/2 hours.

The integrated fast flux exposure for the irradiated material is estimated to be between 3.5×10^{21} and 6×10^{21} nvt > 1 MeV.

5.1.8.1.2 Results

The test results are presented in Table 19. Examples of specimens that were tested at the various temperatures are shown in Figures 86(a) through 86(d). As expected, the irradiated material showed significantly increased strength and decreased ductility compared to the unirradiated Fuel Cycle Program archive material. The least effect of irradiation on yield strength, ultimate strength, and *total* elongation was shown at 454°C (850°F).

At room temperature (22°C or 72°F) the average yield and ultimate strengths of the irradiated specimens were 6900 kg/cm² (97 kpsi) and 7700 kg/cm² (110 kpsi), and the uniform and total elongations were about 1 percent and 3 percent. Among the specimens that were held at temperature for the normal period, the high temperature ultimate strengths ranged from about 5000 kg/cm² (70 kpsi) at 343°C (650°F) to about 3000 kg/cm² (40 kpsi) at 454°C (850°F). The differences between ultimate strength and yield strength were generally ≤ 70 kg/cm² (1 kpsi) in the high temperature tests, although there were some exceptions at 343°C. The uniform elongations were typically 0.5 percent or less. Total elongations were 1 to approximately 1.5 percent at 343°C, up to 2 percent at 399°C (750°F), and ranged from 5 to 12 percent at 454°C.

Holding specimens at 343°C (650°F) for up to 16-1/2 hours had no significant effect on any of the 343°C tensile properties. [The maximum wall-average operating temperature of the cladding is estimated to have been between 329°C and 343°C (625° and 650°F).] The ultimate and yield strengths of one specimen held at 399°C (750°F) for 7 hours before testing at that temperature were, respectively, about 800 kg/cm² (11 kpsi) and 850 kg/cm² (12 kpsi) lower than the minimum values obtained on specimens tested at 399°C after the normal soaking period. The elongations did not change. A specimen held for 16-1/2 hours at 399°C showed ultimate and yield strengths approximately 950 kg/cm² (13.5 kpsi) and 1200 kg/cm² (17 kpsi) lower than any specimen tested by the normal procedure and, in addition, it showed somewhat greater uniform and total elongations (1.2 percent and 3.6 percent). The 454°C tensile properties of the irradiated cladding apparently were not affected significantly by increasing the soaking time at that temperature to 1 hour. The ultimate strengths of three irradiated specimens held at 454°C for 16-1/2 hours before testing approached that of the unirradiated material. One of the three showed increased uniform elongation and ultimate-yield strength differential, while another showed a total elongation at least as high as those of the unirradiated specimens and was of relatively high strength. There are no certain reasons for these differences in behavior.

5.1.8.2 Ring-on-Mandrel Tensile Tests

The tensile properties of irradiated fuel cladding in the transverse direction are of interest because of the possibility of mechanical interaction between the fuel and the cladding during the course of operation. It is expected that for a given fuel rod power level, the likelihood (or degree) of interaction will increase with time through the mechanism of fission-product-induced fuel swelling. With the objective of determining some of the transverse tensile properties, particularly ductility, several ring-on-mandrel tests were performed on SA-1 cladding samples. This type of test had been carried out previously under the Fast Ceramic Reactor Development Program [Contract AT(04-3)-189, Project Agreement 10] on samples of irradiated stainless steel cladding.⁶

5.1.8.2.1 Procedure and Scope

The specimen in this test was a transverse cladding section, generally somewhat less in length than the inside diameter of the cladding. This ring of cladding was placed over and centered on a metal cylinder that was somewhat longer than the ring, and of a diameter slightly smaller than the inside diameter of the cladding. The diameter of the ring was increased to the point of fracture by compressing the ends of the cylindrical mandrel. Pressure was applied to the mandrel by means of a compression cage device used in conjunction with an Instron Model TT-C-L tensile testing machine. The diameter or circumference of the ring at fracture was measured, and the value $\Delta D/D_i$ was calculated.

Table 19
TENSILE TESTS ON LONGITUDINAL COUPON CLADDING SPECIMENS

Specimen Identification	Tubing Lot Number	Estimated Fast Fluence Exposure (nvt > 1 MeV X 10 ⁻²¹)	Test Temperature [°C (°F)]	Holding Time at Test Temperature (h)	0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation [% in 2.03 cm (0.8 in.)]	
					kg/cm ²	kpsi	kg/cm ²	kpsi	Uniform	Total
1	CA-3	0	Room	1/4	2570	36.6	5170	73.6	14.4	24.5
5	CA-2	0			3160	45.0	4500	64.0	14.8	>23.6
6	CA-2	0			3300	47.0	4650	66.2	17.2	27.4
13	CA-4	0			3620	51.5	5050	71.8	18.0	31.6
14	CA-3	0			3800	54.0	5200	74.0	15.8	28.0
A13-I2	CA-2	4.5			6920	98.4	7870	111.9	1.1	3.0
A41-G1	CA-4	5.0			6550	90.3	7450	106.0	0.8	3.2
A41-G2	CA-4	5.0			7250	103.1	7920	112.7	0.8	3.0
2	CA-3	0			1450	20.6	2410	34.3	11.8	19.6
7	CA-2	0			1550	22.0	2710	38.5	14.7	22.2
8	CA-2	0	343 (650)	1	1480	21.0	2460	35.0	11.0	20.5
15	CA-4	0			1650	23.5	2460	35.0	15.2	26.8
A13-B1	CA-2	5			4060	57.8	4640	66.0	0.7	1.2
A13-B2	CA-2	5			4650	66.1	4900	69.7	0.4	1.4
A41-B1	CA-4	5			4660	66.3	4680	66.5	0.3	1.2
A41-B2	CA-4	5			3890	55.3*	5210	74.1	1.1*	2.2*
A46-D1	CA-2	4.5			4710	67.0	4750	67.5	0.3	1.1
A46-D2	CA-2	4.5			3300	46.9*	4650	66.2	1.7*	3.0*
A46-M1	CA-2	4			4800	68.3	4800	68.3	0.2	1.0
B97-F1	CA-2	4.5			5320	75.7	5360	76.2	0.3	1.1
A46-L2	CA-2	4	399 (750)	16-1/2	4630	65.9	4750	67.6	0.3	1.2
A46-O2	CA-2	3.5			4810	68.4	4810	68.4	0.2	1.7
A46-P2	CA-2	3.5			4630	65.9	4680	66.6	0.3	1.4
3	CA-3	0			1420	20.2	2180	31.0	7.7	18.3
9	CA-2	0			1490	21.2	2070	29.5	17.0	21.2
10	CA-2	0			1620	23.0	2250	32.0	14.6	19.5
17	CA-3	0			1790	25.4	2400	34.2	12.9	19.8
18	CA-3	0			2170	30.8	2710	38.5	10.8	19.2
A46-C1	CA-2	4.5			4190	59.6	4210	59.9	0.4	2.0
A46-C2	CA-2	4.5			4360	62.0	4390	62.4	0.3	0.6
A46-L1	CA-2	4	454 (850)	7	4330	61.6	4330	61.6	0.2	1.9
B97-G2	CA-2	4.5			3340	47.5	3420	48.7	0.4	2.0
B97-G1	CA-2	4.5			3000	42.7	3260	46.3	1.2	3.6
4	CA-3	0			1400	19.9	1980	28.1	6.8	19.9
11	CA-2	0			1300	18.5	2140	30.5	12.4	16.6
12	CA-2	0			1320	18.8	2100	29.8	9.6	16.2
19	CA-3	0			1510	21.5	2180	31.0	12.2	19.5
20	CA-3	0			2060	29.3	2430	34.6	7.0	14.2
A46-J1	CA-2	4			2690	38.3	2730	38.8	0.5	12.1
A46-J2	CA-2	4			3220	45.8	3290	46.8	0.5	5.4
A46-M2	CA-2	4	454 (850)	16-1/2	2490	35.4	2560	36.4	0.6	9.7
A46-O1	CA-2	3.5			2720	38.7	2860	40.7	0.6	5.0
A46-R1	CA-2	3.5			2280	32.4	2350	33.4	0.7	8.5
A46-R2	CA-2	3.5			1840	26.1	2040	29.0	2.7	9.5
B97-F2	CA-2	4.5			2610	37.1	2660	37.8	0.6	20.0

*Accuracy of these values is in doubt. Specimens may have slipped in grips.

NOTE: Unirradiated specimens 1 through 4 were prepared out of cell with a Tensilkut machine and were tested in cell.

Specimens 5 through 12 were prepared out of cell with a milling machine and were tested out of cell.

Specimens 13 through 15, and 17 through 20 were prepared in cell with a Tensilkut machine and were tested out of cell.

(a) ROOM TEMPERATURE
SPECIMEN A41-G1

(b) 343°C (650°F)
SPECIMEN B97-F1

(c) 399°C (750°F)
SPECIMEN A46-C1

(d) 454°C (850°F)
SPECIMEN A46-J1

Figure 86. Appearance of Irradiated Longitudinal Coupon Specimens Tested at Various Temperatures

A ring width of 0.445 cm (0.175 inch) was selected for the present series of tests. This width was the same as the width of the reduced section in the aforementioned longitudinal tensile coupons. [The nominal inside diameter and wall thickness of the SA-1 cladding were 0.965 cm (0.380 in.) and 0.056 cm (0.022 in.), respectively.]

The irradiated ring specimens were prepared from two ~15-cm (6-inch)-long sections of fuel rods A13 and A41. The fast fluence exposure was estimated to be approximately 5×10^{21} nvt > 1 MeV for all specimens tested. The ring specimens were cut from the tubing with an abrasive wheel. The fuel was removed from the rod sections by dissolving it in nitric acid before cutting these sections into rings. The external surfaces of rods A13 and A41 were treated earlier with hydrochloric acid to remove the crud deposits.

Different specimens were tested at room temperature, 343°C (650°F), and 454°C (850°F). In the high-temperature tests, the specimens were held at temperature for 15 minutes before the load was applied to the mandrels.

Most of the tests were performed with a machine crosshead speed of 0.025 cm (0.01 in.) per minute, which generally resulted in average specimen strain rates of 0.01 to 0.02 cm per cm/min. A few tests were run with crosshead speeds of 0.0025 cm or 0.005 cm (0.001 in. or 0.002 in.) per minute and correspondingly lower average strain rates. The average specimen strain rate was determined by dividing $(D_f - D_i)/D_i$ by the total test time. The values of $\Delta D/D_i$ were determined by measuring the diameters with a micrometer.

A trace of load on the mandrel versus time was made for each ring test. A given test was run to the point of specimen failure—indicated by a drop in load on the strip chart—to the 4500-kg (10,000-lb) machine load limit, or to a point where the mandrel was estimated to have been compressed to a height only 0.050 cm (~0.020 in.) or so greater than the ring width.

Several mandrel materials (Zircaloy, stainless steel, aluminum, and brass) and different mandrel heights were tried in an attempt to obtain successful tests at all temperatures.

5.1.8.2.2 Results

Some difficulty was encountered in expanding the ring specimens to fracture, particularly in tests carried out at 343°C (650°F). With a mandrel made of a relatively high strength material, such as Zircaloy-2, the load capacity of the Instron machine sometimes was reached before the specimen was expanded to fracture. Mandrels made of softer materials, on the other hand, tended to buckle or fold over the edges of a specimen, and these tendencies increased with increasing mandrel height.

The test results are given in Table 20. Strains to fracture ($\Delta D/D_i \times 100$) of 13 to 27% were obtained at room temperature on the irradiated specimens. Two of these specimens are shown in Figure 87 after testing. Evidence of a slight amount of folding of the mandrel over the edges, or wall, of the specimen can be seen. An unirradiated specimen prepared from SA-1 (Fuel Cycle Program) archive tubing was strained 50% without fracture in a room temperature test.

Specimens from rod A41 were increased in diameter as much as 69 percent without fracturing when tested with normal mandrels at 343°C (650°F). Specimen A41-13 ($\Delta D/D_i = 69\%$) is shown after testing, in Figure 88, with a typical unirradiated specimen that has not been tested. A specimen from rod A13 tested at 343°C fractured at a $\Delta D/D_i$ of 69 percent. However, because the ring was not centered on the mandrel, it underwent an abnormal deformation, and at the end of the test one edge of the ring was flush with the flat surface of the mandrel. These conditions may have caused premature fracturing.

A specimen from rod A41 tested at 343°C on a mandrel that contained a longitudinal groove in its cylindrical surface was expanded 55 percent before breaking at the location of the groove. The groove was intended to simulate a radial crack in a fuel pellet. The ring and mandrel are shown at the end of the test, in Figure 89. The groove shows considerable deformation. It was not possible to observe what changes in form the groove may have undergone while the test was in progress, but it is believed that an unsupported circumferential increment was maintained across the width of the ring.

Two specimens from rod A41 tested at 454°C (850°F) fractured at strains of 34 percent and 45 percent. One of these specimens, A41-4, is shown in Figure 90. It appeared that no folding of the Zircaloy mandrels over the specimen edges had occurred in these tests.

The strains to fracture for specimens from rod A13 were considerably lower than those for specimens from rod A41, in tests at room temperature. The operating histories of these two fuel rods in terms of exposure time, power, and integrated neutron exposure, and such effects of operation as corrosion and increased hydrogen content, were quite similar. The cladding for the two rods was fabricated from two different lots of tubing, but whether some difference(s) between the two lots was responsible for the differences in room temperature ductility was not established. No valid comparison of 343°C (650°F) ductility between specimens from the two rods can be made.

Table 20
SA-1 CLADDING RING TESTS

Specimen Number	Test Temperature °C (°F)	Average Strain Rate min ⁻¹	Mandrel Height cm (in.)	Mandrel Material	Specimen Strain $\frac{\Delta D}{D_i} \times 100$ (%)	Specimen Fracture?	
A-41-1	Room ↓	0.017	1.3 (0.5) ↓	Zircaloy-2	4	No (a)	
A41-9		0.012		Zircaloy-2	15	↓	
A41-11		0.0013		6061 Al	18		
A41-14		0.011		1100 Al ↓	25	Yes	
A41-17		0.012			27	↓	
A13-25		0.009			13		
A13-23		0.010			17	↓	
Unirradiated				0.017		50	No (a)
A41-2	343 (650) ↓	0.015	1.3 (0.5) ↓	Zircaloy-2	25	No (a)	
A41-5		0.013		↓	19	↓	
A41-6		0.0032	↓		30		
A41-7		0.013	6061 Al	42 (c)	Yes		
A41-8		0.0015	Zircaloy-2	25	No (a)		
A41-10		~0.01	1.0 (0.4)	304 S.S.	1	No (a)	
A41-12		0.017	1.3 (0.5)	Brass ↓	50	No (b)	
A41-13		0.017	1.5 (0.6)		69	No (b)	
A41-15		[~0.001 (d)]	↓		(d)	No	
A41-16		0.018	↓		55 (e)	Yes	
A13-22		0.017	↓		69 (f)	Yes	
A41-3	454 (850)	0.015	1.3 (0.5)	Zircaloy-2	34	Yes	
A41-4	454 (850)	0.017	1.3 (0.5)	Zircaloy-2	45	Yes	

(a) Test terminated when machine load limit was reached.

(b) Test terminated when minimum mandrel height was reached.

(c) Mandrel folded over edges of specimen, and premature fracture may have resulted.

(d) Mandrel folded over edges of specimen to the extent that specimen could not be measured.

(e) Mandrel contained a 0.075-cm (0.03-in.)-wide by 0.09-cm (0.035-in.)-deep longitudinal groove in its cylindrical surface.

(f) Specimen may have fractured prematurely. Specimen was not centered on mandrel and underwent abnormal deformation. One edge of ring was flush with flat surface of mandrel at end of test.

(a)

(b)

(c)

Figure 87. Ring Specimens and Mandrels After Testing at Room Temperature:
 (a) Specimen A41-14 (Side View),
 (b) Specimen A13-25 (Side View),
 (c) Specimen A13-25 (Top View).

(a)

(b)

*Figure 88. Specimen A41-13 After Testing at 343°C (650°F):
(a) Side View, and (b) Top View, Shown with an
Unirradiated Specimen That Has Not Been Tested.*

Figure 89. Specimen A41-16 After Testing at 343°C (650°F) with Grooved Mandrel

(a)

(b)

*Figure 88. Specimen A41-13 After Testing at 343°C (650°F):
(a) Side View, and (b) Top View, Shown with an
Unirradiated Specimen That Has Not Been Tested.*

Figure 89. Specimen A41-16 After Testing at 343°C (650°F) with Grooved Mandrel

Figure 90. Specimen A41-4 After Testing at 454°C (850°F)

The effect of strain rate is uncertain. The greatest strains were realized in some of the highest strain rate tests, but none of the tests performed at one of the lower rates was carried out to specimen fracture.

Investigators with the Fast Ceramic Reactor Development Program, who used the ring-on-compressed-cylinder test to measure the tensile ductility of irradiated Types-304 and -316L stainless steel cladding, pointed out that in this type of test the friction between the mandrel and the ring develop surface shear forces which support the entire gage length of the specimen and thus suppress localized necking. When mechanical interaction occurs during reactor operation, the fuel may support the cladding in a manner similar to the support provided the ring test specimens by the mandrels, but the relative extents of support are uncertain. In any event, it was expected that the strains to fracture obtained from ring tests would be greater than both the total elongations obtained from tensile tests in which the gage region was not supported, and the circumferential deformations to fracture obtained from burst tests in which necking instabilities were similarly unsupported.^{6,7} However, the single ring test of the present series that was run at 343°C with a grooved mandrel apparently indicates that the presence of an unsupported increment which is small with respect to the total length over which deformation is occurring does not necessarily "drastically reduce" the strain to fracture of the specimen. Additional, more refined tests of this general type would have to be run, however, before the effects and significance of "notched mandrels" could be fully evaluated.

5.1.8.3 Burst Tests

5.1.8.3.1 Procedure and Scope

Samples of cladding that had been exposed to estimated fast fluences of 6×10^{21} to 7×10^{21} nvt ($E > 1$ MeV) were obtained for burst testing by sectioning out 20-cm (8-in.)-lengths from selected fuel rods. All of the irradiated cladding samples came from tubing lot CA-2. One-half of the SA-1 rods were clad with tubing from this lot; hence it was the most representative and afforded the best selection of samples. For comparison, unirradiated control samples were cut from Type J Zircaloy-2 Fuel Cycle Program tubing that had been autoclaved. All of the control samples came from tubing lot CA-3; unfortunately, only tubing from this lot was in sufficient supply to prepare the required number. The unirradiated samples were tested in the hot cell according to the same procedure used on the irradiated samples.

Before an irradiated sample was tested, the crud and some of the external ZrO_2 were removed from ~ 2 cm ($\sim 3/4$ in.) of each end with emery cloth. Most of the fuel was left intact within the cladding; approximately 0.6 to 1.0 cm ($1/4$ to $3/8$ in.) was removed from one end so that wall thickness measurements could be made with a micrometer. The outside diameter of each sample was measured with a micrometer at the middle and at 5.1 cm (2 in.) from each end in two orientations 90 degrees apart. One end of the sample was sealed with a stainless steel Swagelok cap-type tube fitting. The other end was connected to a 1400 kg/cm^2 (20,000 psi) air-driven gas booster through 0.6 cm ($1/4$ in.) o.d. by 0.21 cm (0.083 in.) wall high-pressure tubing which was joined to the sample by means of another stainless steel Swagelok tube fitting. The length of sample between the fittings was approximately 16 cm ($6-1/4$ in.). The sample was placed in the center of a 3.8 cm ($1-1/2$ in.) i.d. by 0.6 cm ($1/4$ in.) wall by ~ 25 cm (10 in.) long steel shroud tube which was capped at each end (see Figure 91).

The sample then was pressurized to failure with argon at a rate of $53 \pm 21 \text{ kg/cm}^2\text{-min}$ ($750 \pm 300 \text{ psi/min}$). [However, the rate at the time of rupture was unintentionally increased to $320 \text{ kg/cm}^2\text{-min}$ (4600 psi/min) in the case of sample B98C-1, and to $89 \text{ kg/cm}^2\text{-min}$ (1260 psi/min) in the case of the unirradiated 454°C (850°F) control sample.] The pressure was measured by both a Bourdon tube gage and a transducer. The transducer output was fed into a strain gage signal conditioner, and the readout was continuously recorded in terms of pressure on a strip chart recorder.

Tests were performed at nominal temperatures of 343°C (650°F), 399°C (750°F), and 454°C (850°F), in addition to room temperature. To carry out the high-temperature tests, the shrouded sample was placed in an electric resistance tube furnace. The sample temperature was measured by means of three chromel-alumel thermocouples located at the middle and at 5.1 cm (2 in.) from each end of the sample. The middle thermocouple was connected to a saturable reactor temperature controller. The sample was brought to the test temperature and held there $1/2$ hour. It was then pressurized to failure. The temperature at the middle of the sample was somewhat higher than at the other locations measured. The three temperature readings were generally within $5-1/2^\circ\text{C}$ to $8-1/2^\circ\text{C}$ (10°F to 15°F) of each other throughout the test. In the case of the unirradiated 454°C control sample, the temperature at one end was $\sim 17^\circ\text{C}$ (30°F) lower than at the middle.

The diameter of a tested sample was measured with the micrometer at locations just outside of the burst region and, in most cases, at locations somewhat removed from the burst region as well. The measurements were made in two orientations, 90 degrees apart.

Figure 91. Unirradiated Sample Positioned in Open Shroud Tube Prior to Burst Testing

In addition to the foregoing measurements, the distance around a tested sample from one edge of the primary (longitudinal) fracture to the other was measured by using strips of 0.0025-cm (0.001-in.)-thick stainless steel foil, 0.16 cm (1/16 in.) to 0.32 cm (1/8 in.) wide by approximately 25 cm (10 in.) long. While the sample was held in a horizontal position, one of these foil strips—with small lead weights attached to each end—was wrapped around the fracture region at the location of apparent maximum circumferential elongation. Pulling the strip taut about the sample resulted in a crimping of the strip at the edges of the fracture. The distance between the crimp marks (C_f) was then measured out of cell by means of a scale and magnifying glass. The measured distances between crimp marks on duplicate foil strips were found to be within 0.025 to 0.05 cm (0.01 to 0.02 in.) of each other on each of the irradiated samples and on the room-temperature control sample. Reproducibility was poorer on the high-temperature control samples due to the irregular nature of the fractures shown by these samples.

5.1.8.3.2 Results

The control and irradiated samples are shown, after testing, in Figures 92 through 96, and the values of burst pressure, hoop stress at rupture, and percent strain to fracture are listed in Table 21. The $\Delta D/D_i$ values in the table were calculated from selected post-test diameter measurements made near the burst regions and the corresponding pre-test measurements. The locations at which these values were determined for the high test temperature samples are indicated in Figures 97 through 99. $\Delta D/D_i$ values determined at locations away from the burst regions also are designated. The circumferential elongation values $(C_f - C_i)/C_i \times 100$ in Table 21 were calculated from measurements made on the foil strips and the corresponding pre-test diameter measurements.

The average stresses at rupture for irradiated samples tested at room temperature and at nominal temperatures of 343°C, 399°C, and 454°C, were 8000 kg/cm² (114 kpsi), 5100 kg/cm² (72 kpsi), 4900 kg/cm² (69 kpsi), and 4400 kg/cm² (62 kpsi), respectively. Based on these average values for each pair of irradiated samples, the largest difference between irradiated and unirradiated control samples was shown in the 343°C tests (1800 kg/cm² or 25 kpsi) and the smallest difference was shown in the room temperature and 454°C tests (1400 kg/cm² or 19 kpsi).

It should be pointed out that while one of the room temperature samples was tested in a normal manner, the second was held at the highest test temperature investigated in the current series (i.e., 454°C) for the standard holding time before being pressurized at room temperature. Although the stress at rupture shown by the second sample was somewhat lower than that of the first, the difference in values probably was no greater than one might expect to obtain between two comparable non-heat-treated samples. However, as Figure 93 shows, the samples appeared quite different after testing. Sample B98A-2 split longitudinally in two separate orientations approximately 180 degrees apart.

Most of the strain to fracture values shown by the unirradiated high test temperature samples were considerably greater than those shown by the room temperature test sample. However, irradiation markedly decreased the strains to fracture among the high temperature samples; it showed a comparatively small effect at room temperature. The percent strain to fracture did not show any clear temperature dependence between 343°C and 454°C.

It is of interest to note in Figures 97 through 99 that diametral expansions of 2 to 7 percent occurred at locations removed from the burst regions on the various irradiated high test temperature samples.

5.1.8.4 Microhardness Measurements on Metallography Specimens

5.1.8.4.1 Procedure and Scope

Measurements of diamond pyramid hardness (DPH) were made on the cladding of two transverse and one longitudinal fuel rod section metallography specimens. Three-by-three arrays of indentations were made on each specimen at two locations approximately 180 degrees apart, or on opposite wall sections in the case of the longitudinal specimen. A typical array of indentations is shown in Figure 100.

5.1.8.4.2 Results

The DPH values obtained are given in Table 22. The average hardnesses were 217 and 223 DPH for the transverse specimens and 246 DPH for the longitudinal specimen. The measurements on the two specimens from Rod A41 indicate a directional difference in hardness, since the exposures were approximately the same.

The present measurements are probably most significant when compared with data on lower exposure and unirradiated Fuel Cycle Program cladding. The microhardness of an unirradiated transverse specimen was 158 DPH, and that of a longitudinal specimen was 195 DPH. Hardness measurements made on several transverse cladding sections exposed in the VBWR to between 1×10^{21} and about 1.5×10^{21} nvt > 1 MeV showed a maximum value of 201 DPH and an overall average value of 193 DPH.³

Figure 92. SA-1 Cladding Samples After Burst Testing
(See Table 21 for Key to Sample Designation)

(a) UNIRRADIATED

(b) IRRADIATED SAMPLE B98A-2

(c) IRRADIATED SAMPLE A42C-1
(HELD AT 454°C (850°F) FOR
1/2 hr BEFORE TESTING)

Figure 93. Burst Samples Tested at Room Temperature

*Figure 94. Burst Samples Tested at $\sim 343^{\circ}\text{C}$ (650°F):
(Unirradiated Sample No. 3 (left);
Irradiated Sample A47D-2 (right))*

Figure 95. Burst Samples Tested at $\sim 399^{\circ}\text{C}$ (750°F):
Unirradiated Sample No. 6 (left);
Irradiated Sample B98C-1 (right)

Figure 96. Burst Samples Tested at ~454°C (850°F): Unirradiated Sample No. 9 (left, top); Irradiated Samples B50A-2 (left, bottom) and B96C-2 (right)

Table 21
BURST TESTS ON SA-1 CLADDING SAMPLES

Sample Number*	Estimated Fast Fluence Exposure (nvt >1 MeV X 10 ⁻²¹)	Test Temperature °C (°F)	Burst Pressure kg/cm ² (kpsi)	Hoop Stress kg/cm ² (kpsi)	Strain to Fracture Percent	
					$\frac{D_f - D_i}{D_i} \times 100$	Circumferential Elongation
Unirradiated (0)	0	Room	716 (10.19)	6650 (94.6)	9	8
B98A-2 (1)	7	Room	792 (11.27)	8320 (118.4)	—	8
A42C-1 (2)	6	Room**	828 (11.77)	7660 (109.0)	—	6
Unirradiated (3)	0	343 (650)	356 (5.07)	3330 (47.3)	27	≥30
B96A-2 (4)	6.5	348 (659)	564 (8.02)	4980 (70.8)	4	3
A47D-2 (5)	6	348 (659)	586 (8.34)	5200 (74.0)	8	7
Unirradiated (6)	0	403 (757)	338 (4.81)	3150 (44.8)	16	≥12
B96C-1 (7)	6.5	403 (758)	533 (7.58)	4960 (70.6)	3-4	5
B98C-1 (8)	6.5	393 (740)	532 (7.56)	4770 (67.8)	4	5
Unirradiated (9)	0	454 (850)	315 (4.48)	3010 (42.8)	23	≥16
B96C-2 (11)	6	454 (850)	488 (6.94)	4490 (63.8)	2-4	4
B50A-2 (13)	6	459 (859)	478 (6.80)	4270 (60.7)	6	6

* Numbers in parentheses refer to sample designations used in Figure 92.

** Sample was held at 454°C for 30 minutes, cooled to room temperature and pressurized to failure.

—= Could not be measured.

Figure 97. Values of $(D_f - D_i)/D_i \times 100$ at Various Points Along Samples Tested at a Nominal Temperature of 343°C (650°F). (Two determinations 90 degrees apart were made at each axial location indicated.)

Figure 98. Values of $(D_f - D_i)/D_i \times 100$ at Various Points Along Samples Tested at a Nominal Temperature of 399°C (750°F)

Figure 99. Values of $(D_f - D_i)/D_i \times 100$ at Various Points Along Samples Tested at a Nominal Temperature of 454°C (850°F)

100X

Figure 100. Typical Array of Diamond Pyramid Hardness Indentations
(Specimen No. 9957)

Table 22
MICROHARDNESS OF SA-1 CLADDING

Fuel Rod	Metallography Specimen Number	Orientation	Estimated Fast Fluence Exposure $\text{nvt} > 1 \text{ MeV} \times 10^{-21}$	Location	DPH, 0.5 kg Load			
					Outside Diameter	Center	Inside Diameter	Average
A41	9956	Longitudinal	5	1	240	246	228	240
				2	253	246	254	251
A41	9957	Transverse	5	1	218	224	221	221
				2	228	226	222	225
A46	9958	Transverse	4.5	1	219	219	213	217
				2	219	214	217	217

No general difference in microhardness was noted with respect to the outside, center, and inside locations of the cladding wall. With the possible exception of the longitudinal specimen, the hardnesses measured at the two locations of a given specimen were about the same. However, the locations of the arrays of indentations with respect to the orientation of the rods in the fuel assembly during operation are not known.

5.1.8.5 General

The ultimate hoop stresses shown by the SA-1 burst samples were generally somewhat greater than the ultimate strengths shown by the somewhat lower exposure longitudinal coupon specimens, and the strain to fracture values of the burst samples were generally somewhat higher than the total elongations shown by the longitudinal specimens. The difference in strengths increased and the difference in elongations decreased with increasing test temperature.

The average 343°C (650°F) ultimate strength of the SA-1 coupon specimens was about 700 kg/cm² (10 kpsi) greater than the average 343°C ultimate strength of comparable specimens irradiated in the VBWR under the Fuel Cycle Program to $\sim 1 \times 10^{21}$ nvt > 1 MeV, and the total elongations were only ~ 0.3 percent lower. However, burst samples that were irradiated to $\sim 1 \times 10^{21}$ nvt, and were pressurized to failure with a liquid medium at room temperature, showed strains to fracture of 13 to 16 percent, i.e., about two times the elongations shown by the more highly exposed SA-1 samples.³

5.1.9 Crud Analysis (W. Lim)

5.1.9.1 Procedure and Scope

During the initial phase of the program the crud, i.e., the corrosion products deposited from the coolant, were removed from the surfaces of fuel rods A4, A13, A28, A41, B70, and B76 and chemically analyzed. These rods had operated in Dresden 840 days.

Removal of the crud was carried out 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 with fresh acid. Bottom subassembly rods A4 and A13, also A28 and A41, were combined into pairs for crud removal. Top subassembly rods B70 and B76 were de-crudged separately. The resulting eight solutions were analyzed for metallic elements by wet chemical techniques.

During the final phase of the program, the crud was chemically removed from rods A7, A9, A22, A37, A49, and B50. A somewhat different procedure was used on these later rods. The burets were replaced with tubes long enough to accommodate the full length of the rods. Each rod was placed in a separate tube and enough concentrated HCl was added to completely cover the rod. The acid was brought to the desired temperature (somewhat higher than the 70°C temperature used on the earlier rods), held at that temperature for a period of time, cooled to room temperature and drained off. Each rod was then inverted in its tube, and the procedure was repeated with fresh acid. The acid temperatures and holding times are listed below for the different rods.

Rod Number	A7	A9	A22	A37	A49	B50
Run Number 1						
Acid Temperature (°C)	94	94	82	82	82	81
Holding Time (hours)	3-1/2	3-1/2	5	5	5	3-1/2
Run Number 2						
Acid Temperature (°C)	93-99	93-99	83-84	99-100	99-100	83-88
Holding Time (hours)	3	3	3-1/2	3-1/2	3-1/2	2

The solutions obtained from the above rods were not analyzed.

5.1.9.2 Results

Analyses of the solutions, given in Table 23, indicated that nickel, iron, copper, and chromium were the principal metallic elements present in the crud. Nickel constituted approximately 65 to 75 percent of the combined weight of these four elements, which is expressed in terms of milligrams deposited per square decimeter of fuel rod surface. The data in Table 23 are presented in the form of a full-assembly profile. These profiles indicate that in the upper three-fourths of the assembly the deposition of Ni, Fe, Cu, and Cr was, on the average, somewhat greater than 300 mg/dm², while in the lower one-fourth the deposition of these elements was approximately 100 mg/dm². The relative concentrations of the elements did not vary widely with elevation, although it appears that the relative concentration of copper increased somewhat at mid-assembly, while the relative concentration of iron increased slightly at the top and bottom of the assembly.

The nearly solid black surface coloration of the initial phase rods after decrudding and the dark brown color of portions of the final phase rods are not what one would expect in view of the rather thick layers of ZrO₂ revealed by subsequent metallographic examinations of rod sections. It is possible that a very thin film of crud still remained on the surfaces after the dissolution operation. Some crud was, in fact, observed on a metallography specimen of one final phase rod (B50) that had been treated with hydrochloric acid. However, no evidence of remaining crud was detected on the several additional specimens examined.

5.1.10 Neutron Fluence Analysis (C. P. Ruiz, J. P. Peterson, Jr., F. R. Smith)

5.1.10.1 Procedure and Scope

The thermal and fast neutron fluences were measured on selected fuel and cladding samples by two methods. For the fuel samples, a thermal fluence was derived in the BURNUP program⁸ based on the U-235 depletion. A fast fluence was also obtained from the same data set, based on the U-238 fission contribution to the total fission inventory, and by use of a fast fission cross section of 310 mb. The cladding at some of the same locations, and at some additional ones of interest, was also analyzed for these two quantities. For these measurements, Co-60 and Mn-54 were utilized for the thermal and fast fluences, respectively.

The technique utilized with the cladding involved leaching an approximately 0.2 gram sample in concentrated HCl, removal of external deposits, weighing, and dissolution in HF. After complexing of the fluoride with boric acid, the solution was diluted to a known volume and aliquoted for the radiochemical determination which was performed directly by means of a high resolution Ge(Li) detector system. The iron and cobalt were measured by atomic absorption. The appropriate combination of the resultant data yielded the specific activity relative to the particular element. The fluence was obtained by describing the irradiation history in terms of time steps each of which was set equal to a given cycle of reactor operation. The exposure obtained in each cycle was weighted with respect to the power level of reactor operation. A cross section of 60 mb was used for the fast cross section.

During the initial phase of the program, the fuel, but not the cladding, of four burnup samples from different rods was analyzed for thermal and fast neutron fluences. In the final phase, ten cladding samples from six rods were analyzed, and fuel burnup samples from six of the ten locations were analyzed for neutron fluence. For the four locations in which a burnup analysis had not been performed, the burnup was determined from gamma scan data by utilizing the Cs-137 activity, and by estimating the corresponding fluences.

5.1.10.2 Results

The sample locations and the corresponding data are given in Table 24 with the exception of the thermal fluence derived from the cladding. The total fast fluence values ranged from 6×10^{21} to 1×10^{22} nvt ($E > 0.005$ MeV. The fluence > 1 MeV is approximately 0.7 of the total fast fluence.) The largest values were measured at those locations nearest the middle of the assembly on rods that operated to the end of Dresden Reactor Cycle No. 6. The fast fluence data obtained on the final phase samples by the two methods of measurement compare well, especially on consideration of the fact that a 300-day half-life monitor was used to obtain flux integrated over an 8-year period.

The magnitude of the thermal fluence for each sample based on U-235 depletion ranged from 2×10^{21} to 3.5×10^{21} nvt and follows the fast fluence variations. The data obtained from analysis of the cladding were found to be erratic. This could have been due to failure to remove the last traces of cobalt in the cladding deposition prior to dissolution. This contention is supported by widely varying apparent cobalt contents in the cladding, i.e., from 6.7 ppm to 19 ppm, which range is significantly larger than the range of error for the cobalt measurement by atomic absorption.

Table 23
CHEMICAL ANALYSIS OF CRUD SOLUTIONS

Fod	Distance from: Bottom of Reactor Active Fuel Zone [cm (in.)]	Fe		Cu		Ni		Cr		Fe, Cu, Ni, Cr Total Deposition (mg/dm ²)
		Deposition (mg/dm ²)	Relative Concentration (%)	Deposition (mg/dm ²)	Relative Concentration (%)	Deposition (mg/dm ²)	Relative Concentration (%)	Deposition (mg/dm ²)	Relative Concentration (%)	
B70	24.3 to 260.0	69	18.8	18	4.9	274	74.7	6	1.6	367
B76	(84-3/8 to 102-3/8)	72	23.1	14	4.5	226	72.4	<1	—	312
B70	155.9 to 214.3	34	13.9	14	5.7	187	76.3	10	4.1	245
B76	(61-3/8 to 84-3/8)	61	14.8	50	12.2	295	71.8	5	1.2	411
A4 + A13	103.9 to 154.6	44	17.1	34	13.2	176	68.5	3	1.2	257
A28 + A41	(42-7/8 to 60-7/8)	71	17.8	69	17.2	255	63.8	5	1.2	400
A4 + A13	50.5 to 108.9	24	18.9	6	4.7	94	74.0	3	2.4	127
A28 + A41	(19-7/8 to 42-7/8)	22	22.0	8	8.0	69	69.0	1	1.0	100

Table 24
FAST AND THERMAL NEUTRON FLUENCE

Sample Number	Location* (cm [in.])	Total Fast Fluence (nvt X 10 ⁻²¹ [E > 0.005 MeV])**		Thermal Fluence from U-235 (nv ₀ t X 10 ⁻²¹)
		From U-238	From Mn-54	
		Initial Phase		
A13-67	a) 27.3 (10-3/4) b) 126.7 (49-7/8)	8	—	2.3
A41-68	a) 27.6 (10-7/8) b) 126.4 (49-3/4)	8	—	2.4
A46-69	a) 27.6 (10-7/8) b) 126.4 (49-3/4)	7	—	2.4
B70-70	a) 26.4 (10-3/8) b) 181.6 (71-1/2)	7	—	2.3
Final Phase				
A11G-4	a) 80.3 (31-11/16) b) 73.5 (28-15/16)	7 [†]	7	2.6 [†]
A11E-2	a) 25.2 (9-15/16) b) 128.6 (50-11/16)	9	9	3.5
A33A-3	a) 25.2 (9-15/16) b) 128.6 (50-11/16)	7	8	2.9
A37H-2	a) 25.2 (9-15/16) b) 128.6 (50-11/16)	9	7	3.5
A47D-3	a) 81.8 (32-3/16) b) 72.2 (28-7/16)	6 [†]	7	2.1 [†]
A47D-1	a) 27.5 (10-13/16) b) 126.5 (49-13/16)	8	10	3.5
B62H-2	a) 28.3 (11-1/8) b) 183.5 (72-1/4)	9	9	3.5
B62J-4	a) 81.8 (32-3/16) b) 237.0 (93-5/16)	7 [†]	9	2.7 [†]
B96A-3	a) 28.3 (11-1/8) b) 183.5 (72-1/4)	9	10	3.5
B96C-4	a) 81.8 (32-3/16) b) 237.0 (93-5/16)	6 [†]	7	1.8 [†]

* a) Distance from center of specimen to-shoulder of short end plug.

b) Distance from bottom of Dresden Reactor active fuel zone.

** To obtain the fluence >1 MeV, these values may be multiplied by 0.7.

† These values were derived from Cs-137 gamma scan data.

5.2 IRRADIATED UO_2 CHARACTERIZATION STUDIES (H. S. Rosenbaum, Technical Director; U. E. Wolff)

The irradiated UO_2 fuel in some of the SA-1 rods was examined by several techniques in addition to that of optical (light) metallography (subsection 5.1.5). Replication electron microscopy was employed to investigate the microstructure of a metallographically prepared cross section at higher magnifications, and thin slivers of UO_2 extracted from a rod section were examined by thin foil transmission electron microscopy. Fracture surfaces were examined by replication electron microscopy. Fuel particles extracted from different radial locations of a rod cross section were analyzed by x-ray diffraction primarily to determine any relative changes in lattice parameter.

5.2.1 Examination of Metallography Specimens by Replication Electron Microscopy (U. E. Wolff, W. H. Kimball)

5.2.1.1 Procedure and Scope

In conjunction with the earlier light metallographic examination of specimen No. 9954 from fuel rod A13, cellulose acetate replicas were made of the polished UO_2 surface in both a light (3-second) etched condition and the standard (45-second) etched condition. Chromium-shadowed carbon replicas then were prepared from the plastic replicas and examined by electron microscopy with 80-kV electrons. The direction of shadowing was from the center of the fuel toward the cladding. The regions of the UO_2 examined are indicated on the light micrograph of figure 81.

Rod A13 was the most highly exposed rod removed from SA-1 at the end of Dresden Reactor Cycle No. 4. The transverse section examined had an average burnup of 8.1×10^{20} fissions/cm³ (29,700 MWd/tU).

5.2.1.2 Results

It was found that the standard etch revealed much more structure than did the light etch. There was no evidence of grain growth.

The interior of the grains in the central region of the specimen contained many small precipitates (see Figures 101, 102, and 103). These were also observed by light microscopy. Figure 81 shows that their concentration seemed to increase with distance from the center and then at a certain radius, 0.24 cm (0.094 in.) from the fuel periphery, dropped off sharply to form a ring. The concentration of precipitates was relatively low between the ring and a location about 0.01 cm (0.004 in.) from the pellet periphery (Figures 104, 105, and 106). Between the latter location and the periphery the concentration of precipitates was sharply increased. The intragranular precipitates adjacent to the cladding were apparently somewhat larger than those in the interior of the fuel (Figures 107 and 108). At all radial locations they appeared to have a crystallographic relationship to the mother grain.

The grain boundaries near the periphery of the UO_2 were more heavily etched than the centrally located grain boundaries, and they contained numerous precipitates which finally appeared to merge into continuous sheets covering the grain boundary surfaces (see Figures 105, 106, and 107). The radial distribution of the grain boundary precipitates and variation in the severity of grain boundary etching apparently correlate with the fuel burnup which increases toward the periphery (see subsection 5.3). Berman presented evidence that the heavy grain boundary attack in irradiated UO_2 coincided with the presence of fission products in the grain boundaries.⁹ It is therefore very likely that the grain boundary precipitates in specimen No. 9954 are fission products.

The volume fraction of the intragranular precipitates, as seen in the etched condition, had a bimodal radial distribution with one peak at the location of the darkly etched ring and the other peak at the fuel-cladding interface.

5.2.2 Examination of Thin Particles by Transmission Electron Microscopy (U. E. Wolff, E. S. Darlin)

5.2.2.1 Procedure and Scope

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.

The foils were obtained by extracting thin slivers of UO_2 from the fractured surface of a transverse metallography specimen. Hardness indentations were made with a 5000 g load at four different distances from the cladding to fracture the specimen surface. About 20 five-mm-diameter replicas were then made from all portions of this surface with the replicating material "Technovit." 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. 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). The thin slivers embedded in the final replicas were examined with either the 100 kV microscope at VNC or with the 650 kV microscope at the University of California at Berkeley.

The particles examined were extracted from metallography specimen No. 9954 from rod A13.

ETCHED 45 SECONDS

3000 x

Figure 101. Center Region of Irradiated Fuel After Standard Etch, Showing Some Precipitates and Light Grain Boundary Attack. [0.36 cm (0.14 in.) from Pellet Periphery] (Specimen No. 9954)

ETCHED 45 SECONDS

3000 x

Figure 102. Ring Region 0.30 cm (0.12 in.) from Pellet Periphery. Note Numerous Precipitates. (Specimen No. 9954)

ETCHED 45 SECONDS

3000 x

*Figure 103. Ring Region 0.24 cm (0.09 in.) from Pellet Periphery
(Specimen No. 9954)*

ETCHED 45 SECONDS

3000 x

*Figure 104. Outside of Ring Region 0.18 cm (0.07 in.) from Pellet Periphery.
Note Lack of Precipitates. (Specimen No. 9954)*

ETCHED 45 SECONDS

3000 x

Figure 105. 0.13 cm (0.05 in.) from Pellet Periphery, Where Increased Grain Boundary Attack Appears (Specimen No. 9954)

ETCHED 45 SECONDS

3000 x

Figure 106. 0.06 cm (0.02 in.) from Pellet Periphery, Where Large Precipitates Start to Appear. (Specimen No. 9954)

Figure 107. Fuel-Cladding Interface Region. Note Numerous Large Precipitates in UO₂ (Specimen No. 9954)

Figure 108. Large Intragranular Precipitates of Figure 107 Shown at Higher Magnification. Note Orientation.

5.2.2.2 Results

Some of the slivers had edges thin enough for electron microscopy with 100-kV electrons. Figure 109 shows such a thin edge. Dislocation loops and several small pores are visible.

A number of replicas were examined with 650-kV electrons.

a. Area near cladding:

Figure 110 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 111 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 108).

b. Area about 1.3 mm (0.05 in.) from cladding:

A small chip (Figure 112) was transparent in its entirety to 650 kV electrons. A dense dispersion of defects is seen in bright and dark field. Similarly, Figure 113 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 (0.15 in.) from cladding:

Two small chips are shown in Figure 114. 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.

5.2.3 Examination of Fracture Surfaces by Replication Electron Microscopy

(U. E. Wolff, W. C. Oh, E. S. Darlin)

5.2.3.1 Procedure and Scope

This investigation was undertaken to gain more insight into the grain boundary structure of highly irradiated UO_2 fuel than could be obtained from the two previously described electron microscopic techniques. Since irradiated UO_2 is very brittle and apparently fractures intergranularly, such fracture surfaces appeared to be suitable for grain boundary examination at the high magnifications obtainable by electron microscopy of replicas.

The starting material was specimen No. A584 from the peak burnup region of rod A11. This rod operated to the end of Cycle No. 6 and attained a peak burnup of 10.0×10^{21} fissions/cm³ (36,600 MWd/tU). The section prepared was the surface mating with metallography specimen No. A582. The microstructure of the latter showed platelet precipitates with maximum density near the cladding and again in a ring at about mid-radius (see Figure 80). It was very similar to the structure observed in previously mentioned specimen No. 9954 from rod A13. Specimen No. A584 was polished without using water in order to retain water-soluble fission products.

Particles of UO_2 were pulled from the fuel cross section at selected locations again with the aid of Technovit replicating material, but applied in this case with a small mold. This mold is a patented device made of plastic called a T&B "Ty-Rap" (used by electricians to harness electrical cables) and contains a 5-mm diameter hole. The device also has a ~18-cm (7-in.) tail and, therefore, can be handled remotely rather easily (see Figure 115). The Ty-Rap was secured to the desired area of the fuel cross section with double-backed masking tape. In some cases, the opening was restricted to a diameter smaller than 5 mm by cutting an appropriately smaller hole into the masking tape. The Technovit replicating material was poured into the hole and allowed to cure. After curing, the Technovit plug adhered tenaciously to the UO_2 . When the Ty-Rap was lifted off the UO_2 , particles of UO_2 were pulled off with the Technovit. The particles firmly adhered to the Technovit and presented fresh UO_2 fracture surfaces for further replication. Because of the brittleness of the irradiated UO_2 it was not necessary in this case to make hardness indentations as a means of producing fractures.

To correlate each Technovit plug with its original position on the UO_2 cross section, a photograph was taken of the section with the empty mold in place (Figure 116[a]), another one after removal of the Technovit plug (Figure 116[b]), and a third of the stripped plug with the embedded UO_2 particles (Figure 116[c]). By comparison of the UO_2 crack pattern on these photographs, the location of the replica with respect to the UO_2 cross section could be determined. Such groups of photographs were taken for each Technovit plug.

Up to this stage all operations were done remotely. Next, the plastic molds with the Technovit were removed from the hot cell, the Technovit plugs were pressed out of the mold, and carbon was evaporated at 45 and 90 degrees onto the surface containing the UO_2 particles. The Technovit was dissolved in acetone leaving the carbon replicas, usually in several pieces, floating in the acetone. These carbon replicas contained embedded the majority of the UO_2 particles. Since the particles were large and not transparent to electrons, they were dissolved by immersion of the replicas in diluted (1:1) nitric acid for about one week. After washing the replicas in several changes of a solution of

Figure 109. Irradiated UO_2 , 8×10^{20} Fissions/cm³ 1.3 ± 0.7 mm from Cladding

BRIGHT FIELD

DARK FIELD

650 KV ELECTRON MICROGRAPHS

Figures 110. Irradiated UO_2 , 8×10^{20} Fissions/ cm^3 $0.2^{+0.7}_{-0.2}$ mm from cladding

650 KV ELECTRON MICROGRAPH

75,000x

Figure 111. Irradiated UO_2 , ~0.2 mm from Cladding. Platelet Precipitates in Matrix

DARK FIELD

75,000x

BRIGHT FIELD

75,000x

Figure 112. Irradiated UO_2 , ~1.3 mm from Cladding

DARK FIELD

60,000x

BRIGHT FIELD

60,000x

DARK FIELD

60,000x

Figure 113. Irradiated UO_2 , ~1.3 mm from Cladding

DARK FIELD

75,000x

BRIGHT FIELD

75,000x

Figure 114. Irradiated UO_2 , Near Fuel Center

(a) OVERALL VIEW

(b) ENLARGED DETAIL

Figure 115. Plastic Mold for Replicating Resin

(a) MOLD FASTENED ON FUEL CROSS-SECTION.

(b) FUEL CROSS-SECTION AFTER STRIPPING OF TECHNOVIT; ROUGH SURFACE AREA INDICATES STRIPPED FUEL.

(c) TECHNOVIT IN MOLD WITH STRIPPED UO_2 IN PLACE.

Figure 116. Replication Stages with Technovit, Replica No. 7

1 part methanol in 5 parts of water, they were examined by transmission electron microscopy. All micrographs were taken as stereo pairs to aid in interpretation. However, only single micrographs are included in this report.

In the series of strippings, the first few Technovit plugs were only about 1 mm in diameter. These had not pulled out observable UO_2 particles. The first plug with appreciable amounts of UO_2 was replica No. 7 (Figure 116). This plug had a diameter of about 2 mm and came from the periphery of the fuel. Part of the cladding is visible on Figure 116(a).

As the preparation of additional Technovit plugs proceeded, more and more UO_2 particles were removed from the polished surface. Each new Technovit plug, therefore, replicated some old fracture surfaces in addition to pulling out fresh UO_2 particles. Consequently, the final carbon replicas may have contained some areas of two-stage replication and some of one-stage replication of UO_2 fracture surfaces as indicated in Figure 117.

Replica No. 16 was one of the later 5-mm-diameter Technovit plugs from the fuel periphery (Figure 118), and No. 18 was a 5-mm-diameter plug from the center of the fuel (Figure 119).

5.2.3.2 Results

5.2.3.2.1 Replicas No. 7 and No. 16 (Near Cladding)

Two grains, about 10 to 15 μm across, had been pulled out with Replica No. 7 (Figure 120). One grain is a nearly perfect cube; the other one shows five facets. Both have fairly smooth surfaces with a few "bumps." It appears that the five-facet grain contains an inclusion which in turn has a smooth pore on its surface (longer arrow in Figure 120). Another pore is seen on another facet (short arrow). A different type of particle is shown in Figure 121. It appears to have four facets. However, two of them have river markings and might, therefore, not be grain boundaries. The junctions of the facets are rough. At the apex of the particle a short flat split is seen (arrow).

Areas where previously UO_2 particles had been pulled out of the specimen surface are shown in Figure 122 from Replica No. 16. The fracture is intergranular, and both micrographs contain several grains with their junctions. In Figure 122(a), a round second-phase particle is visible near the most prominent junction. The grain boundary surfaces on Figure 122(b) contain a number of large pores (with white "shadows") and a second-phase particle (arrow). Also, a small angular UO_2 particle has been pulled with this replica (double arrow).

5.2.3.2.2 Replica No. 18 (Near Fuel Center)

The fracture surfaces in the fuel center have an appearance quite different from that at the fuel periphery. Figure 123 shows ripples, grooves, and a cell-like structure on the grain boundaries. Similar ripples are seen in Figure 124(a). In addition, the fracture surfaces contain numerous small, uniformly dispersed "bumps" (Figure 124) the nature of which is not clear at present. The bumps might be evidence of small second-phase or fission product particles.

Another feature of Replica No. 18 is the occurrence of fairly flat structures about 5 to 10 μm across (Figures 124(a) and 125). It appears probable that these flats are manifestations of second-phase particles which either have cleaved or parted at the particle-matrix interface. The flat split in Figure 121 might be the same kind of feature. In the optical metallography, no comparable structural details were observed which could be correlated directly with the observed plate-structure. The plates are definitely much larger than the overall platelet precipitation observed within the grains (see Section 5.2.1).

5.2.3.2.3 Summary

The features observed on the UO_2 grain boundaries cannot readily be interpreted. Few pores were seen, but the resolution of replicas is not good enough to detect pores of less than about 100 to 200 $\text{\AA}$ diameter. The platelets seen in the grain interiors by optical metallography and by replication electron microscopy of cross sections were not present on the grain boundary surfaces. This, of course, could be expected since the platelets had never been observed in grain boundaries. However, the grain boundaries might contain continuous second-phase coatings. If so, it would be difficult to detect such phases on replicas of fracture surfaces. Second phases can more readily be seen if they are discontinuous. The "bumps" observed might be such second phases. However, they do not correspond to anything seen in the cross sections.

5.2.4 Lattice Parameter Measurements (J. E. Lewis, J. L. Lakner)

5.2.4.1 Procedure and Scope

X-ray diffraction analyses were performed on three fuel samples from specimen No. 584 from rod A11, i.e., the same specimen used for the examination of fracture surfaces (subsection 5.2.3). The samples were taken from the center, mid-radius, and periphery of the polished fuel cross section.

(a) FIRST STEP: TECHNOVIT APPLIED TO UO₂ SURFACE WITH PARTICLE ALREADY PULLED OUT BY PREVIOUS REPLICA.

(b) SECOND STEP: TECHNOVIT HAS PULLED OUT ANOTHER UO₂ PARTICLE. CARBON COATING PRODUCES REPLICA THAT IS ONE-STAGE OVER THE FRESHLY PULLED PARTICLE AND TWO-STAGE OVER THE REST OF THE SURFACE.

Figure 117. Schematic Representation of Replication

(a) MOLD PLACED ON FUEL CROSS-SECTION

(b) STRIPPED TECHNIVIT PLUG WITH EXTRACTED UO_2

Figure 118. Technovit Replica No. 16

(a) MOLD PLACED ON CENTER OF FUEL CROSS-SECTION

(b) STRIPPED TECHNOVIT PLUG WITH EXTRACTED UO_2

Figure 119. Technovit Replica No. 18

Figure 120. Carbon Replica No. 7 from Near Fuel-Cladding Interface

EXTRACTED UO_2 PARTICLE HAS SOME SMOOTH SURFACES AND SOME SURFACES WITH RIVER MARKINGS. THE JUNCTIONS BETWEEN FACETS ARE ROUGH. ARROW MARKS A FLAT SPLIT IN THE UO_2 .

Figure 121. Carbon Replica No. 7

(a) ROUND SECOND PHASE PARTICLE NEAR MOST PROMINENT JUNCTION.
(BLACK SPOTS ARE ARTIFACTS OR UNDISSOLVED UO_2 .)

(b) SEVERAL PORES (WITH WHITE "SHADOWS") AND AN INCLUSION (ARROW).

Figure 122. Carbon Replica No. 16 Showing Grain Boundary Surfaces

(a)

(b)

GRAIN BOUNDARY SURFACES WITH RIPPLES AND GROOVES

Figure 123. Carbon Replica No. 18 from Center of Fuel

(a)

(b)

GRAIN BOUNDARY SURFACES WITH A UNIFORM DISPERSION OF "BUMPS"
 FLAT AREAS IN (a) ARE POSSIBLE SECOND PHASES.

Figure 124. Carbon Replica No. 18

(a)

(b)

IRREGULAR SURFACES WITH CRACKS, PROBABLY GRAIN BOUNDARY SURFACES.
FLAT AREAS ARE POSSIBLE SECOND PHASES.

Figure 125. Carbon Replica No. 18

This analysis was primarily performed in an attempt to measure the oxygen-to-metal ratio by observing relative changes in the UO_2 fuel unit cell dimension. In addition, checks were made for other crystallographic phases, such as U_4O_9 and fission products and for irradiation damage effects.

Unfiltered Cu x-rays were used with the 114.6-mm diameter Debye-Scherrer powder cameras for the analysis. The x-ray diffraction analysis was performed using a rotating anode x-ray generator system operated at 50 kV and 100 mA. The UO_2 lattice parameter, a_0 , for each powder camera film was calculated from all readable diffraction lines, including those caused by the Cu $K\beta_1$ wavelength component, with diffraction angle 2θ more than 90 degrees. These data were extrapolated by means of the Nelson-Riley function¹⁰ to obtain the corrected values. The standard deviation from the least squares fit of the data to the Nelson-Riley function was taken as the probable error associated with each parameter.

The particle extraction technique described in subsection 5.2.3 was employed to obtain samples for the x-ray diffraction measurements. The size of the hole in the double-backed masking tape used to secure the mold to the specimen was about 2 mm in diameter.

Figure 126 shows the fuel particles attached to the Technovit, and the circles indicate from which area of the replicas the particles were taken. The particles were removed using a microscope and fine steel probe. They were transferred to the end of a 0.12-mm (0.005-in.) diameter glass fiber coated with petroleum jelly which was used as the adhesive for the fuel particles. The glass fibers were held with modeling clay in brass powder camera mounts.

The x-ray diffraction exposure time was predetermined by placing the sample and film in the cameras for various times to determine the maximum permissible background fogging to the film from radiation emitted by the sample.

The radiation level of the prepared powder camera samples as measured with a C.P. meter at contact were as follows:

Sample	Radiation Level (mR/h)		Maximum Film Exposure Time (hr)
	γ	$\beta\text{-}\gamma$	
Center of Pellet	1	19	2.5
Mid-Radius	18	115	0.75
Periphery of Pellet	2	19	2.5

5.2.4.2 Results

No phases other than the UO_2 fuel could be detected. The particles of fuel examined were not removed exactly from the area of highest second-phase concentration, but close enough to the area so that some of the second phase should have been in the x-ray samples. Apparently the concentration of this phase is too small to be observable.

The results of the UO_2 lattice parameter measurements were rather significant. The lattice parameter of the irradiated UO_2 , averaged over all three radial positions, is 0.10 percent larger than that of the unirradiated control specimen. This increase can be attributed to irradiation damage,¹¹ since the fuel specimen was not run at a temperature high enough (1650°C) to anneal out the irradiation damage. (The maximum centerline temperature was approximately 1650°C (3000°F) and was attained early in the period of operation.) The lattice parameter measurements are presented in Table 25.

A small difference in the lattice parameter between the center and the periphery was also noted. However, because of the confidence limits that must be placed on these measurements, the difference may not be significant. If significant, however, this change would indicate an average increase in the lattice parameter of approximately 0.04 percent from the center to the periphery of the fuel. This change, if attributed to an oxygen-metal ratio change based on the UO_2 lattice parameter, would correspond to a difference of approximately 1.3 percent from the center to the periphery.

5.3 FUEL BURNUP AND ISOTOPIC COMPOSITION ANALYSES

(C. P. Ruiz, Technical Director; J. P. Peterson, Jr., F. R. Smith)

5.3.1 Analysis of Fuel Samples

5.3.1.1 Procedure and Scope

Full cross-section samples of fuel and cladding 1.3 cm (1/2 in.) long were cut from four rods that operated to the end of Dresden Reactor Cycle No. 4 and from 16 rods that operated to the end of Cycle No. 6. Samples were taken

(a) CENTER OF FUEL PELLET

(b) MID-RADIUS APPROXIMATELY 3 mm
(~0.1 in.) FROM FUEL CENTER

(c) PERIPHERY OF FUEL APPROXIMATELY
0.5 mm (~0.02 in.) FROM FUEL-
CLADDING INTERFACE

PARTICLES WITHIN CIRCLES WERE USED FOR X-RAY DIFFRACTION ANALYSIS.

Figure 126. Technovit Replicas in Molds with Embedded UO_2 Particles Extracted from Fuel Section A-584

Table 25
LATTICE PARAMETER OF IRRADIATED UO_2

Sample	a_0 (Å)	Increase in a_0 (%)
Unirradiated Control	5.470 ± 0.001	
Specimen No. A584		
Center	5.475 ± 0.001	0.09
Mid-Radius	5.475 ± 0.002	0.09
Periphery	5.477 ± 0.001	0.13
Average Increase		0.10

from rods located in both subassemblies; however, more samples were taken from the bottom subassembly (A-1) than from the top (B-1). Most of the samples were taken from locations of maximum burnup 25 to 30 cm (10 to 12 in.) from the short end plug shoulders. However, in the final phase of the program eight additional samples were taken from axial locations near the ends of the highest exposure "A" rod and "B" rod, primarily to monitor the reliability with which Cs-137 could be used to measure burnup under the operating conditions of this fuel. (Gamma scanning, which is discussed in the following section, was actually performed before the sample cutting to aid in selecting the samples.)

The fuel of each of the above samples was dissolved at ambient temperature in 8 molar nitric acid for a period in excess of 24 hours. A small sample was transferred from the hot cells to the Radiochemical Laboratory for analysis.

In addition to the full cross-section samples, sets of fuel samples were obtained in the initial phase of the program from the maximum burnup locations of two rods to determine burnup and isotopic composition as a function of radial location. The samples were removed by grinding one end of a 4.5-cm (2-in.) rod length toward the center in steps as the piece was rotated. Ten samples were taken from each rod. Figure 127 shows the end of a rod length at the completion of sampling.

Mass spectrometry was employed to measure burnup by the Nd-148 method and measure uranium and plutonium.¹² These data provided the input to the computer program BURNUP.⁸ In addition to yielding the burnup and isotopic composition, the program yields the fraction of fissions from each of the four primary fissionable species, U-235, Pu-239, Pu-241, and U-238, and a set of effective cross sections consistent with the isotopic abundance measured with the burnup, and with the thermal neutron fluence, based on the U-235 depletion. As was discussed earlier, a fast fluence can be estimated from the U-238 fission fraction.

In addition to the uranium and plutonium isotopes usually measured, Pu-236, Pu-238, and the isotopic concentrations of americium and curium were determined on selected samples from both the initial and final-phase rod groups. U-232 was measured on some samples from rods that operated to the end of Cycle No. 6; Np-237 and the fission products Cs-137, Cs-134, Ru-106, and Ce-144 were measured on most of the samples from rods that were removed from SA-1 at the end of Cycle No. 4.

The measurement of the U-232, Pu-236 and Pu-238, and the americium and curium were obtained by alpha particle spectroscopy by use of solid-state detectors, after suitable separations. For U-232 analysis this involved multiple passes through a Dowex-1 anion exchange column using both aqueous HCl and HNO_3 media to selectively separate the uranium from plutonium, the most troublesome alpha active contaminant. After final purification, the uranium was electroplated onto platinum discs for alpha pulse-height analysis from which the U-232 was measured relative to the U-236, which in turn was related to the U-238 by means of the mass spectrometric analysis. The alpha particle spectra of the plutonium-fraction, available from the separation for mass spectrometric analysis, was the basis of the Pu-236 and Pu-238 data. The americium and curium were measured in the initial effluent from the aqueous HNO_3 Dowex-1 column from which the uranium and plutonium had been separated by adsorption on the column.

The above procedure provided data on the abundances of Am-241, Am-243 and Cm-242, Cm-244. With some of the earlier samples anion exchange chromatography of the residual solutions was performed by use of methanolic HNO_3 to separate the americium from the curium and from fission products. The abundances of Am-242 and Cm-243, Cm-245, Cm-246 were then obtained by mass spectrometry.

Figure 127. Appearance of Portion of Fuel Rod B70 After Samples Had Been Removed from Different Radial Locations

The Np-237 was analyzed radiochemically. In brief, the procedure consisted of blending a measured volume of original sample solution with a known amount of tracer Np-239. Isotopic exchange was obtained by reduction to the tetravalent state in HNO_3 , and the neptunium was separated from the other heavy elements and fission products by anion exchange in a reducing media. The neptunium fraction was mounted and gross alpha counted. The fraction of alpha counts due only to neptunium was determined by pulse-height analysis, and the chemical yield determined by comparative gamma pulse-height analysis using the 106 keV peak of Np-239. These data, combined with a knowledge of the plutonium concentration, yielded the Np-237/U-238 atom ratios.

5.3.1.2 Results

The results of the measurements made on full cross-section samples in both the initial and final phases of the program are given in Tables 26, 27, and 28. Table 26 gives the plutonium and uranium concentrations for the more abundant isotopes and the burnup based on the Nd-148 method. The highest exposure was achieved by sample 116 from rod B62 for which a burnup of 10.4×10^{20} fission/cm³ (37,900 MWd/tU) was measured. The axial locations of the 10 samples obtained from rods A37 and B62 are indicated with respect to the Dresden reactor active fuel zone in Figure 128. Single samples from other "A" rods were obtained from axial locations approximately the same as that of sample 105 from rod A37, and single samples from other "B" rods were obtained from axial locations near that of sample 116 from rod B62.

Table 27 gives the isotopic abundances of the less abundant isotopes of uranium and plutonium, as well as those of americium and curium for the nine samples analyzed. All the data have been corrected for growth or decay to the time of fuel discharge where appropriate. These data are useful in defining the magnitude of the various nuclides found in BWR fuel irradiated in these high neutron fluences. Based on these data and appropriate calculations, the effect of these low abundance nuclides can be determined with somewhat greater accuracy; for example, the effect of relatively high levels of U-232 on uranium handling. It is to be noted that in all cases, the specification limit of 110 ppb of U-232 relative to U-235 for reenrichment is exceeded (not only by virtue of U-232 but also because of the low residual abundance of U-235).¹³ The relatively high levels of Pu-236 and Pu-238 must be considered in working with plutonium separated from high exposure fuel. Finally, these measurements provide some data on the quantities of americium and curium available in high exposure fuel which are useful in defining more precisely the heavy element isotopic inventory, of interest in fuel cycle considerations.

The results of the fission product analyses performed on full cross-section samples are given in Table 28.

Fuel samples were taken from different radial positions from the maximum burnup locations of rods A13 and B70, which had cross-sectional average burnups of 8.1×10^{20} fissions/cm³ and 6.9×10^{20} fissions/cm³, respectively. Presented in Tables 29 and 30 as functions of radial location are burnup, uranium and plutonium isotopic compositions, and the atom ratios relative to U-238 of Np-237, Pu-238, Am-241 and Am-243, Cm-242 and Cm-244, and the fission products Nd-148, Cs-137 and Cs-134, Ru-106, and Ce-144. The marked radial dependence of burnup, of plutonium content, and of the concentrations of some other heavy elements and fission products can be noted.

The distributions of fissions among U-235, Pu-239, Pu-241, and U-238 are given for the various full cross-section and radial samples in Appendix D.

5.3.2 Fuel Rod Gamma Scan Data

5.3.2.1 Procedure and Scope

Axial traverses of gamma-ray activity were made on the 10 rods removed from Assembly SA-1 after two cycles of operation in Dresden and on 41 rods that operated through four cycles. The following procedure and system (Figure 129) were used in the final phase of the program. A 40 cc detector was placed in front of a collimator slit which penetrated through the 91-cm (36-in.) hot cell wall. Thus, as the fuel rod was drawn past the appropriate end of the slit (located against the interior of the cell wall), the detector received a collimated gamma ray beam.

The pulses from the detector were passed through a solid-state preamplifier, amplifier, and base line restorer. At this point, the pulses were routed to a 1024 multichannel analyzer and to two single-channel analyzers. One of the single-channel analyzers was set to accept pulses at the energy corresponding to gamma rays from a particular fission product nuclide of interest, while the other single-channel analyzer was set to accept pulses at a slightly higher energy for a measure of the Compton and background distribution. The output pulses from each of these analyzers were fed to scalars and also to two linear count rate meters, from which the signals were fed to a strip chart recorder, such that the background signal count rate was subtracted from the total count rate to yield only a net count rate.

Table 26
BURNUPS AND URANIUM AND PLUTONIUM ISOTOPIC COMPOSITIONS OF FULL CROSS SECTION SAMPLES

Rod Number	Sample Number	Nominal Cold Enrichment (at.% U-235)	Distance From Short End Plug Shoulder [cm (in.)]	Burnup		Atom Percent (Normalized to Total 100%)									
				Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU	Fission	U-234	U-235	U-236	U-238	Pu-239	Pu-240	Pu-241	Pu-242	
Initial Phase															
A46,	69	2.79	27.6 (10-7/8)	6.9	25,300	2.894	0.012	0.572	0.382	95.516	0.331	0.181	0.075	0.037	
B70	70	2.79	26.4 (10-3/8)	6.9	25,300	2.889	0.012	0.622	0.372	95.449	0.352	0.188	0.079	0.036	
A41	68	3.53	27.6 (10-7/8)	7.8	28,500	3.266	0.015	0.736	0.484	94.838	0.347	0.192	0.080	0.041	
A13	67	3.53	27.3 (10-3/4)	8.1	29,700	3.402	0.016	0.777	0.442	94.663	0.376	0.198	0.086	0.041	
Final Phase															
A35	104	2.79	26.4 (10-3/8)	8.42	30,780	3.510	0.010	0.312	0.395	95.053	0.345	0.218	0.092	0.066	
A43	112	↓	↓	8.75	31,980	3.655	0.012	0.450	0.454	94.706	0.356	0.219	0.090	0.058	
A42	111			9.04	33,050	3.850	0.010	0.243	0.405	94.849	0.335	0.222	0.093	0.076	
A47	113			9.04	33,060	3.768	0.009	0.260	0.402	94.820	0.348	0.224	0.095	0.074	
A48	114			9.18	33,560	3.825	0.009	0.245	0.404	94.771	0.347	0.226	0.095	0.078	
A49	115	↓	↓	9.19	33,590	3.828	0.009	0.212	0.408	94.799	0.341	0.226	0.096	0.082	
B96	122			29.4 (11-9/16)	32,080	3.658	0.009	0.279	0.398	94.910	0.358	0.220	0.096	0.071	
B91	121			8.87	32,420	3.696	0.009	0.272	0.415	94.876	0.347	0.223	0.095	0.073	
B98	123			9.10	33,250	3.789	0.009	0.224	0.403	94.796	0.362	0.231	0.102	0.083	
A34	103	3.24	26.4 (10-3/8)	8.82	32,230	3.683	0.011	0.431	0.459	94.708	0.343	0.218	0.088	0.060	
A33	102	↓	↓	8.99	32,875	3.760	0.013	0.518	0.483	94.493	0.361	0.224	0.090	0.057	
A40	110			9.24	33,790	3.850	0.009	0.230	0.403	94.789	0.321	0.226	0.091	0.081	
A9	100			9.60	35,080	4.010	0.011	0.422	0.486	94.318	0.358	0.231	0.096	0.069	
A11	101			10.03	36,650	4.188	0.012	0.373	0.500	94.227	0.305	0.233	0.086	0.074	
A37	105	3.53	26.4 (10-3/8)	10.21	37,330	4.264	0.012	0.359	0.500	94.133	0.331	0.232	0.092	0.076	
↓	106	↓	↓	1.6 (5/8)	9.96	36,400	4.160	0.012	0.301	0.497	94.346	0.309	0.216	0.085	0.074
	107			4.1 (1-5/8)	8.80	32,190	3.684	0.013	0.517	0.485	94.616	0.338	0.211	0.084	0.053
	108			92.2 (36-5/16)	7.25	26,510	3.040	0.013	0.859	0.445	95.055	0.318	0.174	0.065	0.030
	109			94.8 (37-5/16)	7.97	29,130	3.339	0.014	0.651	0.472	94.934	0.300	0.185	0.067	0.039
	B62			29.4 (11-9/16)	10.37	37,900	4.328	0.011	0.365	0.505	94.044	0.333	0.241	0.094	0.078
	117			1.6 (5/8)	9.89	36,130	4.131	0.012	0.329	0.502	94.345	0.305	0.222	0.084	0.071
	118			4.1 (1-5/8)	8.86	32,370	3.704	0.013	0.532	0.479	94.600	0.326	0.211	0.082	0.052
	119			92.2 (36-5/16)	6.19	22,620	2.596	0.015	1.118	0.403	95.238	0.332	0.151	0.058	0.020
	120			94.8 (37-5/16)	6.97	25,460	2.920	0.014	0.944	0.434	95.132	0.307	0.160	0.061	0.026

Table 27

ABUNDANCES OF U-232, Np-237, Pu-236, Pu-238, Am AND Cm ISOTOPES IN FULL CROSS SECTION FUEL SAMPLES

Rod and Sample Numbers	Burnup		Atom Ratios (Corrected to time of fuel discharge)												
	Fissions/cm ³	MWd/tU	U-232 U-238	U-232 U-235	Np-237 U-238	Pu-236 U-238	Pu-238 U-238	Am-241 U-238	Am-242 U-238	Am-243 U-238	Cm-242 U-238	Cm-243 U-238	Cm-244 U-238	Cm-245 U-238	Cm-246 U-238
	(X 10 ⁻²⁰)		(X 10 ⁹)	(ppb)	(X 10 ⁴)	(X 10 ¹⁰)	(X 10 ⁴)	(X 10 ⁵)	(X 10 ⁷)	(X 10 ⁵)	(X 10 ⁵)	(X 10 ⁷)	(X 10 ⁵)	(X 10 ⁷)	(X 10 ⁸)
Initial Phase															
A46-69	6.9	25,300	NA	NA	NA	3.8	0.87	2.7	4.4	4.8	1.11	2.33	0.93	2.81	3.8
B70-70	6.9	25,300	↓	↓	2.8	2.5	0.70	3.2	3.9	4.1	1.17	2.27	1.01	3.35	3.8
A41-68	7.8	28,500	↓	↓	3.4	5.5	1.06	5.5	5.3	5.6	1.52	3.32	1.48	5.59	6.8
A13-67	8.1	29,700	↓	↓	3.4	4.9	1.14	6.5	NA	NA	1.58	NA	1.62	NA	NA
Final Phase															
A49-115	9.19	33,590	*	*	NA	8	2.1	4.4	NA	15.8	1.8	NA	3.8	NA	NA
B98-123	9.10	33,250	1.2	520	↓	8	1.8	3.7	↓	10.9	2.0	↓	2.9	↓	↓
A9-100	9.60	35,080	1.7	380	↓	9	2.1	3.3	↓	9.9	1.8	↓	2.4	↓	↓
A37-105	10.21	37,330	1.7	460	↓	12	2.2	3.2	↓	9.4	1.8	↓	2.9	↓	↓
B62-116	10.37	37,900	1.5	400	↓	8	2.0	2.5	↓	10.1	2.0	↓	2.9	↓	↓

NOTES:

NA = Not Analyzed.

Nominal initial uranium enrichments were 2.79 at.% for rods A46, B70, A49, and B98 and 3.53 at.% for rods A41, A13, A9, A37, and B62.

*These data for sample 115 appeared to be unreasonably high and, hence are not reported.

Table 28
FISSION PRODUCT ANALYSES ON FULL CROSS SECTION FUEL SAMPLES

Rod and Sample Numbers	Burnup		Atom Ratios Relative to U-238*				
	Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU	<u>Nd-148</u> U-238 (X 10 ³)	<u>Cs-137</u> U-238 (X 10 ³)	<u>Cs-134</u> U-238 (X 10 ³)	<u>Ru-106</u> U-238 (X 10 ³)	<u>Ce-144</u> U-238 (X 10 ³)
A46-69	6.9	25,300	0.522	1.9	0.13	0.17	0.31
B70-70	6.9	25,300	0.507	1.7	0.12	0.14	0.34
A41-68	7.8	28,500	0.573	2.3	0.16	0.15	0.42
A13-67	8.1	29,700	0.606	2.4	0.18	0.16	0.41

*Corrected to time of fuel discharge.

The energy region for the single-channel analyzer was set by operating the multichannel analyzer in the coincidence mode. The gating signal was supplied from a given single-channel analyzer. The width of the energy region was set to accept the total photopeak for the signal. A corresponding number of channels was set for the background single-channel analyzer.

A typical gamma-ray spectrum is shown in Figure 130. Of primary interest was Cs-137 to provide relative burnup data. Data were obtained on all 41 rods scanned by using the signal at 0.662 MeV with the background region set at 0.680 MeV. To obtain some information on the relative amounts of Pu-239 fission some of the rods were scanned for Ru-106, which by virtue of its fission yield shows a ~10-fold enhancement over that for U-235 fission. In addition, data were obtained for Ce-144 (285 days half-life) and Zr-95 (65 days half-life) to provide data on more recent relative rod burnups. For the Ru-106, Ce-144, and Zr-95, the signal gating regions were 0.515, 2.19 (Pr-144), and 0.765 MeV (Zr + Nb-95) with the background gating regions set at 0.530, 2.30, and 0.820 MeV, respectively.

In the scanning, the rods from both subassemblies were oriented axially as they had operated in Dresden so that the relative gamma activity could be recorded as a function of increasing distance from the bottom of the active fuel zone of that reactor. The rods were pulled past the slit at 6.4 cm (2-1/2 in.) per minute; the speed of the recorder was 1.3 cm (1/2 in.) per minute. The linear count rate meters had a time constant of two seconds. The number of pulses passed by each single-channel analyzer was accumulated by a scaler for the whole axial traverse. The difference in the scaler counts thus yielded the integral count rate for the data obtained on the chart recorder.

For the Ru-106, Cs-137, and Zr-95, a 0.157-cm (0.062-in.) collimator slit-height was used. Because of the relatively weak intensity of the high energy Pr-144 line, the slit was opened to 0.64 cm (0.25 in.). To limit the count rate to 5×10^4 cps, a 0.64-cm lead filter was used with 0.102-cm (0.040-in.) cadmium interposed between the lead and the detector. The width of the slits used in both cases was 1.90 cm (0.75 in.).

To obtain data on the reproducibility of the scans, rod A37 was selected as a standard rod which was scanned at least once a day throughout the scan period. In general, the reproducibility was within 3 percent.

In the initial phase of the program Cs-137 was the only fission product nuclide measured individually. A 4-cc Ge(Li) detector was used in conjunction with a 256-channel analyzer. A NaI(Tl) detector system, shown schematically in Figure 129, provided a gross gamma scan simultaneously. In the scanning, all 10 rods were oriented axially as they had operated in the VBWR, rather than in Dresden, with the net result that the traces of "A" rods made in the initial phase are reversed with respect to the traces of "A" rods made in the final phase.

Table 29
ANALYSES OF FUEL SAMPLES FROM DIFFERENT RADIAL LOCATIONS, FUEL ROD A13

Sample Number	Distance From Pellet Periphery cm (inch)	Burnup		Fission	Atom Percent (Normalized to Total 100%)								Atom Ratios Relative to ²³⁸ U (Corrected to time of fuel discharge)										
													²³⁷ Np	²³⁸ Pu	²⁴¹ Am	²⁴³ Am	²⁴² Cm	²⁴⁴ Cm	¹⁴⁸ Nd	¹³⁷ Cs	¹³⁴ Cs	¹⁰⁶ Ru	¹⁴⁴ Ce
		Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU		²³⁴ U	²³⁵ U	²³⁶ U	²³⁸ U	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U	²³⁸ U
		(X 10 ⁻²⁰)											(X 10 ⁻⁴)	(X 10 ⁻⁴)	(X 10 ⁻⁴)	(X 10 ⁻⁴)	(X 10 ⁻⁵)	(X 10 ⁻⁵)	(X 10 ⁻³)	(X 10 ⁻³)	(X 10 ⁻³)	(X 10 ⁻³)	(X 10 ⁻³)
82	0.000-0.005 (0.000-0.002)	11.6	42,500	4.84	0.015	0.728	0.453	92.577	0.742	0.362	0.187	0.097	5.4	1.59	0.88	NA	3.00	3.33	0.850	3.1	0.23	0.60	0.46
83	0.005-0.010 (0.002-0.004)	10.6	38,600	4.39	0.015	0.716	0.454	93.314	0.598	0.293	0.147	0.074	4.5	1.39	NA	2.0	2.75	3.26	0.780	3.2	0.17	0.46	0.42
84	0.010-0.018 (0.004-0.007)	9.2	33,700	3.85	0.013	0.720	0.467	94.097	0.461	0.228	0.110	0.055	4.3	1.26	0.74	1.1	1.93	1.89	0.681	2.7	0.20	0.27	0.40
85	0.018-0.025 (0.007-0.010)	9.1	33,400	3.83	0.015	0.726	0.465	94.274	0.372	0.189	0.086	0.042	3.9	1.16	0.80	1.0	1.74	1.83	0.656	2.4	0.18	0.13	0.38
86	0.025-0.038 (0.010-0.015)	8.6	31,600	3.61	0.015	0.737	0.459	94.488	0.369	0.189	0.092	0.041	4.0	1.29	0.52	0.5	1.41	1.47	0.640	2.3	0.17	0.13	0.33
87	0.038-0.051 (0.015-0.020)	8.3	30,400	3.49	0.015	0.742	0.453	94.660	0.346	0.181	0.076	0.036	3.9	1.18	0.58	0.4	1.20	1.25	0.616	2.1	0.16	0.10	0.32
88	0.051-0.076 (0.020-0.030)	7.8	28,500	3.27	0.015	0.758	0.456	94.925	0.312	0.166	0.066	0.031	3.5	0.92	0.40	0.5	1.10	1.01	0.582	1.9	0.13	0.10	0.27
89	0.076-0.127 (0.030-0.050)	7.6	27,700	3.17	0.015	0.758	0.454	95.043	0.301	0.161	0.065	0.031	3.6	1.02	0.32	0.5	1.16	1.07	0.555	1.5	0.11	0.11	0.23
90	0.127-0.254 (0.050-0.100)	8.2	29,900	3.42	0.015	0.771	0.443	94.757	0.321	0.173	0.068	0.031	3.5	1.0	0.66	0.5	1.3	1.1	0.593	1.5	0.13	0.15	0.28
91	0.254-center*	7.9	28,800	3.30	0.015	0.842	0.443	94.796	0.329	0.179	0.066	0.030	3.2	1.14	0.58	0.6	0.98	1.00	0.566	1.8	0.11	0.17	0.35

Notes:

NA = not analyzed.

Nominal initial uranium enrichment for rod A13 was 3.53 atom %.

*Nominal pellet radius = 0.478 cm (0.188 inch).

Table 30
ANALYSES OF FUEL SAMPLES FROM DIFFERENT RADIAL LOCATIONS, FUEL ROD B70

Sample Number	Distance From Pellet Periphery [cm(inch)]	Burnup		Fission	Atom Percent (Normalized to Total 100 Percent)								Atom Ratios Relative to ²³⁸ U (Corrected to time of fuel discharge)										
					²³⁴ U	²³⁵ U	²³⁶ U	²³⁸ U	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu	²³⁷ Np	²³⁸ Pu	²⁴¹ Am	²⁴³ Am	²⁴² Cm	²⁴⁴ Cm	¹⁴⁸ Nd	¹³⁷ Cs	¹³⁴ Cs	¹⁰⁶ Ru	¹⁴⁴ Ce
		Fissions/cm ³ (× 10 ⁻²⁰)	MWd/tU										(×10 ⁴)	(×10 ⁴)	(×10 ⁴)	(×10 ⁴)	(×10 ⁵)	(×10 ⁵)	(×10 ³)	(×10 ³)	(×10 ³)	(×10 ³)	(×10 ³)
93	0.000-0.005 (0.000-0.002)	10.2	37,400	4.25	0.010	0.724	0.342	93.234	0.770	0.373	0.198	0.099	NA	1.68	0.76	0.6	2.92	3.34	0.763	3.1	0.24	0.28	0.54
94	0.005-0.010 (0.002-0.004)	9.1	33,300	3.79	0.012	0.569	0.375	94.082	0.634	0.305	0.158	0.074	4.5	1.26	0.67	0.5	2.47	2.28	0.691	2.7	0.19	0.33	0.45
95	0.010-0.018 (0.004-0.007)	7.8	28,600	3.25	0.012	0.572	0.375	94.962	0.450	0.219	0.107	0.051	3.1	1.01	0.46	0.3	1.46	1.44	0.593	2.1	0.15	0.21	0.37
96	0.018-0.025 (0.007-0.010)	7.1	25,900	2.96	0.012	0.572	0.371	95.348	0.397	0.199	0.093	0.048	3.6	1.08	0.35	0.5	1.25	1.26	0.543	2.1	0.15	0.18	0.34
97	0.025-0.038 (0.010-0.015)	6.9	25,100	2.87	0.012	0.574	0.361	95.519	0.360	0.181	0.083	0.039	2.8	1.01	0.33	0.3	1.15	1.14	0.511	2.1	0.15	0.26	0.35
98	0.038-0.051 (0.015-0.020)	6.5	23,900	2.74	0.012	0.593	0.369	95.718	0.307	0.158	0.070	0.033	NA	0.95	NA	0.2	1.04	0.73	0.487	1.7	0.14	0.14	0.28
99	0.051-0.076 (0.020-0.030)	6.8	25,000	2.86	0.012	0.597	0.367	95.598	0.310	0.160	0.066	0.031	3.4	0.96	0.16	0.2	1.12	0.88	0.513	1.9	0.14	0.13	0.30
100	0.076-0.127 (0.030-0.050)	6.8	24,900	2.85	0.012	0.607	0.361	95.513	0.355	0.188	0.075	0.038	3.3	1.01	0.18	0.2	0.92	0.81	0.464	2.0	0.14	0.15	0.32
101	0.127-0.254 (0.050-0.100)	6.7	24,400	2.79	0.012	0.621	0.360	95.625	0.322	0.173	0.066	0.031	3.1	0.88	0.28	0.2	0.89	0.84	0.473	2.0	0.14	0.28	0.33
102	0.254-center* (0.100-center)	6.2	22,600	2.59	0.012	0.636	0.364	95.834	0.306	0.166	0.063	0.029	2.4	0.79	0.20	0.2	0.77	0.68	0.458	1.5	0.11	0.12	0.25

Notes:

NA = not analyzed.

Nominal initial uranium enrichment for rod B70 was 2.79 at.%.
*Nominal pellet radius = 0.478 cm (0.188 inch).

Figure 128. Locations of Burnup and Isotopic Composition Samples from Rods A37 and B62 in Terms of Distance from the Bottom of the Reactor Active Fuel Zone

Figure 129. Schematic Drawing of Ge(Li) and NaI(Tl) Gamma Scanning Systems

Figure 130. Typical Gamma Ray Spectrum Obtained with the 40 cc Ge(Li) Detector on a 1024 Multichannel Analyzer

5.3.2.2 Results

Gross gamma scan traces of an "A" rod and a "B" rod that were removed from SA-1 at the end of Cycle No. 4 and of rod A37, which operated to the end of Cycle No. 6, are shown in Figures 131 through 133. Gamma scan traces for Cs-137 are shown in Figures 134 through 136 for rods representative of those that operated to the end of Cycle No. 6. Table 31 gives the ratios of peak-to-average gamma activity along the length of each rod scanned, based on gross activity with the initial phase rods and on Cs-137 with the final phase rods. It is seen that the values are slightly higher for the top subassembly than for the bottom subassembly. The ratios are relatively lower, in general, for the final phase rods of both subassemblies. The average burnups for those rods from which burnup samples were obtained were determined by applying the gross or Cs-137 gamma scan data to the sample burnup, determined from neodymium. The integral Cs-137 data provided relative burnup values on the remaining rods that had been scanned, so that by comparing these relative values with the burnup of one rod selected as a standard, rod-average and peak burnup values could be determined for all scanned rods. These burnup values are listed in Section 4 (Table 2).

The adequacy of gamma scan data in providing information on relative burnup is indicated by a comparison of the relative burnup values based on Cs-137 obtained from fuel rod scanning with the values obtained by use of the Nd-148 method. The comparison as presented in Figures 134, 135, 137, and 138 where the Cs-137 values given are those measured at the same axial position as the samples taken for burnup analysis by the Nd-148 method. All data have been normalized to sample 105, which was obtained from the maximum flux position of rod A37. Slight corrections of the Cs-137 data have been made to allow for the differences in fission yield from the contributing fissionable species.

The data show that under these irradiation conditions, and the exceptionally long exposure period, the relative Cs-137 intensities are in good agreement with the burnups based on the Nd-148 method. This is true not only at the more central locations for each rod, given in Figures 137 and 138, but also at the various axial positions measured, which include the end points of the fuel columns (Figures 134 and 135). Thus axial redistribution of the Cs-137 under the irradiation conditions of this fuel is not significant. Therefore, Cs-137 is an adequate burnup monitor for use in gamma scanning in spite of the fact that radial migration has undoubtedly occurred. (Compare radial distributions of Cs-137 and Nd-148 in samples of Tables 29 and 30.)

Gamma scan traces for each of the three remaining fission products investigated are shown for rods A37 and B86 in Figures 139 through 144. It is seen that significant differences appear on comparisons of the traces obtained from the four fission products. The traces for Zr-95 show the axial rod power distribution during the last period of exposure by virtue of its 65-day half-life. Apparent differences between the count rates of the A and B rods shown by the four sets of traces are not significant because of source detector geometry changes. The slight depressions seen in the traces are due to the spacers. In the final phase of the program all data were obtained using A37 as a standard rod; hence, this rod was used for normalization. The integrals of the count rate curves for all rods in which gamma scan measurements were made are given in Figures 145 and 146. Although trends are somewhat perturbed by the varying enrichments and rod vacancies within the subassemblies, the relative burnup (based on Cs-137) is still seen to correlate with the enrichment and position of the rods within the bundles. A somewhat different pattern emerges based on the other fission products, which can be interpreted qualitatively in the same way as previously described with regard to the axial traces. The error in each of the values is estimated to be $\pm 2\%$ (1σ). The reason for the relatively low value for the Ru 106 and high value of Ce 144 for rod A-47 is not understood.

Since Ru-106 has a fission yield for plutonium which is about 10 times higher than that for U-235, the possibility exists of using this information, which can be obtained in gamma scanning to measure the plutonium fission rate relative to that of uranium.^{14,15} Since Ru-106 has a 1-year half-life, the Pu-239, Pu-241 fission rate is being monitored during only the later stages of exposure for this fuel, which has a relatively long irradiation history. Since Ce-144 has a comparable half-life, i.e., 285 days, and a fission yield which is roughly the same for the four principal fissioning species, the ratio of Ru-106 to Ce-144 activity is proportional to the ratio of fissions due to Pu-239, Pu-241 to the total fissions during the same exposure period. The gamma scan data obtained for Ru-106 and for Ce-144 and their ratio at the five burnup sample locations for rod A-37 are given in Figure 147. For comparison, the fission ratio of Pu/(U + Pu) was estimated from the measured isotopic data of Table 26 utilizing the fission cross sections obtained from the program BURNUP and by making the simplifying assumption that the isotopic distribution was invariant over the exposure period monitored by the two fission products. All the data have been normalized to the highest exposure location. It is seen in this crude comparison, the fission product ratio is responsive to the ratio of plutonium-to-total fission in this very high exposure fuel. Thus, gamma scan data have the potential for yielding this type of information but, obviously, further work is required to refine the data analysis.

Table 31
RATIOS OF AXIAL PEAK TO ROD-AVERAGE
GAMMA RAY INTENSITIES

Subassembly A-1		Subassembly B-1	
Rod Number	Peak-to-Average Ratio	Rod Number	Peak-to-Average Ratio
Rod Removed from SA-1 at the End of Cycle No. 4 (Data Based on Gross Gamma Activity)			
A4	1.18	B70	1.25
A13	1.16	B76	1.30
A28	1.13	B88	1.25
A41	1.19	B97	1.20
A45	1.16		
A46	1.15		
Rods That Operated to the End of Cycle No. 6 (Data Based on Cs-137)			
A1	1.06	B50	1.13
A7	1.11	B52	1.10
A9	1.09	B56	1.12
A11	1.10	B57	1.11
A15	1.11	B58	1.16
A18	1.12	B60	1.16
A22	1.09	B61	1.10
A26	1.09	B62	1.14
A27	1.11	B83	1.08
A32	1.11	B85	1.12
A33	1.07	B86	1.13
A34	1.07	B89	1.06
A35	1.07	B91	1.15
A37	1.10	B92	1.16
A38	1.08	B93	1.15
A39	1.08	B95	1.11
A40	1.09	B96	1.15
A42	1.08	B98	1.17
A43	1.06		
A47	1.11		
A48	1.09		
A49	1.08		
B90	1.13

Figure 131. Gross Axial Gamma Profile of Rod A13

Figure 132. Gross Axial Gamma Profile of Rod B97

Figure 133. Gross Axial Gamma Profile of Rod A37

Figure 134. Comparison of Relative Burnups at Various Axial Locations by Cs-137 from the Rod Scan with Values Obtained by Nd-148 Method for Rod A-37

Figure 135. Comparison of Relative Burrs at Various Axial Locations by Cs-137 from the Rod Scan with Values Obtained by Nd-148 Method for Rod B-62

Figure 136. Gamma Scan of Rod B86 for Cs-137

(ROD ARRANGEMENT SHOWN IS FOR THE LAST TWO OF FOUR CYCLES OF OPERATION)

			11 3.49% 0.98 0.97			
			X		X	
	X					
			X			
	X			33 3.20% 0.88 0.87	34 3.20% 0.86 0.86	35 2.76% 0.82 0.87
	37 3.49% 1.00 1.00			40 3.20% 0.90 0.89	9 3.49% 0.94 0.95	42 2.76% 0.88 0.90
43 2.76% 0.86 0.88				47 2.76% 0.88 0.90	48 2.76% 0.90 0.90	49 2.76% 0.90 0.90

SUBASSEMBLY A-1 (BOTTOM)

ROD	WT%
NO:	^{235}U
	^{148}Nd
	^{137}Cs

Figure 137. Comparison of Relative Burnups by Cs-137 from Rod Gamma Scan Data at Specific Axial Locations with Those Obtained by the Nd-148 Method at the Same Locations for Subassembly A-1. Data are Normalized to the Sample Point from Rod A-37.

		X		X	62 3.49% 1.02 1.02	
		X		X		
	X					91 2.76% 0.87 0.83
				96 2.76% 0.86 0.85		98 2.76% 0.89 0.92

ROD Wt%
NO. 235_U
148Nd
137Cs

-197-

Figure 139. Gamma Scan of Rod A37 for Ru-106

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Figure 140. Gamma Scan of Rod B86 for Ru-106

Figure 141. Gamma Scan of Rod A37 for Pr-144

Figure 142. Gamma Scan of Rod B86 for Pr-144

Figure 143. Gamma Scan of Rod A37 for Zr/Nb-95

Figure 144. Gamma Scan of Rod B86 for Zr/Nb-95

CONTROL
ROD

(ROD ARRANGEMENT SHOWN IS FOR THE LAST TWO OF FOUR CYCLES OF OPERATION)

1	2.8%			11	3.5%			7	2.8%
0.95	-			1.00	-			0.97	-
-	-			-	-			-	-
		90	3.5%						
		0.98	-						
		-	-						
15	2.8%			18	3.5%				
0.88	-			0.94	-				
-	-			-	-				
22	2.8%					26	3.5%	27	3.5%
0.88	-					0.94	-	0.96	-
-	-					-	-	-	-
				32	3.5	33	3.2	34	3.2%
				0.90	-	0.86	0.98	0.87	0.94
				-	-	0.94	1.03	0.95	1.04
		37	3.5%	38	3.2%	39	3.5%	40	3.2%
		1.00	1.00	0.88	0.97	0.96	0.96	0.88	0.96
		1.00	1.00	0.93	0.97	0.94	0.97	0.93	0.98
43	2.8%					47	2.8%	48	2.8%
0.93	-					0.90	1.02	0.91	0.86
-	-					0.69	0.89	0.86	0.89
								0.95	0.90
								1.02	0.95

ROD NO.
W/O ^{235}U
 ^{137}Cs ^{144}Ce
 ^{106}Ru ^{95}Zr

Figure 145. Relative Rod-Average Fission Product Activity Values
Obtained from Rods from Subassembly A-1 (Bottom)

CONTROL
ROD

(ROD ARRANGEMENT SHOWN IS FOR THE LAST TWO OF FOUR CYCLES OF OPERATION)

50	2.8%		52	2.8%			56	2.8%
0.91	-		0.88	-			0.92	-
-	-		-	-			-	-
57	2.8%	86	3.5%		60	3.5%	62	3.5%
0.85	-	0.95	1.11		0.95	-	0.98	-
-	-	1.01	1.03		-	-	-	-
						83	3.2%	
						0.85	-	
						-	-	
85	2.8%				89	3.2%	58	3.5%
0.87	-				0.84	0.97	0.92	1.01
-	-				0.92	0.91	0.94	1.00
92	2.8%	93	2.8%		95	2.8%	96	2.8%
0.91	-	0.86	-		0.84	1.00	0.85	0.87
-	-	-	-		0.96	0.81	0.96	0.81
							61	3.2%
							0.82	1.05
							0.84	0.99
							98	2.8%
							0.90	0.91
							0.99	0.88

ROD NO.
W/O ²³⁵U
¹³⁷Cs ¹⁴⁴Ce
¹⁰⁶Ru ⁹⁵Zr

Figure 146. Relative Rod-Average Fission Product Activity Values
Obtained from Rods from Subassembly B-1 (Top)

Figure 147. Comparison of the Ru-106/Ce-144 Ratio for an Estimate of the $\text{Pu}/(\text{U} + \text{Pu})$ Fission Ratio for Rod A37 During Its Most Recent Exposure History

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15. Forsyth, R. S., and Blackadder, W. H., *Use of Fission Product Ru-106 Gamma Activity as a Method for Estimating the Relative Number of Fission Events in U-235 and Pu-239 in Low Enrichment Fuel Elements*, 1970 (AE-390).

APPENDIX A

LIST OF REPORTS ISSUED

Prior reports to the U. S. Atomic Energy Commission under the Zircaloy-Clad UO_2 Fuel Rod Evaluation Program (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).
- k. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Quarterly Progress Report No. 12, August–October 1970," November 1970 (GEAP-10287).
- l. "Zircaloy-Clad UO_2 Fuel Rod Evaluation Program, Progress Report No. 13, November 1970–March 1971," April 1971 (GEAP-10363).
- m. "Design and Fabrication of Special Assembly SA-1," April 1971 (GEAP-10355).

APPENDIX B

VBWR OPERATING DATA ON SA-1 RODS

Table B-1
VBWR OPERATING DATA ON SA-1 RODS

Assembly 1J										Assembly 4J									
Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Burnup (Fissions/cm ³ × 10 ⁻¹⁹)		Peak Heat Flux in W/cm ² and Btu/h-ft ² Rods A2, A8, B51, B57				Core Location	Burnup (Fissions/cm ³ × 10 ⁻¹⁹)		Peak Heat Flux in W/cm ² and Btu/h-ft ² Rods A5, A29, B52, B53, B64, B71, B78					
					Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power			Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power			
132	90	4	9	F-4	0.126	0.126	52	166,000	16	51,000	D-6	0.137	0.137	56	178,000	17	55,000		
133	11	0	6		0.008	0.134	31	99,000	12	39,000		0.071	0.208	27	87,000	11	34,000		
133A	227	5	12		0.342	0.476	62	198,000	42	133,000		0.315	0.523	55	175,000	37	118,000		
134	706	13	23		1.308	1.784	62	198,000	53	169,000		1.204	1.727	55	175,000	47	149,000		
135	347	9	28		0.498	2.282	57	180,000	32	102,000		0.471	2.198	53	169,000	30	96,000		
135A	87	5	17		0.104	2.386	57	180,000	25	78,000		0.098	2.296	53	169,000	23	73,000		
136	59	3	15		0.055	2.441	48	151,000	12	39,000		0.055	2.351	50	160,000	13	41,000		
136A	393	12	14		0.561	3.002	63	201,000	36	114,000		0.566	2.917	67	214,000	38	121,000		
136B	162	4	10		0.189	3.191	42	134,000	27	87,000		0.192	3.109	45	142,000	29	92,000		
137	294	3	8		0.492	3.683	59	187,000	40	127,000		0.495	3.604	63	199,000	43	135,000		
138	145	3	5		0.219	3.902	53	167,000	40	127,000		0.219	3.823	56	177,000	42	134,000		
139	41	1	9		0.044	3.946	49	156,000	13	42,000		0.041	3.864	50	158,000	14	43,000		
140	26	2	2		0.030	3.976	47	150,000	23	72,000		0.027	3.891	48	153,000	23	73,000		
141	30	1	1		0.027	4.003	42	132,000	23	72,000		0.030	3.921	43	135,000	23	74,000		
142	131	3	5		0.282	4.285	68	216,000	57	180,000		0.274	4.195	169	220,000	58	183,000		
143	225	3	3		0.525	4.810	68	216,000	62	198,000		0.520	4.715	69	220,000	64	202,000		
144	393	11	18		0.977	5.787	84	265,000	65	205,000		0.949	5.664	86	272,000	67	211,000		
145	88	3	5		0.077	5.864	39	124,000	17	54,000		0.085	5.749	43	136,000	19	59,000		
146	42	1	3		0.044	5.908	50	160,000	20	64,000		0.047	5.796	55	176,000	22	70,000		
147	207	3	3		0.413	6.321	70	223,000	54	170,000		0.451	6.247	77	245,000	59	187,000		
148	307	3	5		0.487	6.808	69	220,000	42	133,000		0.555	6.802	75	239,000	45	144,000		
149	418	10	14		0.752	7.560	72	228,000	45	142,000		0.780	7.582	74	236,000	46	147,000		
150	96	4	4		0.170	7.730	61	192,000	36	113,000		0.181	7.763	65	207,000	38	122,000		
151	201	4	5		0.367	8.097	61	192,000	49	154,000		0.394	8.157	65	207,000	52	166,000		
152	0	0	0		0.000	8.097							8.157						
153	419	9	12		0.772	8.869	77	244,000	44	141,000		0.826	8.983	83	262,000	48	151,000		
154	203	12	14		0.356	9.225	94	298,000	48	152,000		0.380	9.363	68	215,000	35	110,000		
155	425	7	6		0.840	10.065	73	231,000	60	190,000		0.897	10.260	79	251,000	65	207,000		
156	124	3	2		0.181	10.246	64	203,000	42	133,000		0.197	10.457	68	216,000	45	142,000		
157	51	2	2		0.104	10.350	66	209,000	52	165,000		0.109	10.566	70	223,000	55	176,000		
158	275	8	7		0.410	10.760	50	159,000	43	137,000	M-8	0.432	10.998	53	169,000	46	146,000		
159	490	4	3		0.914	11.674	65	205,000	61	193,000		1.146	12.144	71	225,000	67	212,000		
160	336	3	3		0.607	12.281	65	205,000	58	185,000	K-14	0.761	12.905	71	225,000	64	203,000		
161	902	8	14		1.319	13.600	51	162,000	39	124,000		1.226	14.131	49	154,000	37	118,000		
162	141	6	7		0.161	13.761	48	152,000	31	98,000	M-12	0.153	14.284	44	140,000	29	91,000		
163	149	2	1		0.183	13.944	38	121,000	36	113,000		0.172	14.456	35	112,000	33	105,000		
164	154	1	1		0.183	14.127	39	125,000	35	111,000		0.172	14.628	36	115,000	32	102,000		
165	402	1	1		0.446	14.573	37	117,000	35	111,000		0.506	15.134	40	128,000	38	122,000		
166	278	3	3		0.312	14.885	39	125,000	30	96,000		0.356	15.490	44	140,000	34	108,000		
Totals																			
1J	9075	179	300																
4J																			

NOTES:

Hours at temperature is defined as the number of hours the reactor power was greater than 5 MWt.

A power cycle is defined as a reactor core power variation from less than 5 MW to greater than 20 MW and returned to less than 5 MW.

A thermal cycle is defined as a reactor core power variation from zero power to greater than 5 MW and return to zero power.

This variation indicates the number of times that the reactor is brought to full operating temperature and pressure during a run.

Table B-1 (Continued)

Assembly 5J														Assembly 6J											
Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Peak Heat Flux in W/cm ² and Btu/h-ft ²										Peak Heat Flux in W/cm ² and Btu/h-ft ²										
					Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A14, A21, A28, A35, A44, A45, A46				Rods A1, B50, B54				Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A42, A48, A49, B56, B91, B97, B98				Rods A47, B84, B92, B96				
					Δ	Cumulative	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power	Δ	Cumulative	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power	At Maximum Reactor Power	At Average Reactor Power					
132	90	4	9	D-7	0.153	0.153	64	202,000	20	62,000	57	182,000	18	56,000	D-11	0.134	0.134	55	175,000	17	54,000	50	158,000	15	48,000
133	11	0	6		0.008	0.161	30	95,000	12	37,000	27	86,000	11	34,000		0.005	0.139	25	79,000	10	31,000	22	71,000	9	28,000
133A	227	5	12		0.353	0.514	60	189,000	40	127,000	54	170,000	36	114,000		0.290	0.429	50	158,000	33	106,000	45	142,000	30	96,000
134	706	13	23		1.354	1.868	60	189,000	51	161,000	54	170,000	46	145,000		1.111	1.540	50	158,000	43	135,000	45	142,000	38	121,000
135	347	9	28		0.520	2.388	57	182,000	32	103,000	52	164,000	29	93,000		0.440	1.980	49	155,000	28	88,000	44	140,000	25	79,000
135A	87	5	17	E-6	0.109	2.497	57	182,000	25	79,000	52	164,000	22	71,000	G-6	0.090	2.070	49	155,000	21	67,000	44	140,000	19	61,000
136	59	3	15		0.060	2.557	53	167,000	14	43,000	47	150,000	12	39,000		0.085	2.155	78	247,000	20	64,000	70	222,000	18	57,000
136A	393	12	14		0.607	3.164	70	223,000	40	126,000	63	201,000	36	114,000		0.862	3.017	104	330,000	59	187,000	94	297,000	53	168,000
136B	162	4	10		0.205	3.369	47	148,000	30	96,000	42	133,000	27	86,000		0.290	3.307	69	220,000	45	143,000	62	198,000	41	129,000
137	294	3	8		0.534	3.903	65	207,000	44	140,000	59	186,000	40	126,000		0.766	4.073	97	308,000	66	209,000	87	277,000	59	188,000
138	145	3	5		0.235	4.138	58	185,000	44	141,000	52	166,000	40	126,000		0.334	4.407	87	275,000	66	209,000	78	248,000	59	188,000
139	41	1	9		0.049	4.187	57	182,000	15	49,000	52	164,000	14	44,000		0.066	4.473	76	242,000	20	65,000	69	218,000	19	59,000
140	26	2	2		0.033	4.220	55	175,000	26	84,000	50	158,000	24	76,000		0.044	4.517	73	233,000	35	112,000	66	210,000	32	101,000
141	30	1	1		0.036	4.256	49	155,000	27	85,000	44	140,000	24	76,000		0.047	4.564	65	205,000	35	112,000	58	184,000	32	100,000
142	131	3	5		0.315	4.571	80	253,000	67	211,000	72	228,000	60	190,000		0.424	4.988	106	335,000	88	279,000	95	302,000	79	252,000
143	225	3	3		0.596	5.167	80	253,000	73	232,000	72	228,000	66	209,000		0.804	5.792	106	335,000	97	307,000	95	302,000	87	277,000
144	393	11	18		1.070	6.237	95	301,000	73	233,000	85	271,000	66	210,000		1.395	7.187	121	385,000	94	298,000	109	346,000	84	268,000
145	88	3	5		0.090	6.327	43	135,000	19	59,000	38	122,000	17	53,000		0.123	7.310	60	190,000	26	83,000	54	171,000	23	74,000
146	42	1	3		0.052	6.379	55	175,000	22	70,000	50	158,000	20	63,000		0.068	7.378	78	246,000	31	98,000	70	221,000	28	88,000
147	207	3	3		0.482	6.861	77	244,000	59	186,000	69	220,000	53	188,000		0.657	8.035	108	343,000	83	262,000	97	309,000	74	236,000
148	307	3	5		0.635	7.496	80	255,000	49	154,000	73	230,000	44	139,000		0.815	8.850	104	331,000	63	199,000	94	298,000	57	180,000
149	418	10	14		0.914	8.410	82	259,000	51	162,000	73	233,000	46	146,000		1.264	10.114	104	331,000	65	207,000	94	298,000	59	186,000
150	96	4	4		0.208	8.618	70	223,000	42	132,000	63	201,000	38	119,000		0.260	10.374	90	285,000	53	168,000	81	256,000	48	151,000
151	201	4	5		0.454	9.072	70	223,000	56	178,000	63	201,000	51	161,000		0.564	10.938	90	285,000	72	228,000	81	256,000	65	205,000
152	0	0	0		-	9.072	-	-	-	-	-	-	-	-		-	10.938	-	-	-	-	-	-	-	
153	419	9	12		0.947	10.019	90	286,000	52	165,000	81	257,000	47	148,000		1.190	12.128	113	359,000	65	207,000	102	323,000	59	186,000
154	203	12	14		0.441	10.460	69	220,000	35	112,000	62	198,000	32	101,000		0.607	12.735	96	305,000	49	156,000	86	274,000	44	140,000
155	425	7	6		1.034	11.494	81	256,000	67	211,000	73	230,000	60	189,000		1.447	14.182	112	356,000	92	293,000	101	320,000	83	263,000
156	124	3	2		0.224	11.718	71	225,000	47	148,000	64	202,000	42	133,000		0.306	14.488	97	307,000	64	202,000	87	276,000	57	181,000
157	51	2	2		0.123	11.841	73	232,000	58	183,000	66	209,000	52	165,000		0.167	14.655	100	317,000	79	250,000	90	285,000	71	224,000
158	275	8	7		0.490	12.331	55	176,000	48	152,000	50	158,000	43	137,000		0.722	15.377	76	241,000	66	208,000	68	217,000	59	187,000
159	490	4	3		1.075	13.406	70	222,000	66	209,000	63	200,000	59	188,000		1.480	16.857	91	288,000	85	271,000	82	259,000	77	243,000
160	336	3	3		0.714	14.120	70	222,000	63	201,000	63	200,000	57	181,000		0.993	17.850	91	288,000	82	260,000	82	259,000	74	234,000
161	902	8	14		1.702	15.822	71	225,000	54	172,000	64	202,000	49	154,000		2.306	20.156	93	294,000	71	225,000	84	265,000	64	202,000
162	141	6	7		0.191	16.013	55	175,000	36	113,000	50	158,000	32	102,000	H-13	0.175	20.331	48	153,000	31	99,000	44	138,000	28	89,000
163	149	2	1	0.216	16.229	44	140,000	41	131,000	40	126,000	37	118,000	0.197		20.528	38	122,000	36	114,000	35	110,000	32	103,000	
164	154	1	1	0.224	16.453	47	150,000	42	133,000	43	135,000	38	119,000	0.189		20.717	37	117,000	33	104,000	33	105,000	29	93,000	
165	402	1	1	0.635	17.088	50	157,000	47	150,000	44	141,000	42	134,000	0.596		21.313	46	145,000	44	138,000	41	130,000	39	124,000	
166	278	3	3	J-12	0.421	17.509	50	157,000	38	121,000	44	141,000	34	109,000		0.413	21.726	50	159,000	38	122,000	45	143,000	35	110,000

Totals																								
5J	9075	179	300																					
6J																								

Table B-1 (Continued)

Assembly 8J														Assembly 9J													
Peak Heat Flux in W/cm ² and Btu/h-ft ²														Peak Heat Flux in W/cm ² and Btu/h-ft ²													
Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A10, A12, A16, A30, B59, B61, B65, B79				Rods A25, B74				Core Location	Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A20, A34, A38, A40, B83, B89				Rods A33, B69, B82, B87					
					Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power			Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power			
132	90	4	9	K-4	0.156	0.156	63	201,000	20	62,000	57	181,000	8	56,000	J-13	0.148	0.148	61	193,000	19	59,000	55	174,000	17	53,000		
133	11	0	6	↓	0.008	0.164	31	99,000	12	39,000	28	89,000	11	35,000	↓	0.008	0.156	35	110,000	14	43,000	31	99,000	12	39,000		
133A	227	5	12	↓	0.323	0.487	62	198,000	42	133,000	56	178,000	38	120,000	↓	0.364	0.520	69	220,000	47	148,000	62	198,000	42	133,000		
134	706	13	23	↓	1.242	1.729	62	198,000	53	169,000	56	178,000	48	152,000	↓	1.398	1.918	69	220,000	59	188,000	62	198,000	53	169,000		
135	347	9	28	↓	0.498	2.227	59	188,000	34	107,000	53	169,000	30	96,000	↓	0.572	2.490	68	217,000	39	123,000	61	195,000	35	110,000		
135A	87	5	17	↓	0.104	2.331	59	188,000	26	81,000	53	169,000	23	73,000	↓	0.118	2.608	68	217,000	30	94,000	61	195,000	26	84,000		
136	59	3	15	J-3	0.047	2.378	40	128,000	10	33,000	36	115,000	9	30,000	K-3	0.047	2.655	44	141,000	11	36,000	40	127,000	10	33,000		
136A	393	12	14	↓	0.468	2.846	54	171,000	31	97,000	49	154,000	27	87,000	↓	0.460	3.115	59	188,000	34	107,000	53	169,000	30	96,000		
136B	162	4	10	↓	0.156	3.002	36	114,000	23	74,000	32	103,000	21	67,000	↓	0.156	3.271	39	125,000	26	81,000	35	112,000	23	73,000		
137	294	3	8	↓	0.405	3.407	50	159,000	34	108,000	45	143,000	31	97,000	↓	0.410	3.681	55	175,000	38	119,000	50	158,000	34	107,000		
138	145	3	5	↓	0.181	3.588	45	142,000	34	108,000	40	128,000	31	97,000	↓	0.178	3.859	49	156,000	38	119,000	44	140,000	33	106,000		
139	41	1	9	J-4	0.049	3.637	57	180,000	15	48,000	51	162,000	14	44,000	J-13	0.049	3.908	56	179,000	15	48,000	51	161,000	14	43,000		
140	26	2	2	↓	0.033	3.670	55	174,000	26	84,000	50	157,000	24	75,000	↓	0.033	3.941	55	173,000	26	83,000	49	156,000	24	75,000		
141	30	1	1	↓	0.036	3.706	48	153,000	26	83,000	44	138,000	24	75,000	J-12	0.041	3.982	57	181,000	31	99,000	51	163,000	28	89,000		
142	131	3	5	↓	0.320	4.026	79	250,000	66	208,000	71	225,000	59	187,000	↓	0.394	4.376	93	296,000	78	247,000	84	266,000	70	222,000		
143	225	3	3	↓	0.610	4.636	79	250,000	72	229,000	71	225,000	65	206,000	↓	0.725	5.101	93	296,000	85	271,000	84	266,000	77	244,000		
144	393	11	18	↓	1.116	5.752	96	304,000	74	236,000	86	274,000	67	212,000	J-13	1.015	6.116	86	274,000	67	212,000	78	247,000	60	191,000		
145	88	3	5	↓	0.096	5.848	48	151,000	21	66,000	43	136,000	19	59,000	↓	0.090	6.206	45	142,000	20	62,000	40	128,000	18	56,000		
146	42	1	3	↓	0.055	5.903	62	196,000	25	78,000	55	176,000	22	70,000	↓	0.052	6.258	58	185,000	23	74,000	52	166,000	21	66,000		
147	207	3	3	↓	0.520	6.423	86	273,000	66	209,000	78	246,000	59	188,000	↓	0.490	6.748	81	256,000	62	196,000	73	230,000	55	176,000		
148	307	3	5	↓	0.635	7.058	80	255,000	49	154,000	73	230,000	44	139,000	J-12	0.752	7.500	99	314,000	60	189,000	89	283,000	54	171,000		
149	418	10	14	↓	0.873	7.931	81	258,000	51	161,000	73	232,000	46	145,000	D-8	0.955	8.455	88	280,000	55	175,000	79	252,000	50	157,000		
150	96	4	4	↓	0.192	8.123	68	217,000	40	128,000	61	195,000	36	115,000	↓	0.213	8.668	79	250,000	47	148,000	71	225,000	42	133,000		
151	201	4	5	↓	0.419	8.452	68	217,000	55	174,000	61	195,000	49	156,000	↓	0.462	9.130	79	250,000	63	200,000	71	225,000	57	180,000		
152	0	0	0	↓	-	8.452	-	-	-	-	-	-	-	-	↓	-	9.130	-	-	-	-	-	-	-			
153	419	9	12	L-5	0.988	9.530	94	298,000	54	172,000	84	268,000	49	155,000	↓	0.955	10.085	97	307,000	56	177,000	87	276,000	50	159,000		
154	203	12	14	↓	0.440	9.970	74	234,000	38	119,000	67	211,000	34	108,000	↓	0.427	10.512	72	229,000	37	117,000	65	206,000	33	105,000		
155	425	7	6	↓	1.048	11.018	86	273,000	71	225,000	78	246,000	64	202,000	↓	0.999	11.511	84	266,000	69	219,000	75	239,000	62	197,000		
156	124	3	2	↓	0.222	11.240	74	235,000	49	154,000	67	212,000	44	139,000	↓	0.208	11.719	71	225,000	47	148,000	64	202,000	42	133,000		
157	51	2	2	↓	0.120	11.360	76	242,000	60	191,000	69	218,000	54	172,000	↓	0.115	11.834	73	232,000	58	183,000	66	209,000	52	165,000		
158	275	8	7	↓	0.484	11.844	58	184,000	50	159,000	52	166,000	45	143,000	↓	0.468	12.302	55	176,000	48	152,000	50	158,000	43	137,000		
159	490	4	3	Out	0.000	11.844	-	-	-	-	-	-	-	-	E-10	1.256	13.558	82	259,000	77	243,000	73	233,000	69	219,000		
160	336	3	3	↓	0.000	11.844	-	-	-	-	-	-	-	-	↓	0.843	14.401	82	259,000	74	234,000	73	233,000	66	210,000		
161	902	8	14	↓	0.000	11.844	-	-	-	-	-	-	-	-	↓	2.118	16.519	86	272,000	66	208,000	77	245,000	59	187,000		
162	141	6	7	E-10	0.252	12.096	79	250,000	51	162,000	71	225,000	46	146,000	F-9	0.342	16.861	97	307,000	63	199,000	87	276,000	56	179,000		
163	149	2	1	↓	0.287	12.383	63	199,000	59	186,000	56	179,000	53	167,000	↓	0.410	17.271	77	245,000	72	229,000	69	220,000	65	206,000		
164	154	1	1	F-9	0.413	12.796	87	275,000	77	243,000	78	248,000	69	219,000	G-10	0.399	17.670	88	277								

Table B-1 (Continued)

Assembly 11 J														Assembly 12J											
Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Peak Heat Flux in W/cm ² and Btu/h-ft ²										Peak Heat Flux in W/cm ² and Btu/h-ft ²										
					Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A13, A37, A41, B62, B86, B90				Rods A19, A31, B72				Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A9, A27, B58, B76, B88				Rods A17, B68, B80				
					Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power		Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power		
134	706	13	23	G-6	2.301	2.301	103	327,000	88	279,000	93	294,000	79	251,000	G-11	2.419	2.419	109	346,000	93	295,000	98	311,000	84	265,000
135	347	9	28	↓	1.031	3.332	116	368,000	66	209,000	104	331,000	59	188,000	↓	0.949	3.368	110	348,000	62	197,000	99	313,000	56	177,000
135A	87	5	17	↓	0.216	3.548	116	368,000	50	159,000	104	331,000	45	143,000	↓	0.197	3.565	110	348,000	48	151,000	99	313,000	43	136,000
136	59	3	15	K-6	0.107	3.655	99	314,000	26	81,000	89	283,000	23	73,000	L-8	0.109	3.674	103	326,000	26	84,000	92	293,000	24	76,000
136A	393	12	14	↓	1.042	4.697	132	418,000	75	237,000	119	376,000	67	213,000	↓	1.122	4.796	137	435,000	78	246,000	124	392,000	70	222,000
136B	162	4	10	↓	0.361	5.058	88	278,000	57	181,000	79	250,000	51	162,000	↓	0.375	5.171	91	290,000	59	188,000	82	261,000	54	170,000
137	294	3	8	↓	0.958	6.016	123	391,000	84	265,000	111	352,000	75	239,000	↓	0.993	6.164	128	406,000	87	275,000	115	365,000	78	248,000
138	145	3	5	↓	0.419	6.435	110	349,000	84	265,000	99	314,000	75	239,000	↓	0.432	6.596	115	364,000	87	277,000	103	328,000	79	249,000
139	41	1	9	L-6	0.068	6.503	83	264,000	22	71,000	75	238,000	20	64,000	↓	0.082	6.678	99	315,000	27	85,000	90	284,000	24	76,000
140	26	2	2	↓	0.047	6.550	80	255,000	38	122,000	73	230,000	35	110,000	J-12	0.047	6.725	68	216,000	33	104,000	61	194,000	29	93,000
141	30	1	1	↓	0.047	6.597	71	224,000	38	122,000	64	202,000	35	110,000	K-11	0.052	6.777	75	237,000	41	129,000	67	213,000	37	116,000
142	131	3	5	↓	0.460	7.057	115	365,000	96	304,000	103	328,000	86	273,000	↓	0.482	7.259	122	388,000	102	323,000	110	349,000	92	291,000
143	225	3	3	↓	0.867	7.924	115	365,000	106	335,000	103	328,000	95	301,000	↓	0.914	8.173	122	388,000	112	356,000	110	349,000	101	320,000
144	393	11	18	↓	1.466	9.390	130	412,000	101	319,000	117	371,000	91	288,000	J-12	1.275	9.448	114	361,000	88	280,000	102	325,000	79	252,000
145	88	3	5	↓	0.129	9.519	73	231,000	32	100,000	66	208,000	28	90,000	↓	0.118	9.556	57	181,000	25	79,000	51	163,000	22	71,000
146	42	1	3	↓	0.071	9.590	79	249,000	32	100,000	71	224,000	28	90,000	↓	0.066	9.632	74	235,000	30	94,000	67	212,000	27	85,000
147	207	3	3	↓	0.681	10.271	109	345,000	83	264,000	98	310,000	75	237,000	↓	0.629	10.261	103	326,000	79	249,000	92	293,000	71	224,000
148	307	3	5	K-6	0.810	11.081	113	358,000	69	218,000	102	322,000	61	194,000	H-3	0.528	10.789	71	225,000	43	136,000	64	202,000	38	122,000
149	418	10	14	↓	1.239	12.320	115	365,000	72	228,000	103	328,000	65	205,000	L-6	1.218	12.007	110	348,000	68	217,000	99	313,000	62	196,000
150	96	4	4	↓	0.276	12.596	96	303,000	56	179,000	86	273,000	51	161,000	↓	0.268	12.275	91	288,000	54	170,000	82	259,000	48	153,000
151	201	4	5	↓	0.596	13.192	96	303,000	76	242,000	86	273,000	69	218,000	↓	0.577	12.852	91	288,000	73	230,000	82	259,000	65	207,000
152	0	0	0	↓	—	13.192	—	—	—	—	—	—	—	↓	—	12.852	—	—	—	—	—	—	—	—	
153	419	9	12	↓	1.338	14.530	127	402,000	73	232,000	114	362,000	66	209,000	↓	1.261	14.113	121	385,000	70	222,000	109	346,000	63	200,000
154	203	12	14	L-6	0.572	15.102	91	289,000	46	147,000	82	260,000	42	133,000	K-6	0.621	14.734	97	307,000	50	157,000	87	276,000	44	141,000
155	425	7	6	↓	1.357	16.459	106	337,000	87	277,000	96	303,000	79	249,000	↓	1.477	16.211	113	358,000	93	295,000	102	322,000	84	265,000
156	124	3	2	↓	0.306	16.765	100	316,000	66	208,000	90	284,000	59	187,000	↓	0.320	16.531	98	312,000	65	205,000	89	281,000	58	185,000
157	51	2	2	↓	0.167	16.932	103	326,000	81	257,000	92	293,000	73	231,000	↓	0.172	16.703	102	322,000	80	254,000	91	290,000	72	228,000
158	275	8	7	↓	0.673	17.605	78	248,000	67	214,000	70	222,000	61	192,000	↓	0.684	17.387	77	245,000	67	212,000	69	220,000	60	190,000
159	490	4	3	J-6	1.767	19.372	114	360,000	107	338,000	102	324,000	96	305,000	E-9	1.486	18.873	96	305,000	90	287,000	86	274,000	81	258,000
160	336	3	3	↓	1.185	20.557	114	360,000	102	325,000	102	324,000	92	293,000	↓	1.001	19.874	96	305,000	87	276,000	86	274,000	78	248,000
161	902	8	14	L-6	2.109	22.666	99	315,000	76	241,000	90	284,000	68	217,000	↓	2.460	22.334	97	309,000	74	236,000	88	278,000	67	212,000
162	141	6	7	H-7	0.383	23.049	99	315,000	64	204,000	90	284,000	58	184,000	J-10	0.364	22.698	95	302,000	62	196,000	86	272,000	55	176,000
163	149	2	1	↓	0.435	23.484	79	249,000	73	233,000	71	224,000	66	209,000	↓	0.416	23.114	76	242,000	71	226,000	69	218,000	64	204,000
164	154	1	1	↓	0.451	23.935	85	270,000	75	239,000	77	243,000	68	215,000	↓	0.402	23.516	79	251,000	70	222,000	71	226,000	63	200,000
165	402	1	1	↓	1.185	25.120	82	261,000	79	249,000	74	235,000	71	224,000	↓	1.133	24.649	83	264,000	79	251,000	75	238,000	72	227,000
166	278	3	3	↓	0.824	25.944	90	285,000	69	219,000	81	256,000	62	197,000	↓	0.788	25.437	80	262,000	80	217,000	80	254,000	61	195,000
Totals																									
11J																									
12J					8747	170	273																		

Table B-1 (Continued)
Assembly 13J

Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Peak Heat Flux in W/cm ² and Btu/h-ft ²										
					Burnup (Fissions/cm ³ X 10 ⁻¹⁹)	Rods									
						A11, A23, A26, A32, A39, B60, B75, B81				Rods B66, B73					
						Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power	
134	706	13	23	J-6	2.498	2.498	112	356,000	96	304,000	101	320,000	86	273,000	
135	347	9	28	↓	1.105	3.603	127	402,000	72	228,000	114	362,000	65	205,000	
135A	87	5	17		0.230	3.833	127	402,000	55	174,000	114	362,000	50	157,000	
136	59	3	15		K-5	0.074	3.907	72	229,000	19	59,000	65	206,000	17	53,000
136A	393	12	14		0.813	4.720	96	305,000	55	173,000	86	274,000	49	155,000	
136B	162	4	10		0.268	4.988	64	204,000	42	133,000	58	184,000	38	120,000	
137	294	3	8		0.717	5.705	90	285,000	61	193,000	81	256,000	55	174,000	
138	145	3	5		0.312	6.017	80	255,000	61	194,000	73	230,000	55	175,000	
139	41	1	9		0.060	6.077	72	228,000	19	61,000	65	205,000	17	55,000	
140	26	2	2		0.041	6.118	69	219,000	33	105,000	62	197,000	30	95,000	
141	30	1	1		0.044	6.162	61	193,000	33	105,000	55	174,000	30	95,000	
142	131	3	5	↓	0.402	6.564	99	315,000	83	262,000	90	284,000	75	237,000	
143	225	3	3		0.774	7.338	99	315,000	91	289,000	90	284,000	82	260,000	
144	393	11	18		1.327	8.665	84	267,000	65	207,000	76	240,000	59	186,000	
145	88	3	5		0.118	8.783	55	175,000	24	76,000	50	158,000	22	69,000	
146	42	1	3		0.063	8.846	72	227,000	29	91,000	64	204,000	26	82,000	
147	207	3	3		0.637	9.483	99	315,000	76	241,000	90	284,000	68	217,000	
148	307	3	5		G-11	0.832	10.315	118	373,000	71	225,000	106	336,000	64	203,000
149	418	10	14		1.316	11.631	120	381,000	75	238,000	108	343,000	67	214,000	
150	96	4	4		0.260	11.891	91	289,000	54	171,000	82	260,000	48	153,000	
151	201	4	5		0.569	12.460	91	289,000	73	231,000	82	260,000	66	208,000	
152	0	0	0	↓	—	12.460	—	—	—	—	—	—	—	—	
153	419	9	12		1.250	13.710	121	385,000	70	222,000	109	346,000	63	200,000	
154	203	12	14		0.566	14.276	88	279,000	45	142,000	79	251,000	40	128,000	
155	425	7	6		1.330	15.606	102	325,000	84	267,000	92	292,000	76	240,000	
156	124	3	2		0.309	15.915	94	297,000	61	195,000	84	267,000	55	175,000	
157	51	2	2		0.167	16.082	96	306,000	76	241,000	87	275,000	68	217,000	
158	275	8	7		0.673	16.755	73	233,000	63	201,000	66	210,000	57	181,000	
159	490	4	3		H-11	1.726	18.481	113	358,000	106	337,000	102	322,000	96	303,000
160	336	3	3		1.152	19.633	113	358,000	102	323,000	102	322,000	92	291,000	
161	902	8	14		2.315	21.948	93	296,000	71	226,000	84	266,000	55	173,000	
162	141	6	7	↓	F-7	0.347	22.295	100	316,000	65	205,000	90	284,000	58	184,000
163	149	2	1		0.386	22.681	79	251,000	74	235,000	71	226,000	67	211,000	
164	154	1	1		0.410	23.091	86	273,000	76	242,000	78	246,000	69	218,000	
165	402	1	1		1.078	24.167	86	272,000	82	259,000	77	245,000	73	233,000	
166	278	3	3		0.747	24.916	94	297,000	72	229,000	84	267,000	65	205,000	

Totals															
13J }															
14J }	8747	170	273												

Assembly 14J

Core Location	Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Peak Heat Flux in W/cm ² and Btu/h-ft ²				
			Rods A18, A24, B67				
	Δ	Cumulative	At Maximum Reactor Power		At Average Reactor Power		
J-12	2.224	2.224	100	318,000	85	271,000	
↓	0.922	3.146	114	360,000	64	204,000	
	0.186	3.332	114	360,000	49	156,000	
	0.085	3.417	81	256,000	21	66,000	
	0.873	4.290	108	341,000	61	193,000	
	0.287	4.577	72	227,000	47	148,000	
	0.774	5.351	100	318,000	68	216,000	
	0.331	5.682	90	284,000	68	216,000	
↓	E-10	0.063	5.745	71	225,000	19	61,000
	0.041	5.786	68	216,000	33	104,000	
	0.047	5.833	60	191,000	33	104,000	
	0.389	6.222	98	312,000	82	260,000	
	0.750	6.972	98	312,000	90	286,000	
	1.382	8.354	118	375,000	92	291,000	
	↓	M-12	0.096	8.450	47	150,000	20
0.052		8.502	61	195,000	25	78,000	
0.520		9.022	85	269,000	65	205,000	
↓	M-11	0.711	9.733	98	310,000	59	187,000
		1.040	10.773	93	294,000	58	184,000
	0.213	10.986	73	232,000	43	137,000	
	0.465	11.451	73	232,000	59	186,000	
	—	11.451	—	—	—	—	
	0.988	12.439	98	311,000	57	180,000	
	N-8	0.391	12.830	59	187,000	30	95,000
↓	M-8	1.220	14.050	89	283,000	73	233,000
		0.358	14.408	121	385,000	80	253,000
	0.197	14.605	125	396,000	98	312,000	
	0.788	15.393	95	301,000	82	260,000	
	↓	M-9	1.456	16.849	88	279,000	83
0.974			17.823	88	279,000	79	252,000
2.564		20.387	98	311,000	75	237,000	
0.241		20.628	69	219,000	45	142,000	
0.276		20.904	55	176,000	52	165,000	
0.279		21.183	55	174,000	49	154,000	
0.802		21.985	57	182,000	55	173,000	
N-8	0.421	22.406	49	154,000	38	119,000	

Table B-1 (Continued)

Assembly 16J														Assembly 17J							
Run Number	Hours at Temperature	Power Cycles	Thermal Cycles	Core Location	Peak Heat Flux in W/cm ² and Btu/h-ft ²										Core Location	Peak Heat Flux in W/cm ² and Btu/h-ft ²					
					Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods				Rods A6, A36, B55, B85					Burnup (Fissions/cm ³ X 10 ⁻¹⁹)		Rods A3, A4, A15, A22			
							At Maximum Reactor Power		At Average Reactor Power		At Maximum Reactor Power		At Average Reactor Power					At Maximum Reactor Power		At Average Reactor Power	
							Δ	Cumulative													
135	347	9	28	F-5	0.602	0.602	72	229,000	41	130,000	65	206,000	37	117,000	Out	0.000	0.000	—	—	—	—
135A	87	5	17	↓	0.126	0.728	72	229,000	31	99,000	65	206,000	28	89,000	↓	0.000	0.000	—	—	—	—
136	59	3	15	H-5	0.079	0.807	71	224,000	18	58,000	64	202,000	16	52,000	F-5	0.066	0.066	57	181,000	15	47,000
136A	393	12	14	↓	0.799	1.606	94	298,000	53	169,000	84	268,000	48	152,000	↓	0.673	0.739	76	242,000	43	137,000
136B	162	4	10	↓	0.271	1.877	63	199,000	41	129,000	56	179,000	37	116,000	↓	0.227	0.966	51	161,000	33	105,000
137	294	3	8	↓	0.706	2.583	88	278,000	59	187,000	79	250,000	54	170,000	Out	0.000	0.966	—	—	—	—
138	145	3	5	↓	0.309	2.892	78	248,000	59	188,000	70	223,000	53	169,000	↓	0.000	0.966	—	—	—	—
139	41	1	9	↓	0.060	2.952	67	211,000	18	57,000	60	190,000	16	51,000	F-5	0.052	1.018	59	187,000	16	50,000
140	26	2	2	↓	0.041	2.993	64	203,000	31	97,000	58	183,000	28	88,000	↓	0.033	1.051	57	180,000	27	86,000
141	30	1	1	↓	0.041	3.034	56	178,000	31	97,000	50	180,000	27	87,000	↓	0.033	1.084	50	159,000	27	87,000
142	131	3	5	↓	0.380	3.414	92	292,000	77	243,000	83	263,000	69	219,000	↓	0.328	1.412	82	260,000	68	217,000
143	225	3	3	↓	0.722	4.136	92	292,000	84	268,000	83	263,000	76	241,000	↓	0.627	2.039	82	260,000	75	238,000
144	393	11	18	↓	1.313	5.449	111	351,000	86	272,000	100	316,000	77	245,000	↓	1.146	3.185	100	317,000	78	246,000
145	88	3	5	↓	0.118	5.567	55	175,000	24	76,000	50	158,000	22	69,000	↓	0.098	3.283	49	155,000	21	67,000
146	42	1	3	↓	0.063	5.630	72	227,000	29	91,000	64	204,000	26	82,000	↓	0.057	3.340	63	200,000	25	80,000
147	207	3	3	↓	0.618	6.248	99	315,000	76	241,000	90	284,000	68	217,000	↓	0.534	3.874	87	277,000	67	212,000
148	307	3	5	↓	0.695	6.943	99	314,000	60	189,000	89	283,000	54	171,000	↓	0.624	4.498	86	273,000	52	165,000
149	418	10	14	↓	1.048	7.991	95	302,000	60	189,000	86	272,000	64	170,000	↓	0.958	5.456	87	275,000	54	172,000
150	96	4	4	↓	0.241	8.232	81	256,000	48	151,000	73	230,000	43	136,000	↓	0.219	5.675	74	236,000	44	139,000
151	201	4	5	↓	0.523	8.755	81	256,000	65	205,000	73	230,000	58	184,000	↓	0.473	6.148	74	236,000	60	189,000
152	0	0	0	↓	—	8.755	—	—	—	—	—	—	—	—	↓	—	6.148	—	—	—	—
153	419	9	12	↓	1.111	9.866	101	320,000	58	185,000	91	288,000	52	166,000	↓	0.990	7.138	93	296,000	54	171,000
154	203	12	14	↓	0.520	10.386	83	264,000	43	135,000	75	238,000	38	121,000	↓	0.468	7.606	79	252,000	41	129,000
155	425	7	6	↓	1.228	11.614	97	307,000	80	253,000	87	276,000	72	227,000	↓	1.097	8.703	93	294,000	76	242,000
156	124	3	2	↓	0.263	11.877	83	264,000	55	173,000	75	238,000	49	156,000	↓	0.241	8.944	77	245,000	51	161,000
157	51	2	2	↓	0.145	12.022	86	272,000	67	214,000	77	245,000	61	193,000	↓	0.131	9.075	80	253,000	63	199,000
158	275	8	7	↓	0.583	12.605	65	206,000	56	178,000	58	185,000	50	160,000	↓	0.531	9.606	61	192,000	52	166,000
159	490	4	3	↓	1.248	13.853	75	237,000	70	223,000	67	213,000	63	200,000	↓	1.138	10.744	72	227,000	67	213,000
160	336	3	3	↓	0.837	14.690	75	237,000	67	214,000	67	213,000	61	192,000	↓	0.766	11.510	72	227,000	65	205,000
161	902	8	14	↓	1.915	16.605	76	240,000	58	183,000	68	216,000	52	165,000	↓	1.726	13.236	70	222,000	54	170,000
162	141	6	7	↓	0.233	16.838	65	206,000	42	133,000	58	185,000	38	120,000	↓	0.205	13.441	59	188,000	38	122,000
163	149	2	1	↓	0.265	17.103	52	165,000	49	154,000	47	148,000	44	138,000	↓	0.233	13.674	47	150,000	44	140,000
164	154	1	1	↓	0.271	17.374	55	174,000	49	154,000	50	157,000	44	139,000	↓	0.238	13.912	49	156,000	44	138,000
165	402	1	1	↓	0.681	18.055	50	157,000	47	150,000	44	141,000	42	134,000	↓	0.602	14.514	46	147,000	44	140,000
166	278	3	3	↓	0.471	18.526	54	172,000	42	132,000	49	155,000	38	119,000	↓	0.410	14.930	51	161,000	39	124,000
Totals																					
16J	8041	157	250																		
17J	7168	137	192																		

APPENDIX C

DRESDEN REACTOR WATER CHEMISTRY

Table C-1
DRESDEN REACTOR WATER CHEMISTRY [†]

	pH			Conductivity (μmhos)			Turbidity (APHA Units)			Chloride (ppm)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Cycle No. 3—1964												
June	6.7	7.5	8.2	0.31	0.56	1.8	1.2	6.6	22.0	0.001	0.029	0.030
July	6.6	7.3	8.4	0.27	0.41	0.98	4.2	11.0	30.0	0.007	0.034	0.08
August	6.4	7.4	8.2	0.23	0.36	0.58	5.2	14.1	24.4	0.023	0.037	0.100
September	6.4	7.7	8.9	0.30	0.47	0.97	3.2	8.0	40.0	0.001	0.047	0.174
October	6.7	7.5	8.5	0.10	0.49	1.50	2.4	6.1	10.0	0.006	0.033	0.260
November	6.5	7.4	8.7	0.26	0.48	0.92	2.6	5.0	9.2	0.002	0.034	0.080
December	7.2	7.7	8.8	0.28	0.40	0.60	3.0	5.2	8.4	0.047	0.053	0.133
1965												
January	7.0	8.0	9.2	0.25	0.41	0.82	2.4	5.0	9.2	0.026	0.041	0.100
February	7.2	8.0	8.8	0.30	0.46	0.78	1.8	3.8	8.4	0.017	0.069	0.192
March	7.2	8.0	9.2	0.27	0.43	0.67	1.2	4.6	26.0	0.020	0.043	0.118
Cycle Average	6.8	7.6	8.7	0.26	0.45	0.96	2.7	6.9	18.8	0.015	0.042	0.138
Cycle No. 4—1965												
June	6.9	7.5	8.1	0.25	0.41	0.73	3.0	6.2	14.0	0.004	0.031	0.084
July	7.1	7.5	8.2	0.29	0.44	0.59	2.6	5.3	10.2	0.001	0.038	0.189
August	7.3	7.7	8.0	0.26	0.38	0.59	2.4	4.0	7.0	0.008	0.032	0.083
September	7.6	8.3	8.8	0.27	0.38	0.62	1.8	4.7	7.0	0.014	0.041	—
October	6.7	7.7	8.2	0.30	0.42	0.73	4.0	15.2	95.0	0.02	0.05	0.30
November	6.8	8.0	8.8	0.28	0.39	0.65	1.8	3.9	7.4	0.010	0.043	0.150
December	7.1	7.5	8.2	0.29	0.44	0.59	2.6	5.3	10.2	0.001	0.038	0.189
1966												
January	7.2	8.0	8.7	0.29	0.41	0.87	3.0	7.3	22.0	0.018	0.081	0.138
February	6.8	7.9	8.4	0.25	0.39	0.48	3.0	6.0	12.6	0.010	0.037	0.107
March	6.6	7.8	8.8	0.25	0.37	0.62	3.0	5.4	18.0	0.001	0.039	0.082
April	6.5	7.8	8.5	0.27	0.43	0.63	2.2	4.8	8.0	0.005	0.031	0.061
May	6.9	7.7	8.1	0.28	0.43	0.96	2.8	6.6	15.4	0.005	0.045	0.106
June	6.0	7.2	8.2	0.30	0.42	0.57	1.0	3.5	11.2	0.008	0.040	0.070
July	6.6	7.6	8.5	0.29	0.46	0.95	1.8	3.5	5.0	0.02	0.05	0.160
August	4.2*	7.4	8.3	0.32	3.55*	72.00*	2.4	6.8	20.4	0.014	0.060	0.560*
September	6.1	7.4	8.1	0.28	0.43	0.74	4.8	7.5	14.4	0.016	0.032	0.064
October	6.3	7.6	8.2	0.26	0.38	0.62	2.6	6.2	19.2	0.017	0.033	0.049
November	4.7*	7.7	8.5	0.25	1.36*	28.50*	2.2	7.3	44.0	0.005	0.028	0.043
December	6.4	7.5	8.3	0.31	0.44	1.30	2.2	7.8	14.8	0.010	0.040	0.084
1967												
January	5.7	7.7	8.5	0.29	0.46	0.81	2.0	4.7	12.0	0.01	0.032	0.044
Cycle Average	6.7	7.7	8.4	0.28	0.42	0.72	2.6	6.1	18.4	0.010	0.041	0.111

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Table C-1 (Continued)

	pH			Conductivity (μ mhos)			Turbidity (APHA Units)			Chloride (ppm)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Cycle No. 5—1967												
June	6.4	7.4	8.2	0.33	0.52	0.85	1.6	3.5	7.0	0.014	0.032	0.057
July	6.8	7.5	8.8	0.35	0.45	0.80	0.2	3.3	18.0	0.014	0.048	0.280
August	6.3	7.2	8.8	0.34	0.43	0.86	1.8	3.6	8.4	0.023	0.041	0.117
September	6.2	7.4	8.4	0.33	0.51	1.45	2.4	4.4	8.8	0.021	0.039	0.110
October	6.3	7.2	8.3	0.43	0.60	0.89	2.6	3.9	6.0	0.024	0.034	0.046
November	6.2	7.4	8.3	0.30	0.53	0.73	3.4	6.5	32.0	0.020	0.038	0.092
December	5.8	7.0	8.9	0.32	0.46	0.68	3.0	5.3	13.0	0.020	0.038	0.160
1968												
January	5.0	7.4	8.7	0.32	0.45	0.64	1.8	6.9	12.0	0.001	0.029	0.068
Cycle Average	6.1	7.3	8.6	0.34	0.51	0.86	2.1	4.7	11.1	0.017	0.037	0.116
Cycle No. 6—1968												
June	6.3	7.2	8.7	0.31	0.44	1.0	2.2	5.4	26.0	0.001	0.03	0.06
July	6.0	6.8	7.9	0.32	0.52	0.86	2.0	4.3	10.0	0.000	0.027	0.057
August	6.5	7.2	8.2	0.32	0.42	0.75	1.6	3.5	6.0	0.010	0.042	0.076
September	5.8	7.1	8.1	0.32	0.52	1.30	1.8	4.6	16.0	0.01	0.042	0.164
October	7.0	7.7	8.4	0.30	0.50	1.05	2.2	3.6	5.0	0.02	0.038	0.092
November	6.1	7.2	8.2	0.24	0.43	0.74	2.6	4.1	19.0	0.012	0.037	0.05
December	6.1	6.8	8.5	0.27	0.38	0.55	1.2	4.1	19.0	0.01	0.032	0.071
1969												
January	5.8	6.9	7.8	0.26	0.35	0.49	2.2	4.0	5.6	0.016	0.045	0.083
February	6.0	7.0	7.9	0.30	0.41	0.60	2.2	5.2	15.6	0.02	0.05	0.15
March	6.5	7.5	8.0	0.28	0.41	0.77	2.0	3.9	6.0	0.014	0.040	0.090
April	6.6	7.6	8.2	0.29	0.47	0.84	2.0	4.3	14.8	0.026	0.070	0.088
May	6.5	7.2	8.3	0.30	0.38	0.56	2.0	3.4	5.4	0.018	0.034	0.067
June	5.8	6.6	7.5	0.28	0.43	0.58	2.0	5.8	23.2	0.013	0.036	0.076
July	5.6	6.6	7.6	0.29	0.38	0.80	2.0	5.1	19.4	0.016	0.034	0.069
August	6.1	6.7	7.4	0.29	0.39	0.56	2.0	3.9	8.6	0.01	0.041	0.158
Cycle Average	6.2	7.1	8.0	0.29	0.43	0.76	2.0	4.3	13.3	0.009	0.040	0.090
Four-Cycle Average	6.5	7.5	8.4	0.29	0.44	0.80	2.4	5.5	15.9	0.012	0.040	0.111

†Data in this table were extracted from the monthly reports of the Commonwealth Edison Company on Dresden operation.

*These values were not included in the calculations of cycle averages.

APPENDIX D

**DISTRIBUTION OF FISSIONS
AMONG URANIUM AND PLUTONIUM ISOTOPES**

Table D-1
DISTRIBUTION OF FISSIONS AMONG URANIUM AND PLUTONIUM ISOTOPES
FOR FULL CROSS-SECTION FUEL SAMPLES

Rod Number	Sample Number	Nominal Cold Enrichment (at.% U-235)	Distance From Short End Plug Shoulder (cm [in.])	Integrated Effective 2200 m/sec Flux (nvt X 10 ⁻²¹)	Atom Percent Fission					Burnup*	
					U-235	Pu-239	Pu-241	U-238	Total	Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU
Initial Phase											
A46	69	2.79	27.6 (10-7/8)	2.391	1.787	0.869	0.084	0.192	2.932	7.0	25,700
B70	70	2.79	26.4 (10-3/8)	2.262	1.744	0.885	0.079	0.190	2.898	6.9	25,400
A41	68	3.53	27.6 (10-7/8)	2.393	2.283	0.746	0.104	0.215	3.348	8.0	29,200
A13	67	3.53	27.3 (10-3/4)	2.308	2.251	0.758	0.101	0.213	3.323	7.9	29,000
Final Phase											
A35	104	2.79	26.4 (10-3/8)	3.253	2.032	1.076	0.175	0.217	3.500	8.39	30,680
A42	111	↓	↓	3.624	2.089	1.191	0.207	0.233	3.720	8.93	32,630
A47	113		↓	3.525	2.075	1.196	0.200	0.233	3.704	8.89	32,490
A48	114		↓	3.612	2.087	1.226	0.211	0.236	3.761	9.03	33,000
A49	115		↓	3.835	2.116	1.224	0.227	0.236	3.802	9.13	33,360
B96	122		29.4 (11-9/16)	3.417	2.059	1.138	0.188	0.226	3.611	8.66	31,670
B91	121	↓	↓	3.429	2.061	1.161	0.196	0.228	3.646	8.75	31,980
B98	123		↓	3.749	2.087	1.218	0.226	0.250	3.782	9.08	33,180
A34	103	3.24	26.4 (10-3/8)	3.018	2.300	0.994	0.134	0.226	3.653	8.74	31,960
A9	100	3.53	↓	3.265	2.546	1.038	0.186	0.263	4.033	9.65	35,280
A11	101	↓	↓	3.453	2.588	1.107	0.198	0.269	4.162	9.97	36,430
A37	105		26.4 (10-3/8)	3.515	2.600	1.145	0.201	0.271	4.217	10.10	36,910
↓	106		1.6 (5/8)	3.791	2.648	1.045	0.197	0.255	4.144	9.92	36,250
	107		4.1 (1-5/8)	2.951	2.468	0.858	0.133	0.226	3.685	8.81	32,200
	108		92.2 (36-5/16)	2.164	2.184	0.596	0.072	0.186	3.039	7.25	26,500
	109		94.8 (37-5/16)	2.591	2.356	0.681	0.095	0.205	3.337	7.96	29,110
	B62		116	29.4 (11-9/16)	3.488	2.596	1.190	0.204	0.273	4.264	10.22
↓	117		1.6 (5/8)	3.649	2.624	1.040	0.188	0.266	4.118	9.86	36,020
	118		4.1 (1-5/8)	2.904	2.455	0.864	0.131	0.237	3.688	8.82	32,220
	119		92.2 (36-5/16)	1.664	1.912	0.481	0.046	0.159	2.597	6.19	22,630
	120		94.8 (37-5/16)	2.017	2.115	0.549	0.062	0.186	2.913	6.95	25,390

*From heavy element data.

Table D-2

DISTRIBUTION OF FISSIONS AMONG URANIUM AND PLUTONIUM ISOTOPES
FOR FUEL SAMPLES FROM DIFFERENT RADIAL LOCATIONS
ROD A13

Sample Number	Distance From Pellet Periphery (cm [in.])	Integrated Effective 2200 m/sec Flux (nvt X 10 ⁻²¹)	Atom Percent Fission					Burnup*	
			U-235	Pu-239	Pu-241	U-238	Total	Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU
82	0.000-0.005 (0.000-0.002)	2.423	2.297	1.848	0.262	0.314	4.721	11.4	41,500
83	0.005-0.010 (0.002-0.004)	2.451	2.307	1.362	0.194	0.272	4.135	9.9	36,300
84	0.010-0.018 (0.004-0.007)	2.442	2.302	0.981	0.141	0.238	3.661	8.8	32,200
85	0.018-0.025 (0.007-0.010)	2.425	2.304	0.802	0.111	0.221	3.438	8.2	30,000
86	0.025-0.038 (0.010-0.015)	2.407	2.294	0.788	0.105	0.219	3.406	8.1	29,700
87	0.038-0.051 (0.015-0.020)	2.394	2.286	0.705	0.093	0.211	3.296	7.9	28,800
88	0.051-0.076 (0.020-0.030)	2.362	2.275	0.623	0.079	0.203	3.181	7.6	27,700
89	0.076-0.127 (0.030-0.050)	2.363	2.275	0.611	0.079	0.202	3.167	7.6	27,600
90	0.127-0.254 (0.050-0.100)	2.332	2.260	0.629	0.078	0.202	3.168	7.6	27,600
91	0.254-center†	2.198	2.204	0.640	0.077	0.200	3.120	7.4	27,200

Notes:

Nominal initial uranium enrichment for rod A13 was 3.53 atom %.

*From heavy element data.

†Nominal pellet radius = 0.478 cm (0.188 in.).

Table D-3

**DISTRIBUTION OF FISSIONS AMONG URANIUM AND PLUTONIUM ISOTOPES
FOR FUEL SAMPLES FROM DIFFERENT RADIAL LOCATIONS
ROD B70**

Sample Number	Distance From Pellet Periphery (cm [in.])	Integrated Effective 2200 m/sec Flux (nvt X 10 ⁻²¹)	Atom Percent Fission					Burnup*	
			U-235	Pu-239	Pu-241	U-238	Total	Fissions/cm ³ (X 10 ⁻²⁰)	MWd/tU
93	0.000-0.005 (0.000-0.002)	2.046	1.680	1.901	0.267	0.281	4.129	10.0	36,400
94	0.005-0.010 (0.002-0.004)	2.418	1.822	1.467	0.200	0.251	3.740	9.0	32,900
95	0.010-0.018 (0.004-0.007)	2.412	1.817	1.039	0.140	0.212	3.208	7.7	28,100
96	0.018-0.025 (0.007-0.010)	2.415	1.815	0.919	0.121	0.201	3.056	7.3	26,800
97	0.025-0.038 (0.010-0.015)	2.408	1.809	0.824	0.107	0.192	2.931	7.0	25,600
98	0.038-0.051 (0.015-0.020)	2.356	1.797	0.701	0.089	0.180	2.766	6.6	24,200
99	0.051-0.076 (0.020-0.030)	2.345	1.795	0.682	0.084	0.182	2.743	6.6	24,000
100	0.076-0.127 (0.030-0.050)	2.323	1.783	0.811	0.102	0.189	2.885	6.9	25,200
101	0.127-0.254 (0.050-0.100)	2.288	1.776	0.706	0.083	0.173	2.738	6.5	23,900
102	0.254-center† (0.100-center)	2.237	1.736	0.667	0.076	0.172	2.652	6.3	23,200

Note:

Nominal initial uranium enrichment for rod B70 was 2.79 at. %.

*From heavy element data.

†Nominal pellet radius = 0.478 cm (0.188 in.).

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