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FABRICATION AND PREIRRADIATION INFORMATION ON VIBRATORILY COMPACTED ThO_2-UO_2 FUEL RODS FOR EXPERIMENTS ETR-I AND MTR-III

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METALS AND CERAMICS DIVISION

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JANUARY 1966

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ABSTRACT

As part of our Thorium Utilization Program, the irradiation behavior of powder packed sol-gel thoria-base fuels is being evaluated. Ten capsules containing ThO_2–5.7% UO_2 were fabricated and then irradiated in the ETR and MTR process water at very high thermal ratings.

The principal fabrication variable considered was the gel calcining atmosphere. The oxide for the various rods was fired in Ar–4% H_2, air, or nitrogen. All of the capsules irradiated contained a ternary particle-size distribution except for one binary with air-fired material.

This memorandum describes the fabrication of the capsules and presents pertinent preirradiation data and predicted irradiation conditions. Irradiation started during the latter part of 1963. The MTR specimens are operating at an estimated peak linear heat rating of 85,000 Btu hr^{-1} ft^{-1}, and the intended peak burnup is 100,000 Mwd per metric ton of metal. The ETR specimens, which were discharged in May 1964, ran at an estimated peak heat rating of 149,000 Btu hr^{-1} ft^{-1} to an estimated peak burnup of 22,000 Mwd per metric ton of metal.

INTRODUCTION

Two of the objectives of our sol-gel oxide irradiation program are to determine whether changes in the processing steps have beneficial or detrimental effects on the irradiation performance and to learn the maximum performance characteristics of the vibratorily compacted sol-gel fuel. Accordingly, a series of irradiation experiments was designed to help resolve these questions.

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[2]Chemical Technology Division.

The standard calcining atmosphere in the sol-gel process is Ar–4% H_2. We would like to replace this gas with one that is more adaptable to remote fabrication, namely air or nitrogen. Hence, we evaluated the influence of fabrication atmosphere.

Since ternary particle-size distributions usually result in higher powder-packed densities than binary distributions, they are more widely used. However, we obtained satisfactory densities with a binary fraction. Since this simplifies the process, we decided to irradiate a fuel rod loaded with a binary distribution.

Finally, with the emergence of a standard reproducible product and some understanding of the performance of powder-packed fuels, we wished to define the limits of the vibratorily compacted sol-gel oxide as a nuclear fuel. Thus, we selected heat ratings that would truly push the sol-gel fuel; in fact, the ETR specimens were designed to operate with a molten central region. This report describes the fabrication of these capsules, including salient preirradiation measurements and data.

GENERAL DESIGN AND MATERIALS

The design of the irradiation capsule is shown in Fig. 1. Seamless type 304 stainless steel tubing, 7/16 in. diam × 0.025 in. wall, was used as the cladding for the rods. The material met the requirements of ASTM A-269-61T and passed dimensional, visual, fluid penetrant, and ultrasonic inspection.[3] Chemical analyses and mechanical properties of the tubing as reported by the vendor are listed in Table 1.

The plenum at the top of each fuel rod contained Fiberfrax[4] wool. Approximately 0.2 g of this material was packed in the top end of each tube. The Fiberfrax holds the oxide powder in place during handling, provides space for expansion, and serves as a site for collection of fission gases.

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[3]Inspection Engineering, Request No. 4243.

[4]Fiberfrax is a product of the Carborundum Company. It is composed of equal quantities of Al_2O_3 and SiO_2 plus about 4% ZrO_2 and will not melt below 1760°C.

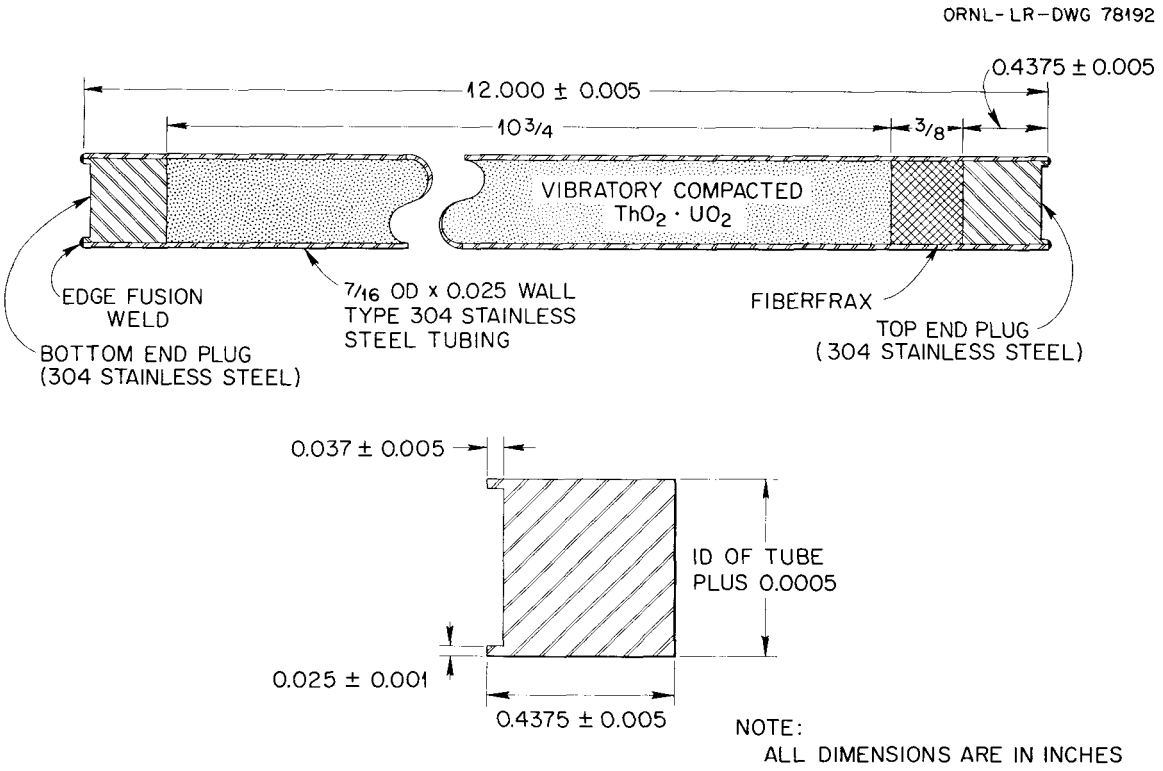

Fig. 1. ThO_2-UO_2 Fuel Cycle Capsule for MTR Group III and ETR Group I Irradiations.

The end plugs were machined from preinspected type 304 stainless steel bar stock. The analysis of this material is given in Table 1.

The capsules were fueled with ThO_2–5.7% UO_2 (93% enriched in ^{235}U) powder that had been prepared by the Oak Ridge National Laboratory sol-gel process. A single batch of sol was divided into three separate fractions and each fraction was calcined in a different atmosphere to produce the individual batches of fuel particles designated Sol-Gel Batch 35-1, 35-2, and 35-3. Figure 2 is a flow sheet of the specific process used in preparing Batch 35. The screen analyses of the various as-fired fractions are listed in Table 2. The isotopic analysis of the uranium in this material was taken from Isotope Analysis Report No. 9, Run Nos. 231 and 232, issued Feb. 17, 1965: 0.972% ^{234}U, 92.92% ^{235}U, 0.191% ^{236}U, and 5.91% ^{238}U. Before the various fractions were vibratorily compacted, the calcined oxide was crushed, milled with porcelain balls, and separated

Table 1. Chemical Analyses and Mechanical Properties of the Stainless Steel Components

	Tubing[a]	End-Cap Stock[b]
Chemical Analysis, %		
Carbon	0.060	0.08
Manganese	1.62	1.64
Phosphorus	0.017	0.014
Sulfur	0.011	0.024
Molybdenum	0.02	
Copper	0.06	
Silicon	0.47	0.82
Chromium	18.26	19.54
Nickel	9.38	8.69
Cobalt	0.036	
Iron	balance	balance
Mechanical Properties		
Ultimate tensile strength, psi	92,600	
0.2% Yield strength, psi	40,000	
Elongation, % in 2 in.	62	

[a]Tube Methods, Inc., Specification ASTM A-269-61T, type 304 seamless stainless steel, heat W94131.

[b]Associated Steel Company, Specification ASTM A-276, type 304 stainless steel, heat 8216, 11/16-in.-diam CG bar.

into the necessary particle-size ranges to provide the particle size distributions used in the loadings. The characteristics of the particles of various sizes from all three fractions as-fired and after crushing are listed in Table 3.

Since the principal purpose of these experiments is to evaluate the effects of calcining atmosphere on the fuel behavior, we measured the quantities and compositions of gas released by the material on heating. In each experiment, three samples of gas were collected as the oxide

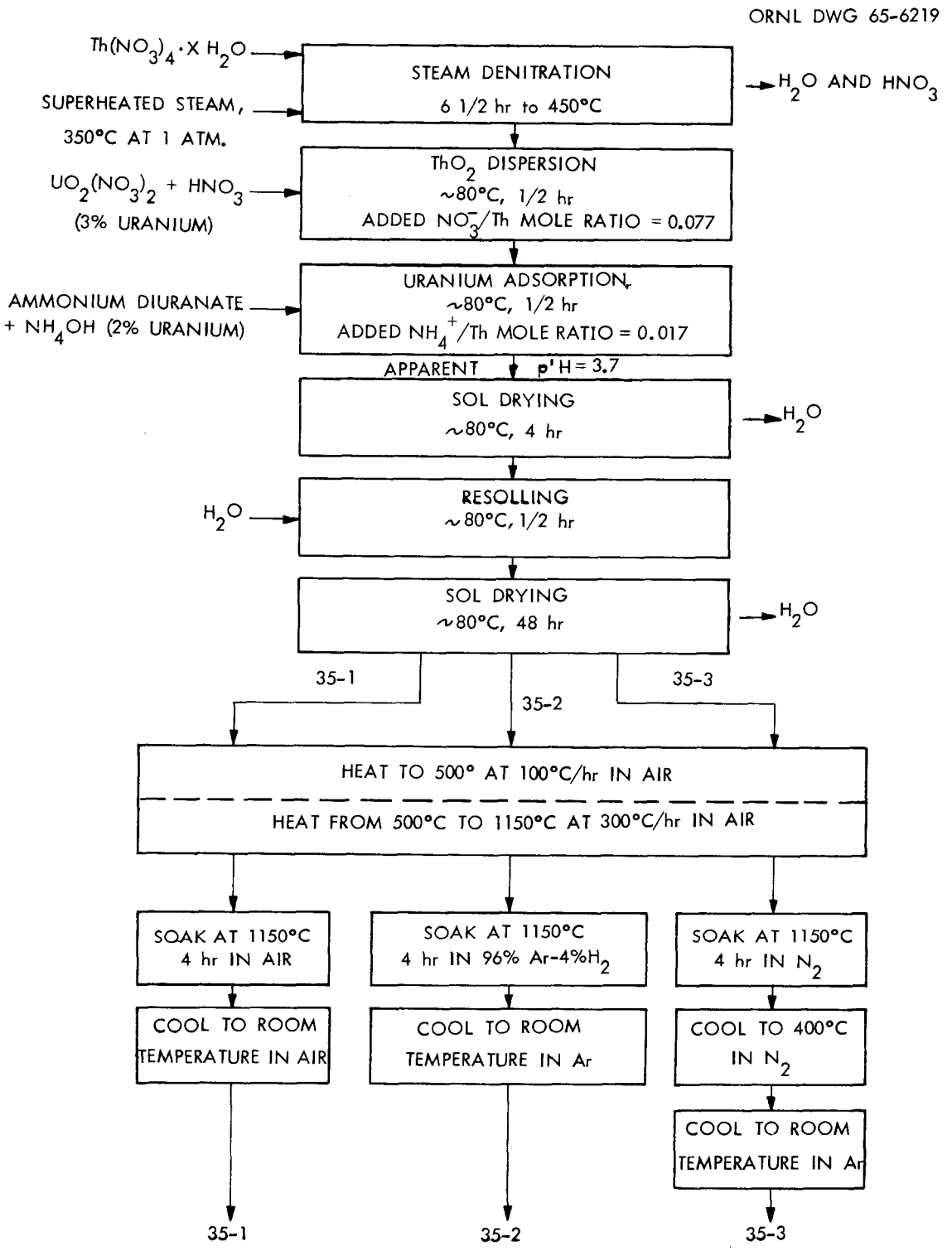

Fig. 2. Flowsheet for Preparation of Sol-Gel Batch 35, Containing 5% U (Fully Enriched).

Table 2. Screen Analysis for As-Calcined Batch-35 $(U,Th)O_2$

Batch	Content in Fraction (%)		
	+16	−16 +35	−35
35-1	94.94	4.14	0.93
35-2	90.93	6.52	3.17
35-3	83.29	10.09	6.62

was heated, comprising gas collected at up to 400°C, that collected from 400 to 800°C, and that collected from 800 to 1200°C. Appendix A gives the gas-release data as a function of temperature range and particle size for the different batches, both as-calcined and after crushing and grinding.

Although there is no clear cut correlation with surface area, the amount of gas released generally increased with increasing surface area. The principal differences caused by the calcination atmosphere in gas release from the as-calcined oxide was in the quantity of oxygen, and the oxygen-to-uranium ratios are in agreement with this observation. Crushing the coarse particles essentially left the gas release unchanged or slightly reduced. However, all the fine material released greater than 0.3 cm^3/g regardless of the calcining atmosphere, perhaps because the prolonged grinding of this material was done in air. Detailed correlation attempts on the limited number of samples represented here would not be in order and could be misleading. We shall compare the data with the gas release quantities and compositions after irradiation in an effort to find any significant differences.

CAPSULE FABRICATION

The three batches of oxide were used to load 14 capsules. Tubes 7/16 in. OD × 0.025 in. wall × 12 in. long were filled by vibratory compaction to a fuel length of approximately $10\frac{3}{4}$ in. Because deep surface

Table 3. Properties of Sol-Gel Batch 35 $(^{235}U,Th)O_2$

Batch Number	Screen Fraction	Composition Variation: U (%)	Composition Variation: Th (%)	Composition Variation: Deviation in Uranium Concentration[a], %	BET Surface Area (m^2/g)	Oxygen-to-Uranium Ratio	Carbon Content (%)	Toluene Density (g/cm^3)	Residue of Al_2O_3 from Dissolution
				As-Calcined					
35-1	+16	5.07	82.46	+0.66	0.003	2.392		9.94	No
	−16 +35	5.06	82.96	+0.82	0.006	2.465			No
	−35	5.02	83.08	−0.01	0.006	2.511			No
35-2	+16	5.13	83.36	+0.33	0.002	2.034		9.91	No
	−16 +35	5.04	82.51	−0.16	0.007	2.043			No
	−35	5.11	82.84	+0.36	0.052	2.061			No
35-3	+16	5.01	83.68	−4.56	0.002	2.174		9.99	No
	−16 +35	5.05	83.11	+2.41	0.008	2.190			No
	−35	5.10	83.00	+2.28	0.060	2.193			No
				After Crushing and Comminution					
35-1	−6 +16	5.17	83.90	+0.08	0.027	2.361	0.023		No
	−50 +140	5.15	83.73	−0.10	0.24	2.382	0.011		Yes
	−200	4.98	81.04	−0.16	0.57	2.429	0.007		Yes
35-2	−6 +16	5.06	82.11	−0.28	0.004	2.023	<0.002		No
	−50 +140	5.05	82.79	−1.28	0.034	2.038	0.003		No
	−200	5.01	79.94	+1.43	0.82	2.046	0.012		Yes
35-3	−6 +16	5.17	81.81		0.005	2.140	0.002		No
	−200	4.98	78.88		0.79	2.204	0.015		Yes

[a] $\frac{\text{Screened Fraction U/Th Mole Ratio} - \text{Weighted Average of Batch U/Th Mole Ratio}}{\text{Weighted Average of Batch U/Th Mole Ratio}}$

scratches were introduced during fabrication, this first group of specimens had to be dismantled, and the fuel was revibrated in new tubes. Nevertheless, to show the effect of refabricating the fuel we shall describe the fabrication of these capsules. Initially, a bottom end plug was tungsten-arc inert-gas fusion welded to each of 22 cut-to-length tubes, from which the best 14 were selected and the others were held in reserve. Helium leak-check, liquid penetrant, and radiographic inspections were performed.

An appropriate quantity of fuel was poured into each capped tube. A ternary particle-size distribution was used in twelve of the capsules and a binary fraction was used in the other two. The fuel was compacted initially on a NAVCO-BH-1$\frac{1}{4}$ pneumatic vibrator during filling and finally on the Branford Variable Impact Vibrator. The bulk densities obtained and some of the physical characteristics of the capsules are listed in Table 4. Conclusions concerning the dependence of bulk density on calcining atmosphere should not be inferred from the data because the compaction process was terminated when the minimum intended density of 8.8 g/cm^3 was slightly exceeded. After the fuel had been compacted, the rods were outgassed in vacuum at 1100°C for about 0.5 hr. Then the top end plugs were fusion welded to the tubes in an atmosphere of helium. The rods were found acceptable by nondestructive testing, which included gamma scans, helium leak check, radiographs of the welds, and fluid penetrant inspection of the welded area.

The rods were then pickled, autoclave tested in steam at 300°C and 1250 psi for 24 hr, and dimensionally inspected. At that juncture, numerous gouge marks, pits, and scratches were observed on the surfaces of the rods. To determine the depth of the discontinuities and perhaps salvage the specimens, they were centerless ground to a diameter about 0.003 in. smaller. Nevertheless, the discontinuities persisted. The rods were inspected with a fluid penetrant, which revealed indications in weld areas and along the tube length in all rods except No. 6.

To futher determine the weld quality, fuel rod 5 was sectioned and the welds were examined metallographically. As shown in Fig. 3, the top weld was in excellent condition, but the bottom weld revealed a poor fit. In view of the available evidence of damaged surfaces and to provide

Table 4. Bulk Fuel Densities and Other Features of the First Capsules

Rod Number	Distribution	Sintering Atmosphere	Void Depth (cm)	Oxide Weight (g)	Bulk Density (g/cm^3)
4	Ternary[a]	N_2	2.5	184.0	8.9
5	Ternary[a]	N_2	2.5	184.0	8.9
7	Ternary[a]	N_2	2.5	183.5	8.9
8	Ternary[a]	N_2	2.5	184.0	8.9
6	Ternary[a]	Ar-H_2	2.8	183.0	8.9
9	Ternary[a]	Ar-H_2	2.5	185.0	8.9
10	Ternary[a]	Ar-H_2	2.9	183.5	9.0
11	Ternary[a]	Ar-H_2	2.8	184.0	9.0
12	Ternary[a]	Air	2.7	183.5	8.9
14	Ternary[a]	Air	2.7	184.0	9.0
15	Ternary[a]	Air	3.0	184.0	9.1
17	Ternary[a]	Air	2.8	185.0	9.0
18	Binary[b]	Air	2.4	185.5	9.0
19	Binary[b]	Air	2.1	185.5	8.9

[a]60% −8 +16, 13.5% −70 +100, 26.5% −200.
[b]70% −8 +16, 30% −200.

improved welds, we decided to reject all the rods and make a new group of capsules using the same fuel. Rod 4 was retained as a control, however, for the nitrogen-fired material.

The new specimens were fabricated in the same manner, but extreme care was taken in each operation, particularly with weld joint fit and with handling the rods. We made 19 bottom end cap welds, from which the 13 best were selected on the basis of radiographs and surface appearance for loading. The rods were filled by pouring the fuel from one of the original rods into the corresponding tube from the new group. The fuel was vibratorily compacted as before, but, as shown in Table 5, the refabricated rods were slightly less dense than their precursors. This may be attributed to a minor change in the particle-size distribution.

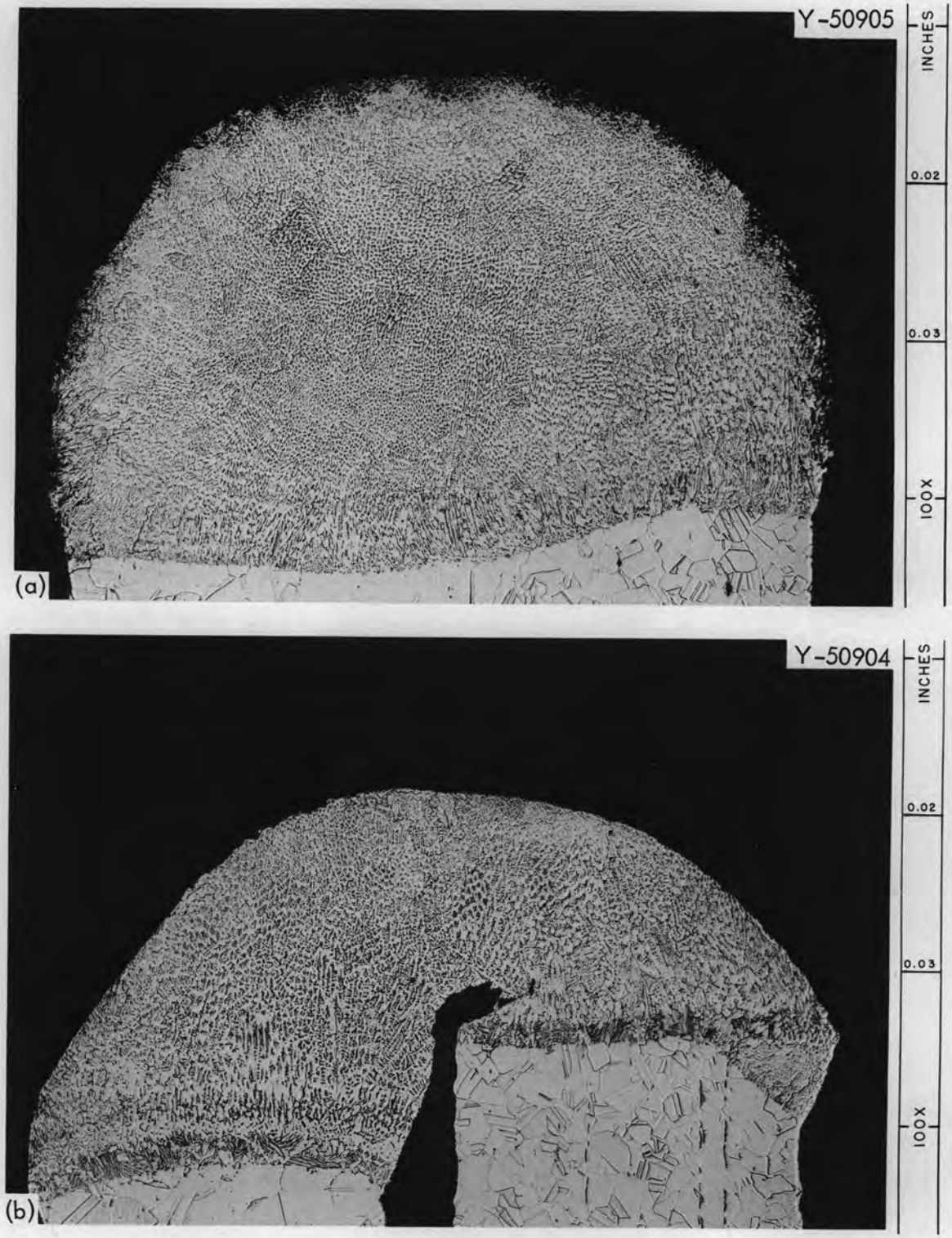

Fig. 3. Metallographic Sections of Fusion Welds of the End Plugs to the Tube in Initial Fabrication Fuel Rod 5. (a) Top or closure weld. (b) Bottom weld.

Table 5. Characteristics of Refabricated MTR-III and ETR-I Fuel Rods

Capsule Code Number	Rod Number	Oxide Firing Atmosphere	Volume (cm^3)	Length (cm)	Void Depth (cm)	Oxide Weight (g)	Bulk Density (g/cm^3)	
							Original	Refabricated
MTR-III-1	14	Air	22.8	29.3	2.6	182.3	9.0	8.76
-2	17	Air	22.6	29.4	2.2	184.0	9.0	8.80
-4	9	Ar–4% H_2	22.7	29.4	2.7	182.2	8.9	8.84
-5	11	Ar–4% H_2	22.9	29.4	2.7	183.1	9.0	8.80
-7	5	N_2	22.9	29.4	2.2	182.5	8.9	8.67
-8	7	N_2	22.7	29.4	2.2	181.3	8.9	8.63
ETR-I-1	18	Air	22.7	29.4	2.7	182.1	8.9	8.84
-2	10	Ar–4% H_2	22.6	29.3	2.7	183.9	9.0	8.97
-3	8	N_2	22.9	29.4	2.0	181.9	8.9	8.54
-4	20	Air[a]	22.8	29.4	2.7	183.3	9.0	8.86
Control	4	N_2			2.5	184.0	8.9	
Control	6	Ar–4% H_2	22.7	29.4	3.4	177.9	8.9	8.85
Control	15	Air	22.7	29.3	2.4	182.6	9.1	8.78
Control	19	Air[a]	22.8	29.3	1.9	182.9	8.9	8.59

[a]Binary particle-size distribution. All others contained ternary fraction.

After vibratory compaction the rods were outgassed in vacuum at 1050°C for about 30 min. The tubes were filled with helium, the top end cap was pressed in place, and the closure was fusion welded. No leaks were indicated by a helium leak detector calibrated to a system sensitivity of 7×10^{-8} cm^3/sec. Fluid-penetrant inspection indicated no discontinuities. The top welds also were radiographed and found to be free of defects. Metallographic examination of specimen 19 revealed excellent quality welds, as seen in Fig. 4.

To better assess fuel homogeneity in the ThO_2-UO_2 rods, density variations were monitored by use of a gamma-attenuation technique. Each rod was scanned at two diametral positions, 90° apart. The fuel rods were passed through a collimated beam from a ^{60}Co radiation source and that part of the beam transmitted through the fuel rod was monitored with a detecting crystal. A change in the fuel concentration resulted in a corresponding change in intensity of the transmitted radiation beam. The output signal from the detector was then integrated and fed to a Brown recorder.

Scanning data for areas that were more than 2% low in fuel concentration are listed in Table 6. Except for the regions of low density so noted, each rod was within ±2% of the average density.

The capsules were picked and then autoclave tested in saturated steam for 24 hr at 300°C and 1250 psi. The negligible weight gains (Table 7) attested to the integrity of the capsules.

Dimensional data for the completed fuel rods are given in Appendix B along with the inspection procedure used. End-view photographs are shown in Figs. 5 and 6. As indicated in Fig. 5, the rods were identified by the appropriate specimen number punched on the bottom end cap.

IRRADIATION CONDITIONS

To load the capsules for irradiation, they were first inserted in pairs into flow holders; in turn each flow holder was inserted into an "x basket." The flow holder is a heavy-wall aluminum tube with internal ribbing designed to center the capsule so as to provide a coolant channel of controlled size. By thus restricting the area one can increase the

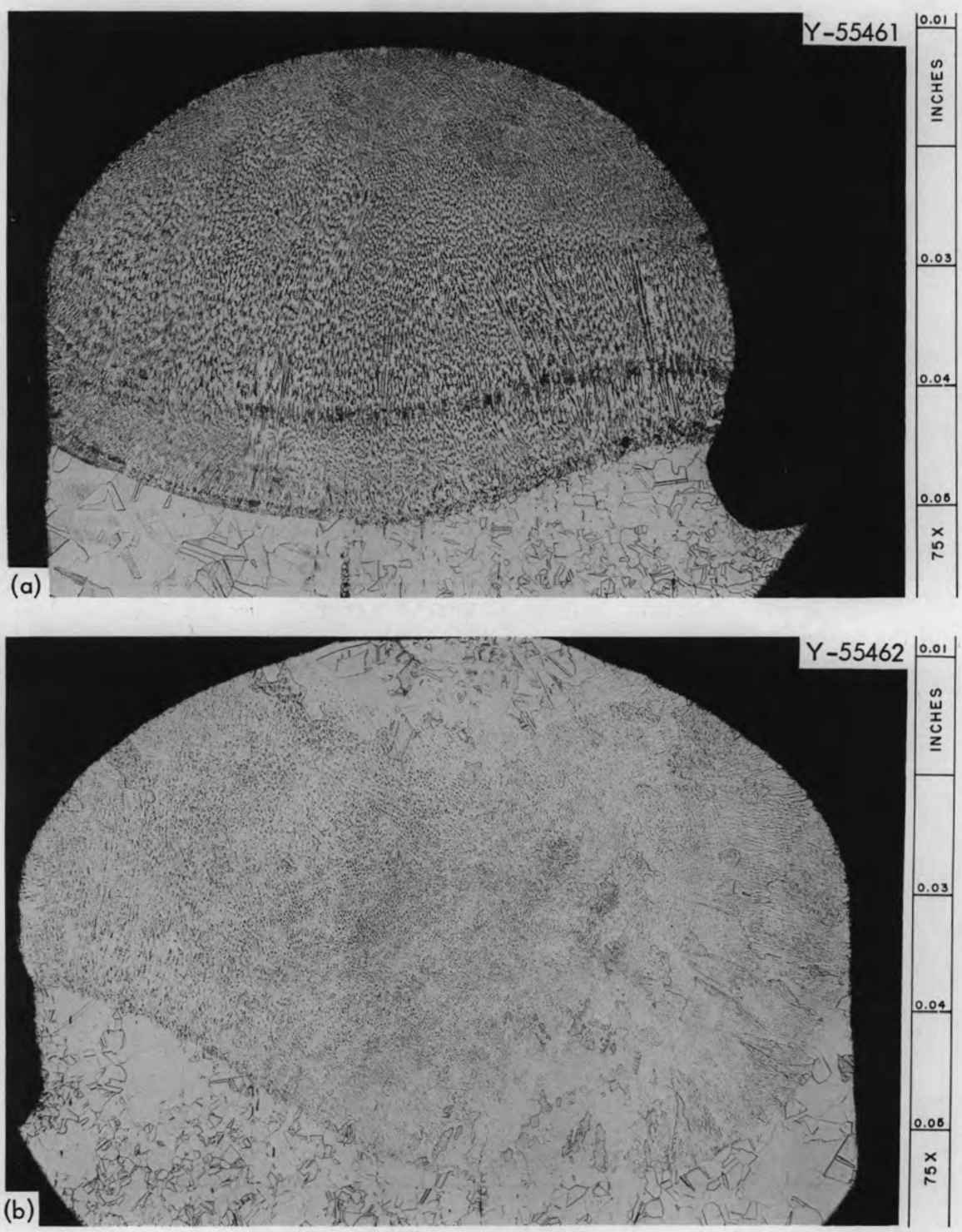

Fig. 4. Metallographic Sections of Fusion Welds of End Plugs to Tube on Refabricated Fuel Rod 19. (a) Top or closure weld. (b) Bottom weld.

Table 6. Compilation of Low-Density Areas in ThO_2-UO_2 Fuel Rods

Rod Number	Location of Low-Density Area With Respect to the Fuel Ends	Length of Low-Density Area (in.)	Deviation From Average Density (%)
5	4 in. from Top	0.5	5
6	4 in. from Top	1	3
10	5 in. from Top	3	3
11	5 in. from Top	0.5	3
15	Throughout Fuel		3
19	$3\frac{1}{2}$ in. from Top	1	5

Table 7. Weight Changes of Rods in Autoclave Tests

Rod Number	Weight Before (g)	Weight After (g)	Weight Change (g)
5	245.9050	245.9050	0.0000
6	242.0929	242.0930	+0.0001
7	245.0428	245.0389	−0.0039
8	244.9780	244.9710	−0.0070
9	246.1480	246.1430	−0.0050
10	244.8110	244.8080	−0.0030
11	246.5440	245.5400	−0.0040
14	246.0810	246.0800	−0.0010
15	246.7103	246.7060	−0.0043
17	247.6880	247.6840	−0.0040
18	245.5429	245.5410	−0.0019
19	245.7663	245.7610	−0.0053
20	247.1250	247.1150	−0.0100

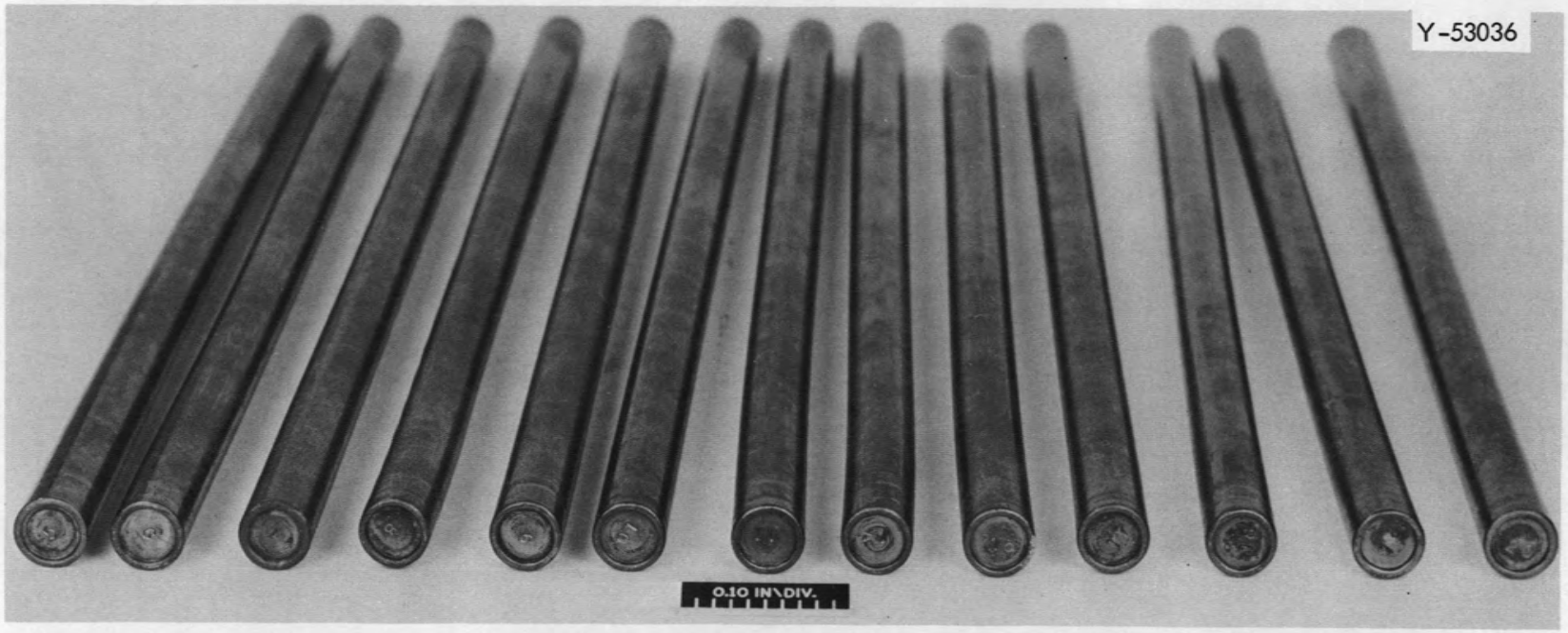

Fig. 5. Completed Fuel Rods Showing Numbered Ends. Original reduced 11%.

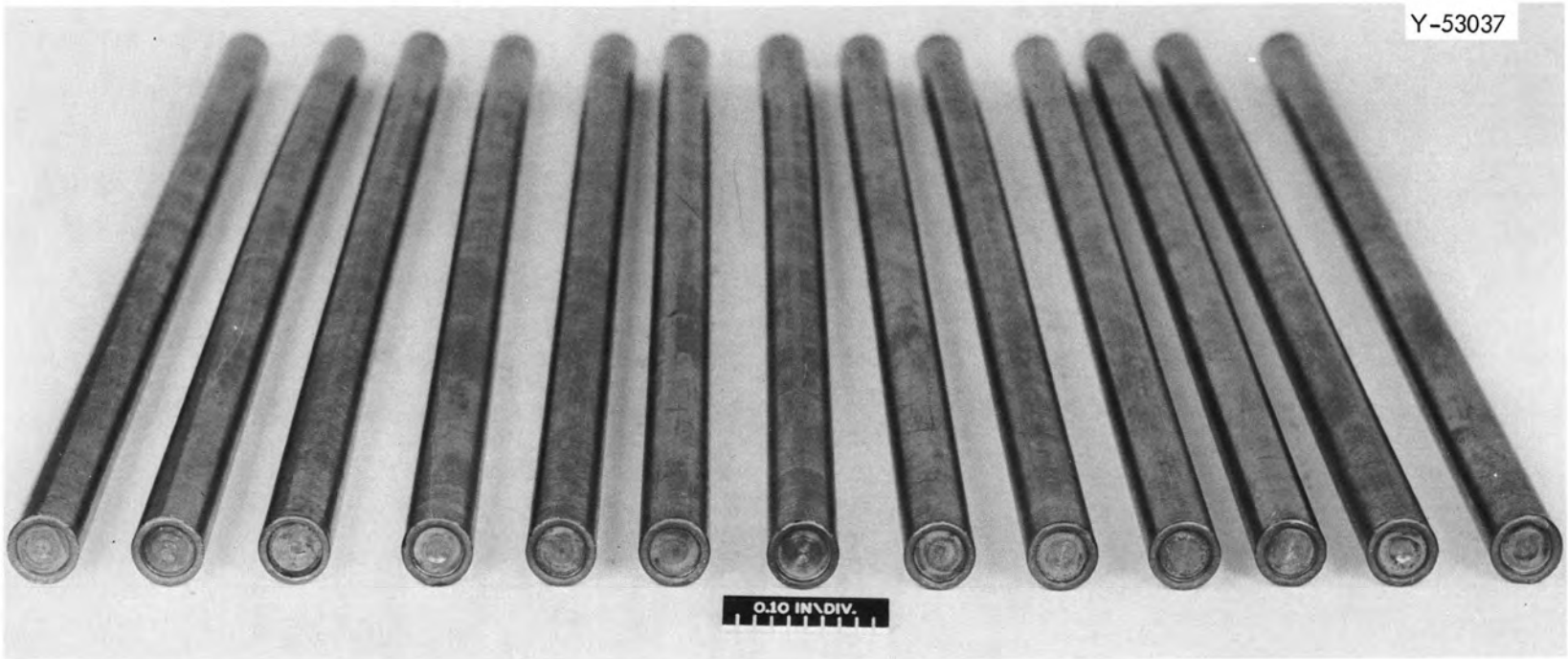

Fig. 6. Completed Fuel Rods Showing Unnumbered Ends. Original reduced 15%.

coolant velocity to provide better fission heat removal. The details of the holder used in these experiments are available on ORNL Drawing C-55859. The "x" basket is a thin-walled aluminum tube used in the MTR and ETR for the insertion and removal of experiments. Four such baskets will fit in one reflector or core location that contains the necessary adaptor piece. The holder was positioned in the reactor with the slotted end up, and each capsule was positioned with the bottom (numbered) end plug down. Table 8 shows the capsule location in each holder.

Table 8. Irradiation Experiment and Fuel Rod Identification

Experiment Number	Rod Number	Oxide Firing Atmosphere	Capsule Location and Holder Number
MTR-III-1	14	Air	Bottom of ORNL-43-77
-2	17	Air	Top of ORNL-43-78
-4	9	Ar—4% H_2	Top of ORNL-43-77
-5	11	Ar—4% H_2	Bottom of ORNL-43-79
-7	5	N_2	Bottom of ORNL-43-78
-8	7	N_2	Top of ORNL-43-79
ETR-I-1	18	Air	Top of ORNL-43-80
-2	10	Ar—4% H_2	Bottom of ORNL-43-80
-3	8	N_2	Bottom of ORNL-43-81
-4	20	Air	Top of ORNL-43-81

Salient reactor operating parameters and calculations are summarized in Table 9. The irradiations were initiated during the final quarter of 1963. The test elements have performed without incident, and the ETR capsules were discharged as scheduled in May 1964.

Table 9. Calculated Irradiation Conditions[a]

	MTR	ETR
Unperturbed thermal flux, neutrons cm^{-2} sec^{-1}	2.35×10^{14}	1.60×10^{14}
Unperturbed dose, neutrons/cm^2	1.42×10^{22}	1.63×10^{21}
Linear heat rating Btu hr^{-1} ft^{-1}	85,300	149,000
Cladding surface heat flux, Btu hr^{-1} ft^{-2}	744,000	1,200,000
Cladding temperature, °F	224	279
Central temperature, °F	5,260	5,990[b]
$\int k d\theta$, w/cm	70	120
Burnup, Mwd/metric ton metal	110,000	22,400

[a]All values are maxima.

[b]Predicted melting point of the oxide.

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In addition, the assistance of the following groups is gratefully acknowledged: Metallography Group of the Metal and Ceramics Division, the Analytical Chemistry Division, the Plant and Equipment Division Specialty Shop, and the Inspection Engineering Department.

APPENDIX A

GAS-RELEASE DATA

Table 10. Analysis of the Gases Evolved from As-Calcined Large (+16 mesh) Fuel Fragments in Three Temperature Intervals

Batch	Gas	Gas Evolution in Various Temperature Intervals[a]					
		25 to 400°C		400 to 800°C		800 to 1200°C	
		(%)	(cm^3/g)	(%)	(cm^3/g)	(%)	(cm^3/g)
35-1 (Fired in air)	H_2						
	H_2O			0.6	0.0004	0.3	0.0013
	N_2 + CO			3.9	0.0024	2.7	0.0119
	CO_2			1.8	0.0011	0.4	0.0018
	CH_4						
	O_2			93.7	0.0581	96.6	0.425
	Ar						
TOTAL			0.003		0.062		0.44
35-2 (Fired in Ar-H_2)	H_2			1			
	H_2O	44	0.0003	5	0.0001		
	N_2 + CO	25	0.0002	29	0.0006	38	0.0004
	CO_2	25	0.0002	63	0.0013	62	0.0006
	CH_4						
	O_2	6		1			
	Ar			1			
TOTAL			0.0007		0.002		0.001
35-3 (Fired in N_2)	H_2					0.2	
	H_2O			6	0.0002	1.2	0.0003
	N_2 + CO	36	0.0004	17	0.0005	2.8	0.0007
	CO_2	64	0.0006	75	0.0023	2.4	0.0006
	CH_4						
	O_2			2		93.4	0.0224
	Ar						
TOTAL			0.001		0.003		0.024

[a]Volumes per gram sample in this and subsequent tables are corrected to standard temperature and pressure. Blank spaces indicate that the gas was not detected or volume was less than 0.00005 cm^3/g.

Table 11. Analysis of the Gases Evolved to 1200°C in Vacuum for Three Size Fractions of As-Calcined Fuel

Batch	Gas	Gas Evolution from Various Size Fractions					
		+16		−16 +35		−35	
		(%)	(cm^3/g)	(%)	(cm^3/g)	(%)	(cm^3/g)
35-1 (Fired in air)	H_2			0.1	0.0004		
	H_2O	0.3	0.0017	0.5	0.0021		
	N_2 + CO	2.8	0.0143	1.6	0.0067		
	CO_2	0.5	0.0029	1.6	0.0067		
	CH_4						
	O_2	95.7	0.4831	96.2	0.4040		
	Ar						
TOTAL			0.505		0.420		
35-2 (Fired in Ar-H_2)	H_2					0.1	0.0001
	H_2O	10.8	0.0004	2.1	0.0001	1.0	0.0005
	N_2 + CO	32.4	0.0012	7.7	0.0005	9.0	0.0047
	CO_2	56.8	0.0021	89.0	0.0053	89.3	0.0473
	CH_4						
	O_2			0.3		0.1	0.0001
	Ar			0.3		0.1	0.0001
TOTAL			0.0037		0.006		0.053
35-3 (Fired in N_2)	H_2			0.3	0.0001	0.3	0.0001
	H_2O	1.8	0.0005	2.1	0.0007	1.8	0.0008
	N_2 + CO	4.3	0.0012	3.0	0.0010	7.8	0.0037
	CO_2	10.3	0.0029	54.5	0.0185	83.0	0.0390
	CH_4			0.1		0.1	
	O_2	80	0.0224	39.3	0.0134	3.9	0.0018
	Ar			0.1		0.1	
TOTAL			0.028		0.034		0.047

Table 12. Analysis of the Gases Evolved in Three Temperature Intervals from the Various Size Fractions of Batch 35-1 (Air Fired) after Crushing and Comminution

Size Fraction	Gas	Gas Evolution in Various Temperature Intervals[a]					
		25 to 400°C		400 to 800°C		800 to 1200°C	
		(%)	(cm^3/g)	(%)	(cm^3/g)	(%)	(cm^3/g)
−6 +16	H_2	7	0.0003	<1		<1	
	H_2O			1	0.0007	1	0.0025
	N_2 + CO	21	0.0008	2	0.0014	2	0.0050
	CO_2	72	0.0029	6	0.0044	1	0.0025
	CH_4						
	O_2			91	0.0664	95	0.247
	Ar			<1			
TOTAL			0.004		0.073		0.26
−50 +140	H_2	5	0.0029	<1		<1	
	H_2O	25	0.0143	4	0.0038	1	0.0019
	N_2 + CO	7	0.004	3	0.0029	2	0.0038
	CO_2	62	0.0353	93	0.0884	16	0.0304
	CH_4						
	O_2	1	0.0006	<1		80	0.152
	Ar						
TOTAL			0.057		0.095		0.19
−200	H_2	4	0.006	1	0.0006	<1	
	H_2O	16	0.024	16	0.0102	1	0.0018
	N_2 + CO	3	0.0045	3	0.0019	2	0.0036
	CO_2	76	0.114	69	0.0442	3	0.0054
	CH_4						
	O_2	<1		12	0.0077	95	0.171
	Ar						
TOTAL			0.15		0.064		0.18

Table 13. Analysis of the Gases Evolved After Crushing and Comminution

Batch	Size Fraction	Gas	Gas Evolution in Various Temperature Intervals					
			25 to 400°C		400 to 800°C		800 to 1200°C	
			(%)	(cm^3/g)	(%)	(cm^3/g)	(%)	(cm^3/g)
35-2 (Fired in Ar-H_2)	−6 +16	H_2	25	0.0005	5	0.0002	38	0.0004
		H_2O	5	0.0001	2	0.0001	12	0.0001
		N_2 + CO	25	0.0005	23	0.0009	35	0.0003
		CO_2	44	0.0009	70	0.0028	8	0.0001
		CH_4						
		O_2					4	
		Ar			1		4	
	TOTAL			0.002		0.004		<0.001
35-2	−200	H_2	8	0.0061	44	0.088	32	0.0138
		H_2O	14	0.0106	<1		3	0.0013
		N_2 + CO	8	0.0061	38	0.076	50	0.0215
		CO_2	70	0.0531	17	0.034	15	0.0065
		CH_4			<1			
		O_2	<1		<1		<1	
		Ar						
	TOTAL			0.076		0.20		0.043
35-3 (Fired in N_2)	−6 +16	H_2	8	0.0002			<1	
		H_2O	8	0.0002	6	0.0001	1	0.0002
		N_2 + CO	13	0.0004	7	0.0001	2	0.0003
		CO_2	70	0.0021	81	0.0016	4	0.0007
		CH_4						
		O_2	<1		6	0.0001	93	0.016
		Ar	<1		1			
	TOTAL			0.003		0.002		0.017
35-3	−200	H_2	7	0.0077	<1		2	0.0004
		H_2O	28	0.0308	17	0.034	35	0.007
		N_2 + CO	8	0.0088	4	0.0080	6	0.0012
		CO_2	57	0.0628	79	0.158	56	0.0112
		CH_4	<1		<1			
		O_2	<1		<1		1	0.0002
		Ar	<1					
	TOTAL			0.11		0.20		0.02

Table 14. Analysis of the Gases Evolved to 1200°C in Vacuum for Three Size Fractions After Crushing and Comminution

Batch Number	Gas	Gas Evolved from Various Fractions					
		−6 +16		−50 +140		−200	
		(%)	(cm^3/g)	(%)	(cm^3/g)	(%)	(cm^3/g)
35-1 (Fired in Air)	H_2	0.1	0.0003	0.8	0.0029	1.6	0.0066
	H_2O	1.0	0.0032	5.9	0.0200	9.2	0.0360
	N_2 + CO	2.1	0.0072	3.1	0.0107	2.5	0.01
	CO_2	2.9	0.0098	45.2	0.1541	41.5	0.1636
	CH_4						
	O_2	92.8	0.3134	44.6	0.1526	45.3	0.1787
	Ar						
	TOTAL		0.337		0.342		0.394
35-2 (Fired in Ar-H_2)	H_2	15.7	0.0011			33.7	0.1079
	H_2O	4.3	0.0003			3.7	0.0119
	N_2 + CO	24.3	0.0017			32.5	0.1036
	CO_2	54.3	0.0038			29.4	0.0936
	CH_4						
	O_2						
	Ar						
	TOTAL		0.007				0.319
35-3 (Fired in N_2)	H_2	0.9	0.0002			2.5	0.0081
	H_2O	2.3	0.0005			21.7	0.0718
	N_2 + CO	3.6	0.0008			5.5	0.018
	CO_2	20.0	0.0044			70.3	0.232
	CH_4						
	O_2	73.2	0.0161				0.0002
	Ar						
	TOTAL		0.022				0.33

APPENDIX B

DIMENSIONAL MEASUREMENTS

INSPECTION PROCEDURE

1. The rods were set in "1/16-in. knife-edge" V-blocks, 1/2 in. from each end, and the height at each V-block was adjusted to a zero reference. The tube was rotated until the maximum upward bow was located, and in this position a notch was scribed on the top of the tube at the numbered end. Bow measurements were read with a "feather-touch indicator" starting 1 in. from the numbered end at 1-in. intervals. Plus readings indicate upward bow and negative readings indicate downward bow with respect to the zero reference.

2. Outside diameters were measured with a "Sheffield Shadow Gage" to ±0.0001 in. starting 1 in. from the numbered end at 1-in. intervals, both in the plane through the notch and in a plane at 90° to the notch.

3. The overall rod length was measured to the nearest 0.0001 in. with a Pratt and Whitney supermicrometer. The length includes weld metal protruding from final end closure.

MEASUREMENTS

Tables 15 through 27 present the dimensions measured as described above.

Table 15. Fuel Rod No. 5 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.440	0.4403	
1	0.4412	0.4405	+0.001
2	0.4413	0.4403	+0.006
3	0.4410	0.4402	+0.015
4	0.4405	0.4402	+0.020
5	0.4405	0.4401	+0.021
6	0.4405	0.4400	+0.021
7	0.4402	0.4401	+0.021
8	0.4401	0.4400	+0.018
9	0.4401	0.4400	+0.013
10	0.4402	0.4401	+0.012
11	0.4400	0.4399	+0.003
11.50	0.4420	0.4399	

Length: 12.015 in.

[a]Notch up at 0°.

Table 16. Fuel Rod No. 6 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4400	0.4397	
1	0.4399	0.4412	+0.013
2	0.4402	0.4410	+0.041
3	0.4403	0.4408	+0.061
4	0.4405	0.4405	+0.066
5	0.4402	0.4402	+0.068
6	0.4400	0.4402	+0.064
7	0.4400	0.4398	+0.056
8	0.4402	0.4401	+0.038
9	0.4403	0.4400	+0.028
10	0.4401	0.4395	+0.017
11	0.4396	0.4398	+0.013
11.50	0.4402	0.4401	

Length: 12.012 in.

[a]Notch up at 0°.

Table 17. Fuel Rod No. 7 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4404	0.4411	
1	0.4419	0.4399	+0.009
2	0.4414	0.4405	+0.015
3	0.4405	0.4404	+0.029
4	0.4408	0.4400	+0.033
5	0.4402	0.4404	+0.034
6	0.4402	0.4400	+0.029
7	0.4399	0.4400	+0.027
8	0.4400	0.4402	+0.022
9	0.4401	0.4402	+0.013
10	0.4399	0.4400	+0.007
11	0.4402	0.4395	+0.003
11.50	0.4405	0.4405	

Length: 12.008 in.

[a]Notch up at 0°.

Table 18. Fuel Rod No. 8 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4410	0.4410	
1	0.4404	0.4418	+0.032
2	0.4403	0.4410	+0.037
3	0.4401	0.4405	+0.037
4	0.4405	0.4403	+0.035
5	0.4400	0.4406	+0.032
6	0.4400	0.4404	+0.030
7	0.4400	0.4402	+0.022
8	0.4400	0.4401	+0.020
9	0.4399	0.4400	+0.014
10	0.4401	0.4398	+0.006
11	0.4400	0.4400	+0.002
11.50	0.4410	0.4411	

Length: 12.007 in.

[a]Notch up at 0°.

Table 19. Fuel Rod No. 9 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4410	0.4402	
1	0.4418	0.4395	+0.008
2	0.4408	0.4400	+0.008
3	0.4405	0.4401	+0.012
4	0.4404	0.4402	+0.011
5	0.4402	0.4401	+0.010
6	0.4402	0.4400	+0.010
7	0.4400	0.4398	+0.009
8	0.4400	0.4396	+0.007
9	0.4398	0.4398	+0.005
10	0.4395	0.4399	+0.001
11	0.4400	0.4395	
11.50	0.4400	0.4400	

Length: 12.007 in.

[a]Notch up at 0°.

Table 20. Fuel Rod No. 10 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4400	0.4401	
1	0.4405	0.4388	0.005
2	0.4398	0.4392	0.009
3	0.4397	0.4390	0.013
4	0.4394	0.4392	0.015
5	0.4395	0.4390	0.015
6	0.4397	0.4390	0.014
7	0.4390	0.4389	0.013
8	0.4390	0.4392	0.011
9	0.4391	0.4391	0.007
10	0.4390	0.4391	0.004
11	0.4399	0.4388	0.002
11.50	0.4390	0.4402	

Length: 12.009 in.

[a]Notch up at 0°.

Table 21. Fuel Rod No. 11 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4415	0.4415	
1	0.4422	0.4385	0.022
2	0.4414	0.4395	0.045
3	0.4410	0.4399	0.045
4	0.4404	0.4401	0.045
5	0.4401	0.4400	0.045
6	0.4402	0.4400	0.043
7	0.4398	0.4400	0.043
8	0.4400	0.4400	0.031
9	0.4400	0.4395	0.026
10	0.4400	0.4395	0.015
11	0.4395	0.4400	0.006
11.50	0.4395	0.4403	

Length: 12.010 in.

[a]Notch up at 0°.

Table 22. Fuel Rod No. 14 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4412	0.4410	
1	0.4383	0.4421	0.022
2	0.4402	0.4402	0.023
3	0.4403	0.4400	0.014
4	0.4402	0.4400	0.008
5	0.4403	0.4400	0.008
6	0.4402	0.4400	0.007
7	0.4400	0.4395	0.005
8	0.4400	0.4398	0.007
9	0.4401	0.4400	0.004
10	0.4400	0.4400	0.002
11	0.4395	0.4401	0.001
11.50	0.4408	0.4415	

Length: 12.007 in.

[a]Notch up at 0°.

Table 23. Fuel Rod No. 15 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4410	0.4405	
1	0.4390	0.4411	0.017
2	0.4403	0.4405	0.034
3	0.4401	0.4403	0.042
4	0.4400	0.4399	0.042
5	0.4400	0.4400	0.041
6	0.4400	0.4400	0.039
7	0.4398	0.4399	0.037
8	0.4399	0.4400	0.029
9	0.4400	0.4396	0.020
10	0.4400	0.4398	0.011
11	0.4400	0.4398	0.002
11.50	0.4395	0.4410	

Length: 12.009 in.

[a]Notch up at 0°.

Table 24. Fuel Rod No. 17 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4398	0.4398	
1	0.4410	0.4410	0.022
2	0.4406	0.4400	0.027
3	0.4400	0.4400	0.028
4	0.4402	0.4399	0.023
5	0.4404	0.4399	0.018
6	0.4402	0.4399	0.015
7	0.4400	0.4399	0.013
8	0.4396	0.4400	0.010
9	0.4398	0.4399	0.008
10	0.4400	0.4395	0.004
11	0.4400	0.4399	0.001
11.50	0.4401	0.4400	

Length: 12.012 in.

[a]Notch up at 0°.

Table 25. Fuel Rod No. 18 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4410	0.4403	
1	0.4400	0.4392	0.009
2	0.4402	0.4390	0.021
3	0.4394	0.4395	0.027
4	0.4392	0.4393	0.029
5	0.4393	0.4395	0.030
6	0.4395	0.4395	0.028
7	0.4395	0.4392	0.027
8	0.4393	0.4392	0.020
9	0.4393	0.4391	0.012
10	0.4395	0.4389	0.008
11	0.4393	0.4390	0.001
11.50	0.4398	0.4400	

Length: 12.004 in.

[a]Notch up at 0°.

Table 26. Fuel Rod No. 19 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4404	0.4410	
1	0.4408	0.4410	0.018
2	0.4404	0.4403	0.027
3	0.4401	0.4402	0.028
4	0.4400	0.4401	0.029
5	0.4400	0.4401	0.022
6	0.4400	0.4401	0.020
7	0.4400	0.4400	0.014
8	0.4399	0.4399	0.011
9	0.4398	0.4400	0.007
10	0.4398	0.4399	0.002
11	0.4400	0.4395	−0.007
11.50	0.4401	0.4401	

Length: 12.010 in.

[a]Notch up at 0°.

Table 27. Fuel Rod No. 20 Dimensions

Distance from Numbered End (in.)	Diameter[a] (in.)		Bow (in.)
	0°	90°	
0.50	0.4410	0.4410	
1	0.4405	0.4415	0.017
2	0.4404	0.4408	0.019
3	0.4402	0.4405	0.013
4	0.4402	0.4402	0.010
5	0.4402	0.4402	0.009
6	0.4401	0.4400	0.009
7	0.4400	0.4400	0.010
8	0.4400	0.4395	0.008
9	0.4400	0.4402	0.006
10	0.4395	0.4404	0.004
11	0.4401	0.4396	0.001
11.50	0.4400	0.4403	

[a]Notch up at 0°.

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