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MASTER

HIGH-BURNUP PERFORMANCE OF MIXED-OXIDE FUEL RODS
CLAD IN TYPE 316SS OF 0.010-[#]AND 0.015-INCH WALL THICKNESS

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by

D. C. Wadekamper

D. E. Plumlee

R. F. Hilbert

Approved:

R. F. Hilbert

Manager, Mixed Oxide Fuel Systems

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Fuel Rod Testing and Analysis

General Electric Company
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Sunnyvale, California

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Letter dated June 30/76

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ABSTRACT

Two short mixed-oxide fuel rods of LMFBR design configuration were irradiated to a burnup of ~ 12.5 atom % in GETR. Profilometry at several intervals during the test indicated that the rod with a 0.010 inch thick cladding exhibited a diametral strain of 0.17% per atom % burnup, while the rod with a 0.015 inch thick cladding exhibited a lower diametral strain rate of 0.12% per atom % burnup. These data present the opportunity for analytical methods to evaluate fuel rod dimensional changes without the complicating effect of metal swelling. Also, the rods incorporated a large plenum space so that pressure from released fission gases was extremely low. These measured strain rates are consistent with the range of fuel diametral strain rates that are associated with solid fission product swelling.

1. INTRODUCTION

A detailed understanding of the fuel rod mechanical state is necessary for the reactor designer to specify the fuel rod and fuel assembly fabrication and operation parameters. Permanent cladding dimensional changes are primarily attributed to metal swelling or inelastic strain caused by various loading mechanisms. Loading mechanisms thought to be of major importance include: fission gas pressure, fuel-cladding mechanical interaction during steady-state and power changes, and fuel rod-spacer interaction. Principal deformation mechanisms by which the cladding responds to these loading mechanisms include: thermal creep, irradiation creep, and plastic yielding. To establish a fuel rod design, the loading mechanisms must be understood, the amount of cladding deformation calculated, and the amount of deformation for each mechanism related to the material integrity or ability to respond.

To provide insight into fuel-cladding mechanical interaction, an irradiation program, E2, was undertaken by the General Electric Company. The program involved irradiation in a thermal flux of two mixed fuel rods in the General Electric Test Reactor (GETR). The experiment was designed so that the fuel rods were de-encapsulated and nondestructively examined (neutron radiography, profilometry, and gamma scan) and re-encapsulated at intervals of ~ 1 at.% burnup. The two fuel rods (E2P and E2Q) were irradiated to a measured burnup (average) of 12.4 and 12.7 at. %, respectively. The primary test parameter was cladding thickness (E2P - 0.015 inch, E2Q - 0.010 inch).

2. DESCRIPTION OF EXPERIMENT

2.1 Capsule Design

The test capsule was designed to permit simultaneous irradiation of the two fuel rods (E2P and E2Q) under similar conditions. The capsule design is shown in Figure A.1 (see Appendix A). The two 0.250-inch fuel rods were positioned one above each other in the capsule. Figure A.2 shows the cross sectional dimensions of the capsule at the fuel axial mid-plane of each rod.

The fuel rods were individually encapsulated to prevent the malfunction of one rod from affecting the operation of the other. Another design feature of the capsule was a bellows assembly to accommodate the thermal expansion of the NaK thermal bond. This design significantly reduced the possibility of entrapment of gas bubbles in the NaK heat transfer medium which could result in hot spots and subsequent fuel failure. The temperature in the thermal dam adjacent to the axial midplane of the fuel column of each rod was measured by chromel-alumel thermocouples. These thermocouples were used to monitor the operating temperature of the top and bottom fuel rod as well as to adjust the capsule relative to the reactor axial flux peak.

The capsule design provided for de-encapsulation of the fuel rods and non-destructive examination of the rods at scheduled intervals.

2.2 Fuel Rod Design

Figure A.3 shows the design for the E2P and Q rods. The rods contained 2 inches of coprecipitated mixed (urania-plutonia) oxide fuel with an upper and lower urania insulator. The fuel composition was nominally 25 w/o plutonia and 75 w/o urania with a 10 percent U-235 enrichment. The cladding was seamless Type 316 annealed stainless steel of 0.250 inch outside diameter with either 0.015 (E2P) or 0.010 (E2Q) inch wall thickness. The fuel rod design parameters are summarized in Table A.1.

The rods were specifically designed with a bellows assembly to reduce the effects of fission gas during irradiation. In addition, the design provided for axial restraint of the fuel column during irradiation.

2.3 Irradiation History

The irradiation was performed in the General Electric Test Reactor (GETR) using a vertical and radially adjustable facility tube (V-RAFT). The use of this facility permitted the irradiation of both fuel rods at similar power levels. This was achieved by adjusting the capsule assembly so that the rods straddled the axial flux peak during irradiation. Figure 2.1 illustrates the relative location of the fuel rods with respect to the maximum and average axial GETR flux profiles. The positions of the fuel rods in the capsule assembly were

Figure 2.1. Positioning of Rods on Axial Flux Peak

interchanged (top-to-bottom, bottom-to-top) after each interim examination to help smooth out irradiation effects caused by positioning.

The fuel rod power values obtained at initiation of irradiation indicated that rod E2Q was operating at nearly 25 percent higher power than the E2P rod. Since no apparent reason for this power difference could be identified, the capsule was adjusted until an indicated power of 9 kW/ft was achieved for each rod.

The first interim examination revealed a significantly higher gamma activity for E2P compared to E2Q as well as center melting. These effects were consistent with a GETR physics calculated power of 23 kW/ft and 15 kW/ft for E2P and Q, respectively.

Review of the capsule design revealed that convection currents could be established within the thermal bonding fluid which distorted thermocouple readings and resulted in the erroneous positioning of the capsule during the initial irradiation interval. As a result, the capsule thermal dams were redesigned to alleviate this problem. The E2Q fuel rod (calculated burnup 0.16 a/o) was re-encapsulated with a new E2P rod (designated E2Pa) and further irradiation initiated. Power calculations from theoretical considerations as well as thermocouple readings for the subsequent irradiation agreed within seven percent. After elimination of the problem associated with initial startup, the fuel rods were irradiated for 570 effective full power days (EFPD) in cycles of 10 to 33 EFPD. The average linear power for the fuel rods (midpoint) varied from 6 to 16 kW/ft during the cycles. The fuel rods were subjected to over 80 thermal cycles during the irradiation period. The variations in power with respect to fuel burnup as determined by theoretical calculations and thermocouple readings are presented in Figure 2.2. The timing of the rod interim nondestructive examinations with respect to average fuel burnup are also shown in Figure 2.2. The cladding I.D. and mean wall temperature of the rods as a function of linear power are presented in Figure 2.3.

FIGURE 2.2 VARIATION OF ROD-CALCULATED AND MEASURED POWER WITH BURNUP AT FUEL AXIAL MIDPLANE

Figure 2.3. Cladding Temperature as a Function of Rod Power

B. ROD EXAMINATION

B.1 Interim Examination

The nondestructive interim examination of the E2P and Q rods were performed at the General Electric Company, Vallecitos Nuclear Center (GE-VNC). These examinations included neutron radiography, gamma scanning, and fuel rod diameter measurements.

B.1.1 Neutron Radiography

Neutron radiography was the first operation performed in the interim radiation evaluations. Examination of the neutron radiographs indicated that rod E2Q exhibited a central void after ~2 at.% burnup while E2P was irradiated until ~1.1 at.% burnup before a central void was observed. The central void once formed was not uniform along the fuel column length. For both rods the center void was significantly larger at one end of the fuel column (top end). The pellet interfaces which were very pronounced at the first irradiation cycle for each rod became less and less distinct with increasing fuel burnup.

B.1.2 Gamma Spectroscopy

Precision scans of the axial distribution of the total gamma activity were obtained at each interim examination. Initially the total gamma activity for each fuel rod was skewed towards the peak flux with spikes of varying magnitude at the end of each fuel column. As the burnup of the fuel rods approached the 11 at.% level, the amount of skewness towards the peak flux began to decrease implying a more uniform axial distribution of gamma activity. Figure B.1 (see Appendix B) illustrates this relative change in axial activity with burnup.

B.1.3 Fuel Rod Dimensional Measurements

At interim examination, profilometry measurements were performed at 45° intervals along the length of the cladding of each rod. The results of these scans are presented in Figure C.1 (see Appendix C).

These profiles showed the cladding diameter to be further increased at each examination. Maximum diameter increases occurred at the top end of the rods until ~8.4 and ~11.2 at.% burnup for E2P and Q, respectively. The position of the maximum diameter increase then began to gradually shift toward the center of the rod. Initially, E2P (15 mil cladding) appeared to exhibit a smaller diameter change than E2Q (10 mil cladding) under similar irradiation conditions. At the end of the irradiation (~12 at.% burnup), both fuel rods obtained a similar diameter change of about 0.009 inches.

3.2 Post-Irradiation Examination

The post-irradiation examination was performed at Los Alamos Scientific Laboratory (LASL). The final examination consisted of betatron radiographs, gross and elemental gamma scans, profilometry, fission gas volume determinations with elemental and isotopic analysis, metallographic examination, electron microprobe examination, and fuel burnup analysis.

3.2.1 Betatron Radiography

Figure 3.1 shows post-irradiation betatron radiographs taken of the two fuel rods. As determined during interim examination, the center void extends for the full length of the fuel column in each rod. The diameter of the center void generally increased from the bottom to the top of the fuel column.

3.2.2 Gamma Spectroscopy

The gross and elemental gamma scans taken of the two rods are shown in Appendix B (Figures B.2 through B.12). E2P and Q revealed significant relocation of Rh-106 at the bottom of the fuel columns; concentration of Ru-103 was also observed at the bottom of E2Q (E2P not analyzed). Additional gamma scans revealed that Cs-134 (E2P not analyzed) and Cs-137 had moved from the fuel to the insulator pellets at the rod ends. The concentration of Cs-134 and Cs-137 also increased at the center of the fuel column. Similar distributions for Zr-95 and Nb-95 also were observed in both fuel rods.

3.2.3 Fuel Rod Dimensional Measurements

Further cladding dimensional increases were observed for the two rods on post-irradiation examination. Table 3.1 shows the maximum and average diametral change measured for each rod during irradiation.

E2Q

E2P

FIGURE 3.1 BETATRON RADIOGRAPHS OF FUEL RODS E2P and E2Q

TABLE 3.1

Summary of Fuel Rod Diameter Changes

GETR Irradiation Interval (Reactor Cycles)	Rod E2P				Rod E2Q			
	Burnup (at. %)		$\Delta D/D^*$ (%)		Burnup (at. %)		$\Delta D/D^*$	
	Peak	Avg.	Max.	Avg.	Peak	Avg.	Max.	Avg.
94-95	0.27***	0.27***	***	***	0.16	0.16	1.15	0.45
102-103	0.99	0.95	1.00	0.31	1.03	0.98	1.15	0.66
106-107	2.23	2.10	1.00	0.36	2.09	2.07	1.51	0.91
111-112	3.25	3.17	1.12	0.53	3.13	3.09	1.75	1.13
114-115	4.12	4.00	1.20	0.64	3.93	3.92	2.03	1.47
117-119	6.30	6.15	1.68	0.95	6.22	6.09	2.07	1.52
121-123	8.42	8.36	1.88	1.05	8.32	8.30	2.54	1.83
125-128	11.64	11.47	3.87	3.31	11.30	11.12	3.05	2.42
130-131 (GE)	12.36	12.15	3.91	3.64	11.94	11.72	3.65	3.10
130-131 (LASL)	-	12.4**	4.35	3.92	-	12.7**	3.73	3.53

* Based on measurements in 4 orientations.

** Measured value.

*** Fuel rod experienced excessive linear power - replaced by rod E2Pa for subsequent irradiation.

3.2.4 Fission Gas Release

Fission gas samples were collected from the two rods. Aliquots of the gas were then taken for gas chromatography and mass spectrometry analysis.

Table 3.2 shows the total gas collected from each rod and the results of the above analyses. Based on these results a fission gas release of 88.2% and 90.9% was calculated for E2P and Q, respectively.

3.2.5 Fuel and Cladding Examination

Two longitudinal and one transverse metallographic specimens were obtained from each rod. Figure 3.2 presents the sectioning diagram. Fuel and cladding examinations were divided into three parts. First, the fuel was examined for microstructural changes. Second, the cladding and specific areas which experienced fuel-cladding chemical interaction were examined. Finally, a detailed microprobe evaluation of fission product and fuel constituent redistribution was made.

3.2.5.1 Fuel Examination

The appearance of the fuel in each rod at the axial midplane is shown in Figures D.1 and D.2 (see Appendix D).

The fuel exhibited the following typical irradiated mixed oxide features; (a) a region with no gross change in grain structure, (b) a region of enlarged equiaxed grains, (c) a region of columnar grains and (d) a central void. The dimensions of these various microstructural zones are given in Table 3.3. The fuel also exhibited numerous radial and circumferential cracks, as well as a fuel-cladding reaction zone at the periphery of the fuel.

3.2.5.2 Fuel-Cladding Reaction

A fuel-cladding reaction zone was observed along the fuel length of each rod. Figures D.3 and D.4 illustrate the typical appearance of the reaction zone before and after etching.

Intergranular attack of the cladding was associated with the reaction zone. Figures D.5 and D.6 show the typical high magnification appearance of the

FIGURE 3.2 SECTIONING DIAGRAM FOR RODS E20 AND E20

TABLE 3.2

Fission Gas Analysis

	<u>E2P</u>	<u>E2Q</u>
Total Gas (gm-moles. x 10 ³)	2.07	2.2
Gas Chromatographic Analysis (mol. %):		
H ₂	< 0.05	< 0.05
He	18.8	17.0
N ₂	< 0.03	< 0.03
O ₂	< 0.02	< 0.02
Ar	0.02	0.03
Kr	5.60	5.68
Xe	75.6	77.3
Xe/Kr	13.5	13.61
Spectrographic Analysis:		
Kr-83/Kr	13.4	13.3
Kr-84/Kr	31.1	31.4
Kr-85/Kr	6.89	6.67
Kr-86/Kr	48.6	48.7
Xe-128/Xe	0.02	0.01
Xe-130/Xe	0.14	0.14
Xe-131/Xe	11.37	11.15
Xe-132/Xe	19.98	19.78
Xe-134/Xe	27.56	27.22
Xe-135/Xe	40.95	41.69

reaction zone and intergranular attack in each rod prior to etching while Figures D.7 and D.8 show the etched appearance of the cladding of each rod adjacent to the fuel column midplane.

The depth of cladding matrix attack and depth of intergranular penetration measured at various axial locations along the fuel column of each rod are shown in Table 3.4. The depth of cladding attack was determined by measuring the distance from the outside of the cladding to the deepest intergranular penetration and subtracting that quantity from the original cladding thickness. The circumferential crack present in some portions of the reaction zone was attributed to thermal contraction and not included in the reaction zone thickness.

Examination of the fuel-cladding interaction region by microprobe showed the following results (see Figure E.1 - Appendix E). A continuous molybdenum-rich layer was observed at the inner edge of the unreacted cladding. Cladding constituents (Fe, Cr, and Ni) were dispersed somewhat irregularly through the reaction zone and as an almost continuous row of metallic particles at the interface between the fuel and the reaction zone.

Single line scans across the interaction zone were made at three additional locations to help characterize the constituents present. The results of these scans are shown in Figures E.2, E.3 and E.4. These scans showed the reaction zone, aside from cladding constituents, to be extremely heterogeneous.

Uranium and plutonium were found irregularly throughout the reaction zone. In most cases these elements were found with the major cladding constituents (Fe, Cr, Ni). Tellurium, and to some extent, cesium and iodine were observed to build up in concentration next to the inner edge of the cladding in irregular areas. Other fission products detected in the scans were Pd, Mo, Ce, and Zr. However, their distribution was exceedingly heterogeneous and irregular.

TABLE 3.3

Measurement of Fuel Structure Radii

<u>Rod</u>	<u>Axial Position</u>	<u>Burnup (at.%)</u>	<u>Power* (KW/FT)</u>	<u>Structure Radii (Fraction of Radius)</u>		
				<u>EEG</u>	<u>CCG</u>	<u>Central Void</u>
E2P	TOP	12.4	13.8	0.87	0.69	0.23
	MIDPLANE	12.2	13.2	0.87	0.70	0.17
	BOTTOM	12.0	13.5	0.85	0.67	0.14
E2Q	TOP	11.9	14.0	0.86	0.72	0.27
	MIDPLANE	11.7	14.5	0.89	0.70	0.14
	BOTTOM	11.5	15.0	0.83	0.66	0.17

* Based on cycle averages above 12 KW/FT

TABLE 3.4

Axial Variation of Fuel-Cladding Interaction

<u>Rod</u>	<u>Axial Position</u>	<u>Cladding Matrix Attack (in.)*</u>	<u>Intergranular Penetration (in.)</u>
E2P	TOP		
	0.01**	0.0009	0.0002
	0.04	0.0009	0.0010
	0.25	0.0009	0.0014
	0.28	0.0009	0.0015
	0.40 (2)***	0.0019	0.0013
	MIDDLE (5)	0.0045	0.0018
	BOTTOM		
	0.00 (2)	0.0003	0.0000
	0.20 (2)	0.0007	0.0002
	0.28 (2)	0.0014	0.0003
E2Q	TOP		
	0.00	-0.0005	0.0000
	0.10	0.0022	0.0025
	0.20 (2)	0.0008	0.0016
	0.25	0.0027	0.0024
	0.28	0.0030	0.0031
	0.29	0.0012	0.0015
	0.40	0.0025	0.0025
	MIDDLE (13)	0.0026	0.0012
	BOTTOM		
	0.05 (2)	0.0004	0.0000
	0.22 (2)	0.0004	0.0001
	0.35 (2)	0.0003	0.0003

* Original cladding thickness: E2P - 0.0149 in.; E2Q - 0.0105.

** Distance in inches from fuel-insulator interface toward rod center.

*** Number of samples averages.

A point count scan was made across the diameter of the E2P rod. The path of the scan is shown on the beta-gamma autoradiograph (Figure E.5) which is shown in the same orientation as the photographic mosaic presented in Figure D.1. The mosaic presents a somewhat different appearance than the autoradiograph since the fuel sample was reground and repolished after the autoradiograph was taken and before the mosaic was made. Several of the major cracks, however, coincide as shown by a comparison of the two figures. In order to ensure that these counts were representative of fission product distribution in the fuel, care was taken that the electron beam was on fuel material and not on a metallic inclusion during the counts. The results of these radial scans are shown in Figures E.6 through E.10. For ease of comparison, scans in the 0° position shown in Figure E.5 are located on the left-hand side of the figures, while those at 180° are on the right hand side.

Ruthenium, rhodium, and palladium were irregularly detectable throughout the fuel and tended to increase in concentration near the outer edge of the fuel in the 180° position, but not in the 0° position. Praseodymium and neodymium were readily detectable throughout the fuel in both positions and showed a tendency to increase in concentration near the outer edge of the fuel in the 180° position.

Of the cladding constituents, iron and chromium rose more sharply in concentration than nickel near the cladding. Zirconium also increased in concentration at the outer edge of the fuel. The increase in concentration extended over a wider region than for the other elements mentioned. Tellurium was low and fairly regularly distributed throughout the fuel in both the 0° and 180° positions. Both iodine and xenon were detected more strongly in the 0° than in the 180° position. It is interesting to note the relatively strong increase in iodine near the central void in the 0° position, but not the 180° position.

Concentrations of barium were low and irregular throughout the fuel. In the 0° position the cesium concentration was found to build up toward the cladding. Molybdenum was low and irregular in concentration throughout the fuel, except for a slight buildup in the outer fuel in the 180° position.

3.2.5.3 Fuel Constituent and Fission Product Distribution

During metallographic examination of the fuel, some metallic fission products in "stringer" like deposits were observed near the exterior of the pellets. These "stringers" were attributed to the deposition of fission products in open cracks. The "stringers" were observed in both open and closed or healed racks. The appearance of the "stringers" is shown in Figure D.9.

Metallic fission product particles were distributed within the fuel across the cross section. In the columnar grain region these deposits existed as rounded particles while in the unstructured and equiaxed grain regions the particles were more irregular in shape, smaller in size, and much more numerous. Figure D.10 shows the representative appearance of these deposits.

Examination of the central void regions of both E2P and E2Q revealed the presence of metallic fission product inclusions or "ingots" only at the bottoms of the fuel rods. These deposits likely contain, at least in part, Ru and Rh since the elemental gamma scans showed spikes due to Ru-103 and Rh-106 at the bottom ends of the fuel columns.

Microprobe analysis showed the metallic inclusions to consist of two distinct types of particles. The major constituents of the particles near the cladding were iron and palladium, with lesser and variable concentrations of molybdenum. Other elements detected in low to trace quantities (but not always all in the same particle) were chromium, tellurium, iodine, xenon, praseodymium, neodymium, manganese, niobium, zirconium, and technetium. Surprisingly, nickel was not detected with the iron. The particles near the central void were rich in molybdenum, ruthenium, and technetium, and much lower quantities of rhodium.

No iron was detected in these particles. The transition between the two types of particles occurred at a distance of .0394 to .0591 inches inward from the cladding, which is slightly over half the distance from the cladding to the center void.

The observed distributions of the fuel constituents are shown in Figure E.11. The concentration of plutonium was observed to increase and that of uranium to decrease as the central void is approached.

3.2.6 Burnup Analysis

Burnup analysis was performed on the fuel from both rods. The samples were obtained from the axial midplane regions of the fuel. Burnup analyses were performed using the Nd-148 method (ASTM E321-69). Calculated and measured burnup values for each rod are shown in Table 3.5. Values agree within 2 to 9 percent.

4. CLADDING DEFORMATION

4.1 Inelastic Strain

The inelastic strain in fuel rod cladding is defined as the total diametral strain (change) minus the diameter change due to cladding swelling. Thus, the cladding inelastic strain is a measure of permanent deformation due largely to some combination of thermal creep, irradiation creep and plastic deformation. Since the E2P and E2Q fuel rods were irradiated in a thermal flux, the cladding swelling is insignificant. Thus, in this test, the total diameter change of the cladding is a direct measure of the cladding inelastic strain. The inelastic strain measured for each rod is shown in Table 3.6.

Fuel rods E2P and E2Q experienced maximum deformation in the upper half of the fuel column until ~6-8 at.% burnup was reached. At this time, the point of maximum deformation began to shift toward the midpoint of the fuel rod (see Figure C.1 - Appendix C). It is to be noted that the majority of the inflection points on the profilometry traces appear to coincide with the fuel column pellet-to-pellet interfaces during the entire irradiation.

Profilometry results indicated that E2P exhibited a smaller initial incremental cladding deformation than E2Q. Assuming similar fuel behavior, the lower deformation rate associated with the larger wall thickness cladding of E2P (0.015 in. versus 0.010 in. for E2Q) might be expected.

TABLE 3.5

<u>Fuel Rod</u>	<u>Burnup Analysis</u>		
	<u>Burnup (at .%)</u>		<u>Nd/Calculated</u>
	<u>Calculated*</u>	<u>Measured Nd-148**</u>	
E2P	12.2	12.4	1.016
E2Q	11.7	12.7	1.085

* Based on published GETR fission rates.

** Based on neodymium to heavy element ratio.

TABLE 3.6

Measured Inelastic Strain (Fuel Axial Midplane)

GETR Irradiation Internal (Reactor Cycles)	E2P				E2Q			
	Calculated Fluence ($n/cm^2 \times 10^{20}$)	Calculated Burnup (at .%)	Cumulative Power Cycles	Inelastic Strain (%)	Calculated Fluence ($n/cm^2 \times 10^{20}$)	Calculated Burnup (at .%)	Cumulative Power Cycles	Inelastic Strain (%)
94-95	0.72*	0.27*	4*	0.64*	0.44	0.16	4	0.45
102-103	2.56	0.95	12	0.31	2.76	0.99	16	0.66
106-107	5.96	2.10	22	0.36	6.15	2.12	26	0.91
111-112	10.16	3.17	33	0.53	10.34	3.11	37	1.13
114-115	14.74	4.00	39	0.64	15.16	3.94	43	1.47
117-119	21.21	6.15	47	0.95	22.05	6.11	51	1.52
121-123	27.95	8.36	58	1.05	29.16	8.31	62	1.83
125-128	38.31	11.47	76	3.31	39.15	11.14	80	2.42
130-131 (GE)	40.64	12.15	84	3.64	41.34	11.74	88	3.10
130-131 (LASL)	-	12.4**	-	3.92	-	12.7**	-	3.53

* Fuel rod experienced excessive linear power - replaced by rod E2Pa for subsequent irradiation.

** Measured value.

A graphical representation of the rod midpoint diameter changes (cladding inelastic strain) as a function of calculated burnup for the E2P and E2Q fuel rods is shown in Figure 4.1. Both rods exhibited a marked cladding strain (0.32 and 0.44 percent) after the first irradiation cycle (0.81 and 0.16 atom percent burnup). After the initial deformation, the inelastic strain values of both fuel rods increased at near linear rates, 0.12%/at.% burnup and 0.17%/at.% burnup for E2P and Q, respectively. When rods E2P and Q reached ~8 and ~11 at. % burnup, respectively, the rods exhibited significant increase in inelastic strain.

4.2 Mechanisms of Fuel-Cladding Interaction

Four possible mechanisms which can cause inelastic strain of the cladding are:

(1) strain arising from differential thermal expansion of fuel and cladding during initial startup, (2) strain arising from fission gas pressure, (3) strain arising from fuel-cladding mechanical interaction caused by fuel swelling, and (4) strain caused by differential thermal expansion combined with fuel cracking on shutdown or mismatch when cracks heal during subsequent startup (usually termed "thermal ratchetting").

Differential thermal expansion of fuel and cladding during initial startup can cause measurable cladding inelastic strain. The magnitude of this strain, which occurs only for pellet fuel, is dependent on the initial fuel-to-cladding gap. This parameter was studied in the F1 experiment,⁽¹⁾ where irradiation exposures were low, eliminating complications such as fuel and cladding swelling. Cladding inelastic strain data presented as a function of initial fuel-to-cladding diametral gap for the F1 experiment is presented in Figure 4.2. Cladding strain increased with decreased fuel-to-cladding gap.

The inelastic strain data for E2P and Q revealed pronounced cladding deformation after completion of the initial irradiation cycle (see Figure 4.1). The midpoint cladding deformations of 0.0008 and 0.0012 inches observed for E2P and Q were similar to the 0.001 inch value predicted from the F1 data for 0.001 inch gap size. Because of the low fuel burnup, the fission gas and fuel swelling contribution to the cladding inelastic strain should be small, implying that the strain observed after the first irradiation cycle was the result of a fuel-cladding thermal expansion mismatch.

Figure 4.1. Cladding Inelastic Strain as a Function of Burnup

Figure 4.2. Cladding Inelastic Strain versus As-Fabricated Gap for GE Group F1 Fuel Rods.

A nearly linear inelastic strain rate was observed for the two rods after the initial thermal expansion deformation. The existence of fuel-cladding mechanical interaction for the rods is confirmed by the inflection points on the profilometry traces at the pellet-to-pellet interfaces.

The E2P and Q fuel rods were designed with a plenum volume of about seven times that of the fuel so that fission gas pressure was small. The end-of-life plenum gas volumes were 46.4 and 49.3 cm³, creating end-of-life hoop stresses of 2700 and 3900 psi for E2P and Q, respectively. The midwall cladding temperatures of the rods during irradiation was ~1100°F. Assuming that the fission gas pressure acted over the total irradiation period of the fuel rods, the resultant deformation would be immeasurable.

Solid-fission product swelling in oxide fuels has been found to range from 0.58% $\Delta V/V$ /at.% burnup⁽²⁾ to 1.32% $\Delta V/V$ /at.% burnup,⁽³⁾ depending on whether the vacancies generated by fissioning are used in fission product accommodation. This corresponds to a linear deformation rate of 0.19%/at.% burnup to 0.57%/at.% burnup. The observed deformation rates for the E2P and Q rods (0.12%/at.% burnup and 0.17%/at.% burnup) are, therefore, of similar magnitude to that observed for solid fission product swelling.

Both rods showed a marked increase in the rate of cladding inelastic strain at ~8 to ~11 at.% burnup. These increases appear to coincide with the shift of the maximum cladding deformation from the rod top to the rod midpoint. In the same burnup period, sufficient oxygen has been generated to increase the mixed oxide fuel oxygen-to-metal ratio to stoichiometry. In light of these facts and the knowledge that cesium seeks the higher oxygen activity areas, it appears possible that the marked increase in cladding deformation resulted from a change in swelling rate caused by the presence of cesium. A similar rationale may explain the higher inelastic strain rates initially observed at the top of the rods which appear to have had a higher cesium concentration than the bottom of the rods.

Cesium forms a number of compounds ($\text{Cs}_2(\text{U}, \text{Pu})\text{O}_4$, Cs_2MoO_4 , etc.) when a threshold oxygen activity is obtained. A volume increase is associated with formation of such compounds. Microprobe evaluation indicated the presence of Cs and particularly Mo in the fuel-cladding reaction zone.

The data from the E2P and Q fuel rods present the opportunity for evaluating fuel rod dimensional changes without the complicating effect of metal swelling. Also, the rods incorporated a large plenum space so that pressure from released fission gases was extremely low. Evaluation of the measured strain showed that they are consistent with the lower range of estimated fuel diametral strain rates associated with solid fission product swelling. Major work remains to evaluate how such cladding diametral strains result from partitioning of the solid fission product swelling between stressing the cladding and by accommodation within the fuel itself.

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APPENDIX A

CAPSULE AND FUEL ROD DESIGN

FIGURE A.1 CAPSULE DESIGN

Figure A.2. Capsule Cross-Sectional Dimensions at Midplane of Rods E2P and E2Q.

TITLE FUEL PIN CONT. ON SHEET

FIRST MADE FOR FCR E2PEQ

NEXT ASSEMBLY - 706E6A

G2	PT	NAME	DESCRIPTION
1	1	END PLUG	211A7432P1
1	2	BELLOWS	ROBERTSNAW # A-C0754-A6
1	3	TUBE	163B8104P3
1	4	TUBE	163B8104P2
1	5	END CAP	163B8104P1
1	6	ADAPTOR	163B8107P1
1	7	ADAPTOR	163B8107P2
2	8	INSULATOR PELLET	163B8108P3
1	9	TUBE	1/40.0 x .010 WALL X 3.200 T.010 LG. 3.200
1	10	TUBE	1/40.0 x .015 WALL X 3.200 T.010 LG. 3.200
8	11	FUEL PELLET	163B8108P1
8	12	FUEL PELLET	163B8108P2
1	13	END PLUG	211A7432P1
1	14	END PLUG	211A7432P2
2	15	INSULATOR PELLET	163B8108P4

REF. 706E686

NOTES:

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[illegible]

MADE BY H.C. Perkins	DATE SEPT 3, 1967	APPROVALS 10-10-67	OFF. OR DEPT. 1350 5094
TEST F.W. 12.1 x 10.0-67	DATE 10-24-67	INITIALS VN-	LOCATION NATION CENTER (470)
5	6	CHKS	1A 10-20-67

FIGURE A.3 E2P AND E2Q FUEL ROD DESIGN

TABLE A.1

E2P and E2Q Fuel Rod Parameters

<u>Blanket/Insulator</u>	E2P*	E2Pa	E2Q
Composition		Natural UO ₂	
Density, %T.D.	94.3/93.8	94.4/94.2	92.5/92.6
Diameter, in.	.2168/.2150	.2165/.2169	.2250/.2251
Length, in.	.2530/.2520	.2517/.2512	.2527/.2522
Type		Solid Pellet	
O/M	1.996/2.007	1.9961/1.9961	2.000/2.000
<u>Fuel</u>			
Composition, Pu/(+Pu)	.2420-.2532	.2547	.2634-.2665
Enrichment, U-235/U	.1020-.1126	.1212	.1160
Density, % T.D.	91.90	92.68	92.20
Fuel Diameter, in.	.2200	.2198	.2296
Fabrication Process		Co-Precipitation	
O/M	1.9702	1.970	1.974
Type		Solid Pellet	
Fuel Length, in.	2.032	1.958	2.028
Fuel Cladding Gap, in.	.0009	.0011	.0011
<u>Cladding</u>			
I.D., in.	.2209	.22085	.2307
Wall, in.	.0148	.0149	.0105
Type		316SS (Annealed, Seamless)	

* Fuel rod experienced excessive linear power during initial irradiation interval. Replaced by rod E2Pa during subsequent irradiation.

APPENDIX B

GROSS AND ELEMENTAL GAMMA SPECTROSCOPY

E2P

0.95 at.% Burnup

6.15 at.% Burnup

12.4 at.% Burnup

E2Q

0.16 at.% Burnup

6.09 at.% Burnup

12.7 at.% Burnup

FIGURE B.1 OBSERVED FLATTENING OF GAMMA
ACTIVITY PROFILES FOR RODS E2P
AND E2Q AT HIGH BURNUP

FIGURE B.2 POST-IRRADIATION GROSS GAMMA SCAN OF CAPSULE

FIGURE B.3 POST-IRRADIATION Cs-137 AXIAL ACTIVITY PROFILE FOR ROD E2P

FIGURE B.4 POST-IRRADIATION Rh-106 AXIAL ACTIVITY PROFILE FOR ROD E2P

FIGURE B.5 POST-IRRADIATION Nb-95 AXIAL ACTIVITY PROFILE FOR ROD E2P

FIGURE B.6 POST-IRRADIATION Zr-95 AXIAL ACTIVITY PROFILE FOR ROD E2P

FIGURE B.7 POST-IRRADIATION Cs-134 AXIAL ACTIVITY PROFILE FOR ROD E2Q

FIGURE B.8 POST-IRRADIATION Cs-137 AXIAL ACTIVITY FOR ROD E2Q

FIGURE B.9 POST-IRRADIATION Ru-103 AXIAL ACTIVITY PROFILE FOR ROD E2Q

FIGURE B.10 POST-IRRADIATION Pu-106 AXIAL ACTIVITY PROFILE FOR ROD E20

FIGURE B.11 POST-IRRADIATION Nb-95 AXIAL ACTIVITY PROFILE FOR ROD E2Q

APPENDIX C

ROD PROFILOMETRY

FIGURE B.12 POST-IRRADIATION Zr-95 AXIAL ACTIVITY PROFILE FOR ROD E2Q

FIGU E C.1 TYPICAL PROFILOMETRY SCANS FOR ONE ORIENTATION OF RODS E2P AND E2Q (FOUR ORIENTATIONS MEASURED)

APPENDIX D

FUEL CLADDING MICROSTRUCTURE

2B143

25X

FIGURE D.1 GENERAL APPEARANCE OF FUEL AT AXIAL MIDPLANE
FOR ROD E2P

2B140

25X

FIGURE D.2 GENERAL APPEARANCE OF FUEL AT AXIAL MIDPOINT FOR
ROI E2Q

2B140

UNETCHED

70X

2E140

ETCHED

70X

FIGURE D.3 UNETCHED AND ETCHED APPEARANCE OF FUEL CLADDING GAP REGION AT THE AXIAL MIDPLANE FOR ROD E2P

2B140

UNETCHED

70X

2B140

ETCHED

70X

FIGURE D.4 UNETCHED AND ETCHED APPEARANCE OF FUEL-CLADDING GAP REGION AT THE AXIAL MIDPLANE FOR ROD E2P
(180 DEGREES TO REGION SHOWN IN FIGURE D.3)

2B143

500X

FIGURE D.5 FUEL-CLADDING INTERACTION SHOWING MATRIX
ATTACK

2B1/4

500X

FIGURE 1.6 FUEL-CLADDING INTERACTION SHOWING INTERGRANULAR
ATTACK

2B140

400X

FIGURE D.7 ETCHED APPEARANCE OF CLADDING ADJACENT TO THE FUEL
AXIAL MIDPLANE FOR ROD E2P

2B142

400X

FIGURE D.8 ETCHED APPEARANCE OF CLADDING ADJACENT TO THE BOTTOM
END OF THE FUEL COLUMN FOR ROD E2Q

FIGURE D.9 TYPICAL APPEARANCE OF METALLIC FISSION PRODUCT DEPOSITION IN HEALED AND UNHEALED CRACKS AT PERIPHERY OF THE FUEL

2B143 UNRESTRUCTURED AND
EQUIAXED GRAIN REGION

500X

2B143 COLUMNAR GRAIN REGION

500X

FIGURE D.10 CROSS-SECTIONAL VARIATION IN APPEARANCE OF METALLIC FISSION PRODUCTS DEPOSITED IN FUEL

APPENDIX E

APPENDIX E
ELECTRON MICROPROBE EXAMINATION

73516

FIGURE E.1 PHOTOMICROGRAPH OF FUEL-CLADDING INTERFACE OF ROD E2P AND X-RAY IMAGES OF FILMENTS DETECTED (CONTINUED)

78515

FIGURE E.1 (CONTINUED) WITHIN INDICATED REGION

FIGURE E.2 ONE DIMENSIONAL SCAN OF FUEL-CLADDING REACTION ZONE OF FUEL ROD E2P AT FUEL AXIAL MIDPLANE (SCAN ONE).

FIGURE E.3 ONE DIMENSIONAL SCAN OF FUEL-CLADDING REACTION ZONE OF FUEL ROD E2P AT FUEL AXIAL MIDPLANE (SCAN TWO - DIFFERENT REGION THAN SCAN ONE)

FIGURE E.4 ONE DIMENSIONAL SCAN OF FUEL-CLADDING REACTION ZONE OF FUEL ROD E2P AT FUEL AXIAL MIDPLANE (SCAN THREE - DIFFERENT REGION THAN SCANS ONE AND TWO)

FIGURE E.5 BETA-GAMMA AUTORADIOGRAPH OF FUEL ROD E2P SHOWING
PATH OF RADIAL POINT COUNT SCANS OF FUEL

FIGURE E.6 RADIAL DISTRIBUTION OF RUTHENIUM, RHODIUM, AND PALLADIUM ACROSS FUEL OF ROD E2P

0° position

180° position

FIGURE E.7 RADIAL DISTRIBUTION OF PRASEODYMIUM, NEODYMIUM, AND CHROMIUM ACROSS FUEL OF ROD E2P

0° Position

180° Position

FIGURE E.8 RADIAL DISTRIBUTION OF IRON, NICKEL, AND ZIRCONIUM ACROSS FUEL OF ROD E2P

0° position

180° position

FIGURE E.9 RADIAL DISTRIBUTION OF TELLURIUM, IODINE, AND XENON ACROSS FUEL OF ROD E2P

FIGURE E.10 RADIAL DISTRIBUTION OF BARIUM, CESIUM AND MOLYBDENUM
ACROSS FUEL OF ROD E2P

FIGURE E.11 RADIAL DISTRIBUTION OF URANIUM AND PLUTONIUM
ACROSS FUEL OF ROD E2P