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URANIUM DIOXIDE FUEL TUBES FOR IRRADIATION IN THE VBWR

A. S. Ferrara

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URANIUM DIOXIDE FUEL TUBES FOR IRRADIATION IN THE VBWR

by

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October 1965

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ABSTRACT

Experimental fuel tubes containing crushed arc-fused uranium dioxide were fabricated for irradiation testing in the Vallecitos Boiling Water Reactor (VBWR). Two of the four tubes delivered were compacted by vibration alone and two were compacted by vibration plus swaging; bulk UO_2 densities were 84% and 92% of the theoretical value, respectively. The elements were approximately three feet long, 2.06 inches in outside diameter, and 0.3 inch in wall thickness including 0.030-inch-thick cladding of low-nickel Zircaloy-2.

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URANIUM DIOXIDE FUEL TUBES FOR IRRADIATION IN THE VBWR

INTRODUCTION

The fabrication of uranium dioxide (UO_2) fuel tubes at Savannah River Laboratory (SRL) by mechanical compaction was part of the Du Pont development program on heavy-water-moderated power reactors. The goal of the over-all program was to advance D_2O reactor technology so that full-scale plants employing such reactors could produce electricity at fully competitive costs. A massive oxide tube clad with thin Zircaloy was an attractive fuel design because of the developed technology of UO_2 under power reactor conditions and the potentially low fabrication cost of large tubes when produced in the volume required for several large reactors. Two or three oxide tubes of appropriate sizes are nested together and contained in a housing tube to produce a fuel assembly. Such a fuel assembly has the following advantages: high specific power, high uranium content per unit length, minimum number of elements to fabricate, and simplicity of design for assembly and operation.[1,2]

Pilot irradiation tests were performed in the Vallecitos Boiling Water Reactor (VBWR) to determine the performance of UO_2 fuel tubes at moderate burnups under power reactor conditions. Previous irradiations of tubular oxide elements had been performed in Savannah River production reactors at temperatures and coolant pressures significantly lower than those expected in power reactors. The Heavy Water Components Test Reactor (HWCTR), built for testing fuel in this program, was still one year from startup at the beginning of the VBWR irradiation.

A secondary purpose of the irradiation was to compare the performance of tubes made by a vibrational compaction process alone and those made by a combined vibrational compaction and swaging process.

This report describes the fabrication techniques used at SRL to make tubular fuel for irradiation in the VBWR, and results of an evaluation of the test pieces and companion elements. The irradiation test is described in DP-837;[3] the results of postirradiation examinations are given in DP-997.[4]

SUMMARY

Tubular uranium dioxide fuel elements, approximately two inches in outer diameter and three feet long, clad with 0.030-inch-thick Zircaloy were fabricated for irradiation testing in the VBWR. Crushed arc-fused UO_2, enriched to 5% ^{235}U, was vibrationally compacted or vibrationally compacted and swaged into a 0.24-inch-thick annulus.

Average densities for the vibrationally compacted tubes and swaged tubes selected for irradiation were 84% and 92% of the theoretical value, respectively. The dimensions and appearance of the elements were satisfactory; maximum diametral variations were ±0.007 inch. After the tubes were autoclaved, the principal surfaces displayed the black and lustrous finish that is characteristic of Zircaloy having good resistance to corrosion in high-temperature water. The welds, however, were gray or dull black, which indicated a somewhat lower resistance to corrosion.

DISCUSSION

BACKGROUND

Previous to the irradiation tests in the VBWR, six series of irradiations of uranium-dioxide tubes sheathed in Zircaloy were conducted in Savannah River reactors. The initial irradiation tests had been made at SRP on UO_2 tubes sheathed in stainless steel.[5,6] From one series to the next, various improvements were made in the fuel elements. For example, the achievement of higher density by vibration alone required less compaction by swaging to reach a given final density.[7] Also, improved weld designs and inspection methods were employed.

Four sheath failures occurred in these early irradiations of Zircaloy-sheathed tubes at SRP. Each of the failures was detected during the return to full-power operation after a reactor shutdown. All of the failures occurred in the outer sheath and had the following characteristics: a) little evidence of sheath ductility, b) severe hydriding of the Zircaloy sheath at the point of rupture and at locations removed from the rupture, both apparently from an internal source of hydrogen, and c) predominantly radial orientation of hydride platelets in the outer sheath and predominantly circumferential orientation in the inner sheath.[8] Examination of unfailed companion tubes revealed hydride formations, predominantly on the inner cladding.

The internal source of hydrogen was believed to be the reaction of moisture with inclusions (uranium or uranium carbide) in the UO_2. To eliminate this source, the fabrication process was modified to include outgassing and drying the UO_2.[9] Tubes fabricated with this treatment and irradiated in a Savannah River reactor operated satisfactorily, and no evidence of sheath hydriding was found by destructive examination of these tubes after irradiation.[10] These modified outgassing and drying steps were used during fabrication of tubes for irradiation tests in the VBWR.

MATERIALS AND PROCEDURES

Seamless tubing and end plug stock of reactor-grade Zircaloy-2 were obtained from Harvey Aluminum Inc., Torrance, California. Nominal dimensions of the tubing were as follows:

Outer diameters	- 2.15, 2.06, and 1.47 inches
Wall thickness	- 0.030 inch
Length	- 9 feet

The tubing was low-nickel Zircaloy-2; material specifications, dimensional tolerances, and chemical analyses are in Appendix I.

Arc-fused UO_2 enriched to 5.1% ^{235}U was obtained from the Spencer Chemical Company, Military, Kansas. Specifications for the core material are in Appendix II. The as-received oxide was pulverized and separated into fractions with particles of the following sizes (U.S. Standard Sieve No.): -10 +16, -16 +20, -40 +100, -325. The UO_2 was outgassed in a vacuum induction furnace at approximately 1000°C for about one hour to remove hydrogenous materials and sorbed gases, and was stored in vacuum or under an inert gas blanket until blended and loaded into tubes.

The sequence of the major fabrication operations is in flowsheet form in Figure 1; a detailed process flowsheet is in Appendix III. The following paragraphs describe the fabrication technique.

Compaction by Vibration Alone

The inner and outer sheath tubes were nondestructively inspected for surface defects, then etched, and welded to temporary bottom end plugs. The blended oxide was poured into the annulus through a funnel that held the inner sheath concentric with the outer sheath; the loaded tubes were vibrated to 83 or 84% of the theoretical density. Permanent end plugs were then inserted and welded, and the welds were pressure tested.

Compaction by Vibration Plus Swaging

Inner and outer sheath tubes were nondestructively inspected for surface defects, and then were etched and welded to temporary collapsible metal end plugs. The tube was attached to the vibration exciter by a friction clamp (the end plugs, clamps, and exciter are described in previous reports).[6,7] The blended oxide was poured into a funnel

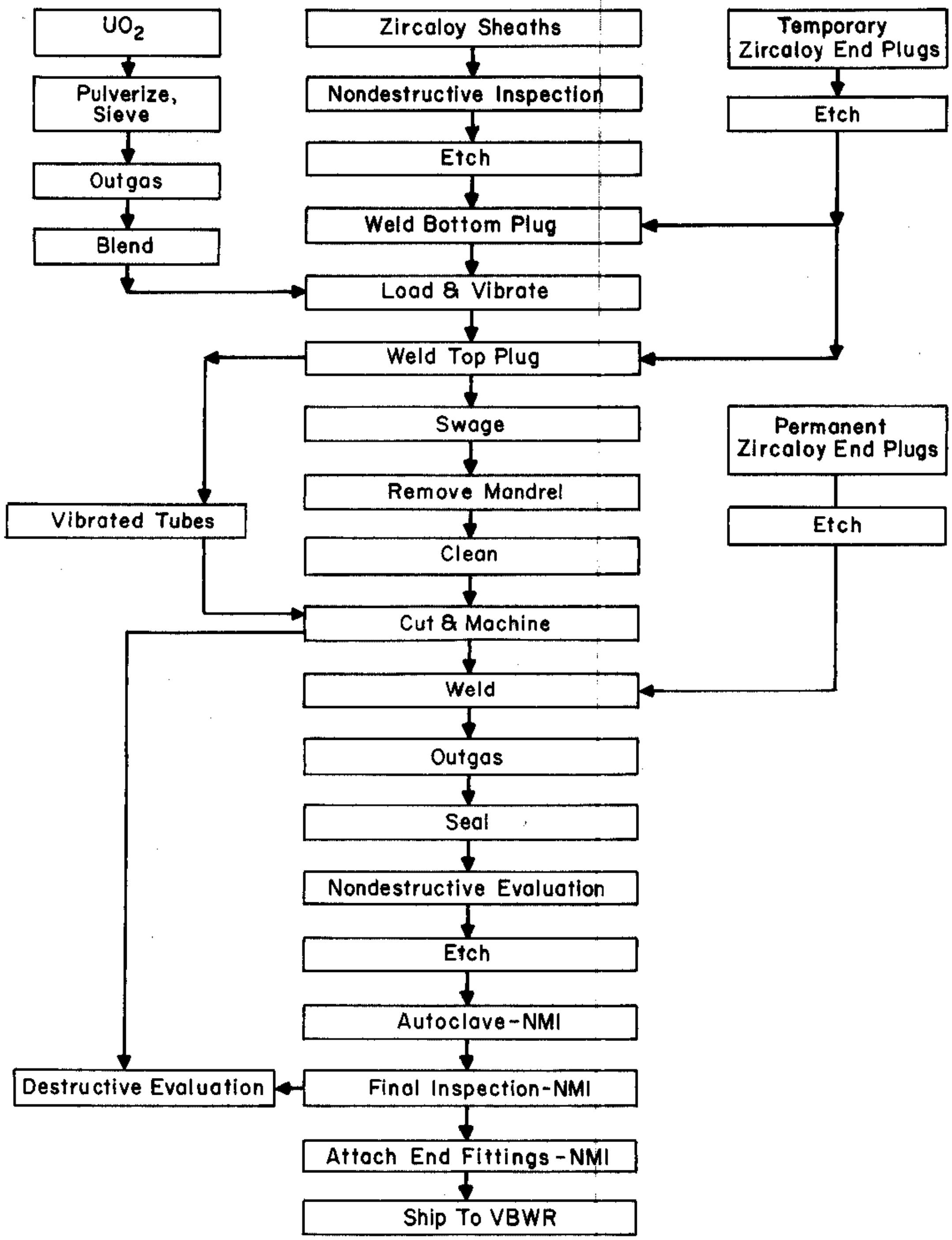


FIG. 1 PROCESS FLOWSHEET

which maintained concentricity of the two sheaths at the top of the sheath assembly; then the loaded tubes were vibrated to 83 or 84% of the theoretical density. After welding the top end plugs in place, the 2.15-inch-diameter tubes were swaged on a mandrel to 92% of theoretical density in two passes; the cross-sectional area of the tubes was reduced about 15%, and the tubes elongated about 6 to 8% during swaging. After swaging, the mandrels were removed from the tubes in a drawbench.

The next step of the process was to cut off the temporary end plugs, trim the tubes to length, and counterbore the oxide to the required depth. The ends of the tubes were fitted with permanent end plugs that were then welded to the sheaths, as shown in Appendix III, Figures A-1 and A-2. The welds were then pressure tested.

Finishing Operations

For tubes made by either compaction process, the UO_2 cores were dried by vacuum outgassing the tube at 200°C for 20 hours through vent holes in the end plugs. The tubes were backfilled with helium gas and the vent holes were sealed. Nondestructive evaluation prior to etching and autoclaving included: X-radiography of the welds, helium leak testing, wall thickness testing,(11) examination with a gamma-ray densitometer,(12) bubble testing, fluorescent-dye testing, and physical measurements. The four best tubes were etched and shipped to Nuclear Metals, Inc., Concord, Mass. for autoclaving; at that time, no autoclave at Savannah River was long enough for these tubes. Autoclave conditions were as follows: 1) three hours in 600°F water (1500 psig), and 2) 72 hours in 750°F steam (1150 psig). Stainless steel adapter-fittings (Appendix III, Figures A-2 and A-3) were plug welded to studs screwed into the Zircaloy end caps. Dimensional measurements were made and the primary irradiation candidates were selected on the basis of visual inspection.

EVALUATION RESULTS

Five of the ten tubes fabricated for irradiation were compacted by vibration alone; five were compacted by vibration plus swaging. Two tubes made by each fabrication method were shipped to the VBWR and two companion tubes of each type were destructively evaluated.

- Dimensions

Dimensional variations of the fuel tubes selected for irradiation, and their alternates, are summarized in Appendix IV. The tubes compacted by vibration plus swaging showed less diametral variation than did the vibrationally compacted tubes. Because vibrational compaction did not affect the tube size, the variation was that of the original sheath tubes. At the tube ends, variations in wall thickness ranged up to 0.015 inch, or 5% of the tube wall. Measurements with a gamma-ray densitometer, which combined the effects of wall thickness and density, showed 3 to 6% greater variation for the vibrated tubes than for swaged tubes.

The minimum sheath thickness for any tube was 22 mils. Outer sheath thicknesses were measured continuously over the tube with an eddy-current instrument. Inner sheath thicknesses were measured with micrometers on rings cut from the ends of each tube; 1.5 mils (for vibratory packed tubes) or 2.5 mils (for swaged tubes) was subtracted from the value for metal loss during etching.

- Surface Appearance

With a few exceptions, the surfaces of the tubes were smooth, black, and lustrous. Die marks were faintly visible on the swaged tubes, and the welds and heat-affected zones of all tubes were gray or dull black. The vibratory compacted tubes exhibited a slight collapse of the outer sheath at the junction of the oxide core and end plug as a result of autoclave treatment at 1150 to 1500 psig.

- Weld and Cladding Integrity

The integrity of the cladding and end seals was satisfactory, as demonstrated by the following tests:

TABLE I

Nondestructive Tests of UO_2 Fuel Tubes

Test	Conditions	Remarks
X-ray of welds	86 kv, 5 ma, 14 - 16 sec	No visible inclusions or voids (limit of detection was 3- to 5-mil void)
Helium pressure Test	200 psig pressure, 1/2 hour submerged in water	No leaks
Helium leak test	200°C, 10^{-8} torr	No leaks
Bubble test	Submerged in ethylene glycol at 50 mm Hg	No leaks
Ultrasonic test for sheath defeds	Detectable defect - 120 square mils	No defects on vibratory-compacted tubes[(a)]

(a) In swaged tubes, the large number and size of indentations in the cladding scattered the ultrasonic beam and the results could not be interpreted.

Destructive Evaluation

- Cladding

Tensile tests were performed on specimens cut from the outer sheaths of companion tubes that were not autoclaved. The results, in Appendix V, show that vibrational compaction did not alter the mechanical properties of the as-received tubing. A 7 to 20% increase in yield and ultimate strengths was observed on sheaths from swaged elements. The ductility of the Zircaloy was significantly diminished by swaging; the elongation-to-fracture values were approximately half of those for the as-received material.

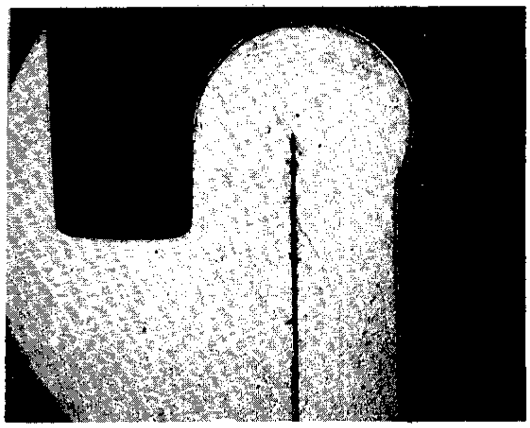
In the swaged tubes, oxide indentations as deep as four mils were measured in samples from the inner sheaths, and as deep as three mils in the outer sheaths. The unlikely combination of the deepest indentation and the minimum cladding thickness would leave a minimum residual cladding of 18 mils.

- Welds

Weld-shear tests were made on both top and bottom plugs from comparable tubes by appling a tensile force to the inner sheath only. The load required to fracture the welds varied from 2700 to 3700 pounds per inch of linear weld; the shear strength equivalent to this loading was approximately the same as the tensile strength of the sheaths. Typical values of weld penetrations from four comparable tubes (64 sections) averaged from 28 to 32 mils; the minimum weld penetration was 17 mils. Typical sections of welds and vent seal are shown in Figure 2.

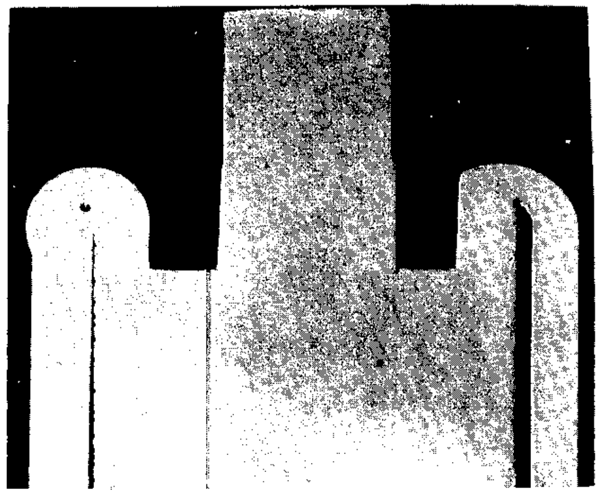
- <u>UO_2 Bulk Density</u>

The density of the UO_2 cores ranged from approximately 84 to 92% of the theoretical value, as shown in Table II. The density of the vibrated tubes was calculated from the weight of UO_2 in the element and the calculated volume of the annulus. The density of the swaged tubes was measured directly on two-inch rings cut from the ends of the tube segments; the lowest value was 91.3%.



NEG 42917 15X

Circumferential Weld in End Cap
Typical Weld Throat - 30 mils



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Circumferential Weld in End Cap
Minimum Weld Throat - 17 mils

NEG 41501 10X

Plug Weld at Vent Seal in Cap

FIG. 2 SECTIONS OF WELDED CLOSURES IN UO_2 FUEL TUBES

TABLE II

Core Density and Oxide Weight of UO_2 Tubes

Compaction Process	Vibration Alone		Vibration Plus Swaging	
Tube Number	ZE-191 (Alternate)	ZE-195 (Test Fuel)	ZE-196 (Alternate)	ZE-197 (Test Fuel)
Density, %				
Average	83.7	84.0	91.9	92.2
Minimum	-	-	91.3	91.9
UO_2 weight,[a] grams	7122	7148	7802	7811

(a) Based on the average density and average diameters.

- Chemical Analyses of Cladding and Core

The hydrogen content in the autoclaved sheaths ranged from 4 to 28 ppm, as determined by vacuum extraction. Typical distributions of the hydride platelets in a transverse direction are shown in Figure 3.

Moisture content of the oxide cores from two companion tubes compacted by vibration alone was less than 30 ppm. Samples were taken and transferred to an electrolytic moisture analyzer under dry conditions (2% relative humidity).

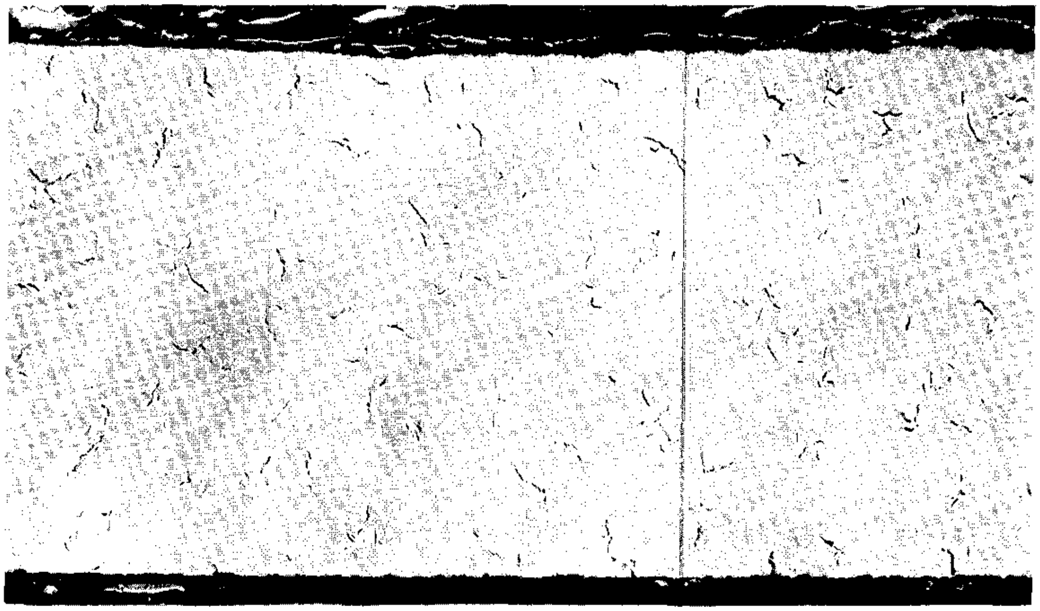
Gas content of the UO_2 from the two companion tubes is shown in Table III.

TABLE III

Gas Content of UO_2, 1000°C Vacuum Extraction

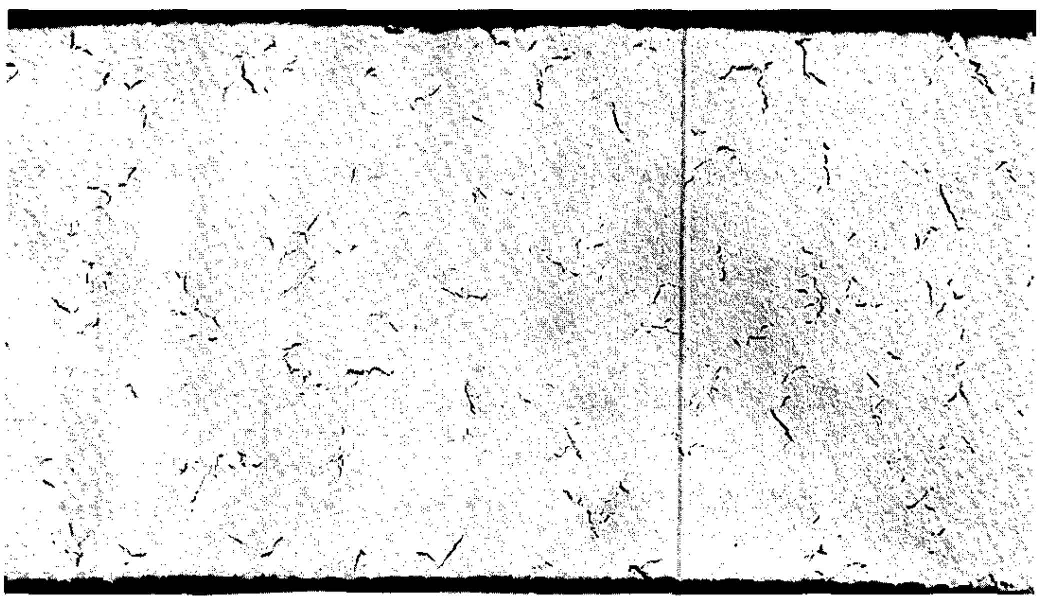
Tube No.	No. of Samples	Total Gas, cc/g	Composition, ppm UO_2: H_2	N_2	CO	CO_2
ZE-193	3	0.07	3	21	9	19
ZE-194	6	0.05	2	16	23	20

Particle size distribution in the samples was essentially the same as in the tube.



NEG 38393 100X

Outer Sheath



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Inner Sheath

FIG. 3 TYPICAL DISTRIBUTION OF HYDRIDE IN LOW-NICKEL ZIRCALOY-2 SHEATHS AFTER AUTOCLAVING

- Collapse and Thermal Cycle Tests

The release of sorbed and fission gas during irradiation may generate internal pressure sufficient to collapse the inner cladding or may rupture the outer cladding of tubular fuel. Collapse pressures were measured by heating both empty tubes and oxide-filled fuel tubes to the maximum cladding temperature expected in-reactor (350°C), and introducing successive 50-psi increments of helium gas pressure until the inner sheath collapsed. The support provided by a vibratory-compacted core (81% of theoretical density) raised the collapse pressure from about 300 psig for an empty tube to 600 psig. Swage-compacted tubes of 91% of theoretical density were approximately 1.4 times more resistent to collapse than vibratory-compacted tubes; the higher core density provided greater support to the cladding. Collapse of the inner sheath during irradiation in the VBWR was unlikely because the internal pressure must exceed the reactor operating pressure by the above values.

Thermal cycling tests to determine dimensional stability were conducted at Nuclear Metals, Inc. on both types of fuel tubes. The fuel tubes were immersed in molten lead for 5 to 10 minutes and then were quenched in boiling water for 2 to 5 minutes. Twenty cycles through a 450 to 100°C temperature range produced about 0.001-inch increase in the outer diameters of both types of fuel. Cycling through a 650 to 100°C temperature range produced the changes shown in Table IV. No apparent change in inside diameter or length occurred, and testing was discontinued when the Zircaloy cladding showed excessive oxidation. These tests, together with all evaluation results, indicated the high integrity and satisfactory quality of the fuel tubes.

TABLE IV

Thermal Cycle Tests; 650 to 100°C

Compaction Process →	Outer Diameter Increase - inches: Vibration Alone	Vibration Plus Swaging
No. of Cycles		
1	0.002	0.003
2	0.001	0.002
5	0.002	0.001
12	0.003	-
Total	0.008	0.006

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APPENDIX I
ZIRCALOY SPECIFICATIONS

Required Alloy:	Low-Nickel Zircaloy-2
Raw Material:	Virgin zirconium sponge converted to ingot by a double vacuum arc-melting process.
Tubing:	Fabricated by standard seamless processes. Furnish tubing in a vacuum-annealed condition and etched (1-2 mils) after final working.
Tube Surface Finish:	Roughness not to exceed 63 rms value. All surfaces to be uniform and free of cracks, tears, pits, laps, and other defects detectable by borescope inspection. All surfaces to be free of copper, iron, and other contaminants. All surfaces to be inspected for surface defects with Zyglo-Penetrex XL-22, or equivalent, fluorescent-dye technique.
Corrosion Resistance:	Samples taken from every 100 feet of tubing to be tested for 14 days in 750°F, 1500 psig steam. Samples must have a continuous and adherent glossy, black corrosion film with no defects after testing. Weight gains of coupons should not exceed 28 ±10 mg/dm^2.

Sheath Dimensions, inches

	Outside Diameter	Inside Diameter	Wall Thickness
Swaged tube Outer sheath	2.150 +0.015 -0.000	-	0.032
Vibratory compacted tube Outer sheath	2.060 +0.015 -0.000	-	0.030
Inner sheath	-	1.465 +0.015 -0.000	0.032

APPENDIX I (Continued)

Chemical Analyses Supplied by Vendor

Ingot Analysis: Samples were taken from three positions equally spaced along the length of the ingot.

Element	Weight Percent
Tin	1.20 to 1.70
Iron	0.12 to 0.18
Chromium	0.05 to 0.15
Nickel	0.007 maximum
Zirconium	Remainder, less impurities

Impurities, maximum content: Same sampling as above

Element	ppm
Aluminum	75
Boron	0.5
Cadmium	0.5
Carbon	270
Chlorine	15
Cobalt	20
Copper	50
Hafnium	200
Lead	130
Hydrogen*	25
Nitrogen*	80

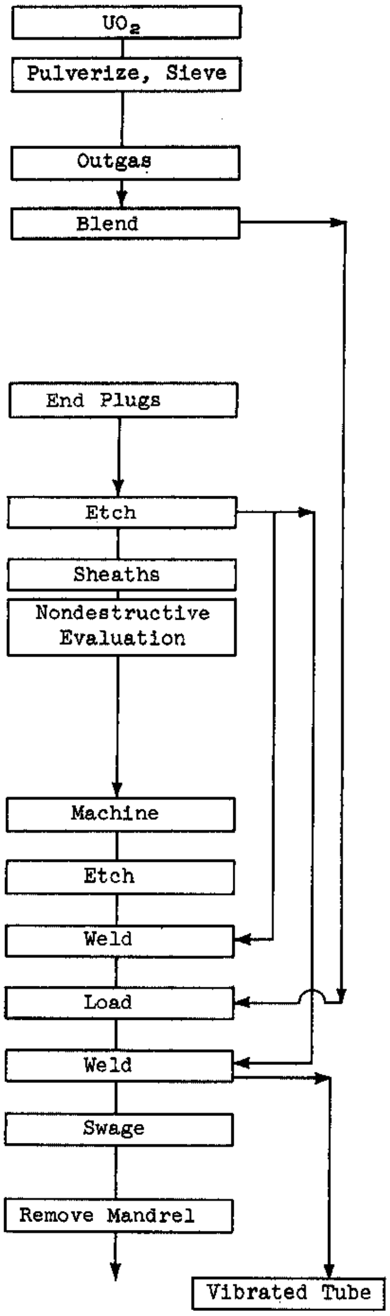
* Additional analyses required on every 100 feet of finished tubing.

APPENDIX II

SPECIFICATIONS AND VENDOR'S ANALYSES FOR URANIUM DIOXIDE

	Specification		Analysis
Material:	Crushed (-2 mesh), fused uranium dioxide		Lot 396-50-1
Stoichiometry:	2.010 max - 2.000 min O/U (determined within ±0.005 by ignition to U_3O_8)		2.008
Uranium Content:	88.0% minimum		88.11%
Uranium as Metal:	None indicated by O/U analysis nor detectable as second phase by metallographic techniques		Traces observed under microscope
Particle Density:	10.8 g/cc minimum by water pycnometry on -20 mesh sample		10.9 g/cc
Neutron absorption cross-section of impurities (equivalent boron):	8 ppm maximum		8 ppm
Moisture:	None detectable by loss of wt of -100 mesh sample held at 105°C for two hours		None detected
Chemical Impurities, maximum content in ppm:	Aluminum	100	10
	Boron	1	0.1
	Cadmium	1	0.2
	Carbon	175	60
	Chromium	75	5
	Copper	20	1
	Fluorine	50	50
	Iron	150	10
	Manganese	50	3
	Nickel	75	3
	Silicon	100	10
Total sorbed gases (exclusive of water), maximum:	0.1cc (STP) per gram of UO_2 evolved upon heating to 900°C under vacuum and holding fifteen minutes		0.1cc/g on basis of other batches

APPENDIX III
DETAILED PROCESS FLOWSHEET



Arc-fused UO_2, -2 mesh

Pulverize and sieve to desired fraction, electromagnetically remove iron particles so that sieved UO_2 contains less than 100 ppm Fe.

Outgas in vacuum induction furnace at 1000°C for about one hour, cool in vacuum 4 hours. Store in vacuum.

Blend size fraction for compaction system.

Vibratory Compaction	Vibratory Plus Swaging
-10 +16 (52%)	-16 +20 (52%)
-40 +100 (28%)	-40 +100 (28%)
-325 (20%)	-325 (20%)

Temporary end plugs as shown in DP-493[e] for use during compaction and swaging. Material: Zircaloy-2
Permanent end plugs as shown in Figure A-2 (1). Material: Low-Nickel Zircaloy-2.

Remove 1/2 mil from each surface in HF-HNO_3 acid bath. Rinse in hot and cold water baths, and finally in deionized water.

Zircaloy sheaths as shown in Table I and Appendix I.

Check dimensions and inspect surfaces visually.

Ultrasonically examine and reject sheaths with defects greater than 120 sq. mils (60 mils long x 2 mils deep). Determine wall thickness variations by eddy current test.

Inspect surfaces with "Zyglo-XL22" dye penetrant for defects, reject sheaths with persistent indications.

Cut sheaths to required length after corrosion samples are taken.

Remove 1 mil from each surface in HF-HNO_3 acid bath.

Weld bottom end plug with T.I.G. system in helium dry box.

Vibrate to 84% bulk density on MB Electronics Model C10E Exciter, driven by T151M amplifier.

Weld top end plug same as above.

Swage to 15% reduction in core area in two passes over a mandrel coated with an asphaltic gear lubricant (16,000 Saybolt second units).

Pull mandrel from tube with drawbench and stripping die.

APPENDIX III (Continued)

Vibrated Tube	
End Plugs	
Swaged Tube	
Clean	Degrease in trichloroethylene liquid.
Machine	Machine to length, counterbore UO_2 as shown in Figure A-1. Cut two-inch specimens from swaged tubes for evaluation.
Weld	Weld permanent end plugs as shown in Figure A-3.
Pressure Test	Pressurize internally with helium gas at 200 psig for 1/2 hour through vent holes while immersed in water to detect leaks.
Dry Core	Vacuum outgas tube at 200°C for 20 hours and backfill with dry helium.
Seal Vents	Insert Zircaloy wire, and fuse to end plug.
Etch	Etch 1-1/2 mils off swaged tube surfaces and 1/2 mil off vibrated tubes in $HF\text{-}HNO_3$ acid bath. Rinse in hot and cold water baths.
Nondestructive Evaluation	X-ray weld beads for porosity and inclusions. Inspect surfaces with "Zyglo-XL22" dye penetrant; reject defects which are persistent after minor polishing and re-etching. Ultrasonic and eddy current test for sheath defects and thickness. Helium leak check tubes at 200°C. Bubble test tubes in ethylene glycol (pressure over liquid 50 mm Hg) for leaks. Measure tube dimensions.
Etch	Flash etch (0.1 to 0.2 mil) tube surfaces in $HF\text{-}HNO_3$ acid bath. Rinse in hot and cold water baths, and finally in dionized water.
Autoclave	Autoclave in 400°C, 1200-1500 psig steam for three days.
Nondestructive Evaluation	Measure tube dimensions. Measure density and wall thickness variations with gamma densitometer. Visually inspect.
Weld	Weld stainless steel adapters as shown in Figures A-2 (4) and A-3.
Ship	
Destructive Evaluation	Examine welds metallographically. Conduct weld shear tests. Conduct strip tensile tests on sheathing. Analyze UO_2 for gas content and water content, O/U ratio. Analyze sheath for hydrogen content. Collapse test vibratory-compacted tube at 350°C. Thermal cycle representative tubes between 100° and 450°C.

APPENDIX III

Sketches of Fuel Assembly and Components

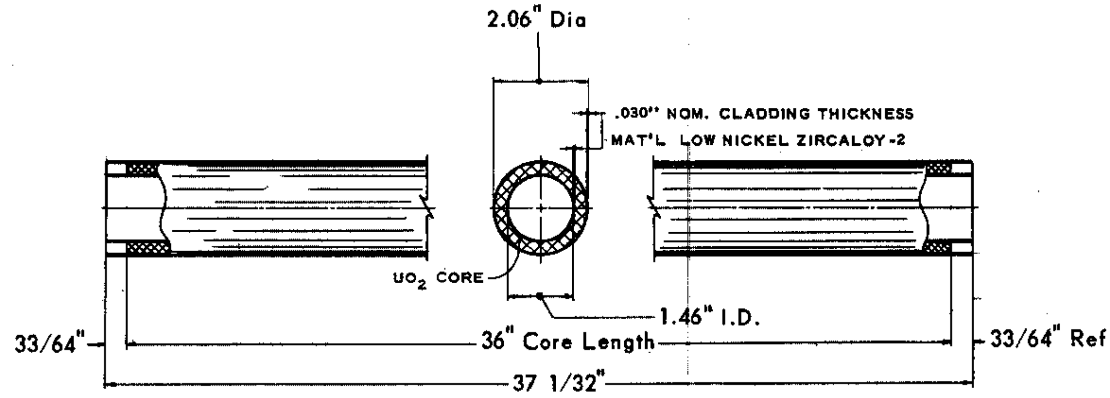


FIG. A-1 FUEL TUBE

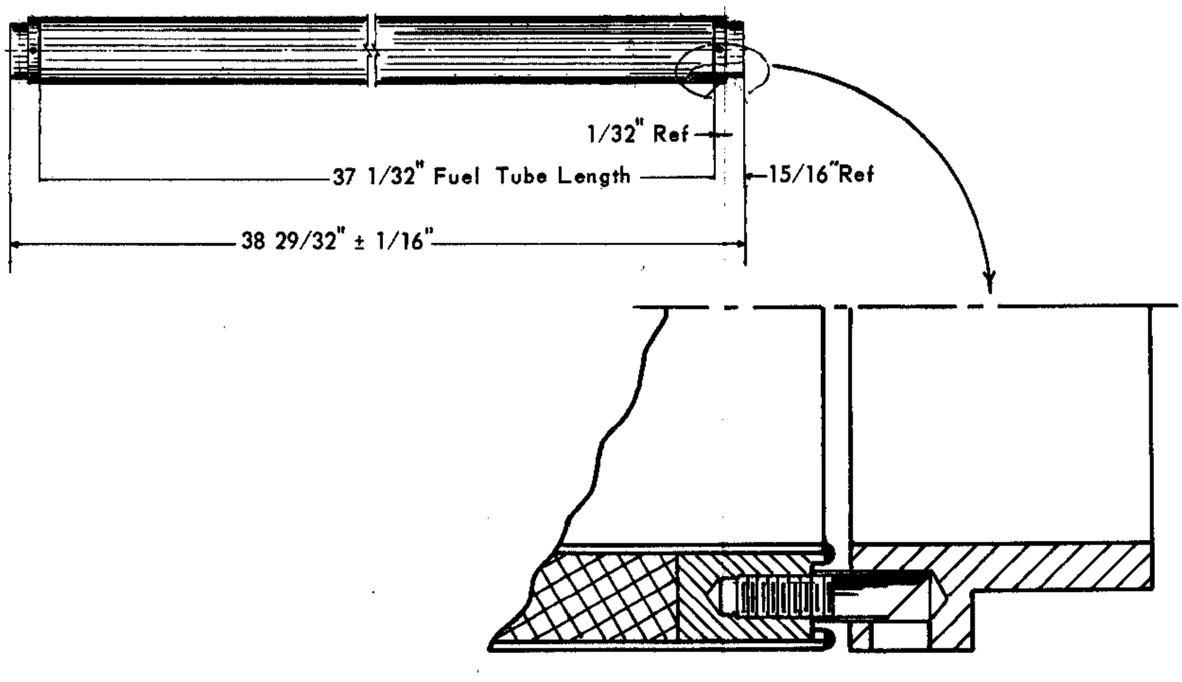
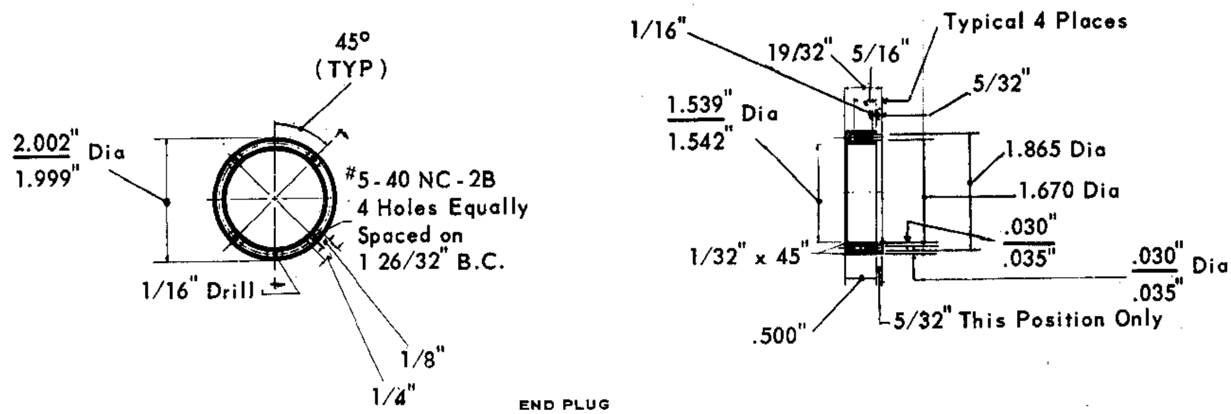


FIG. A-2 FINISHED FUEL TUBE

APPENDIX III

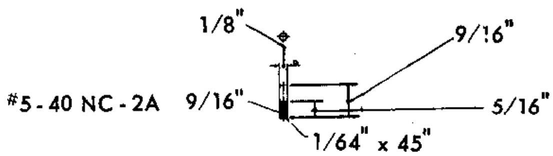
Sketches of Fuel Assembly and Components



END PLUG

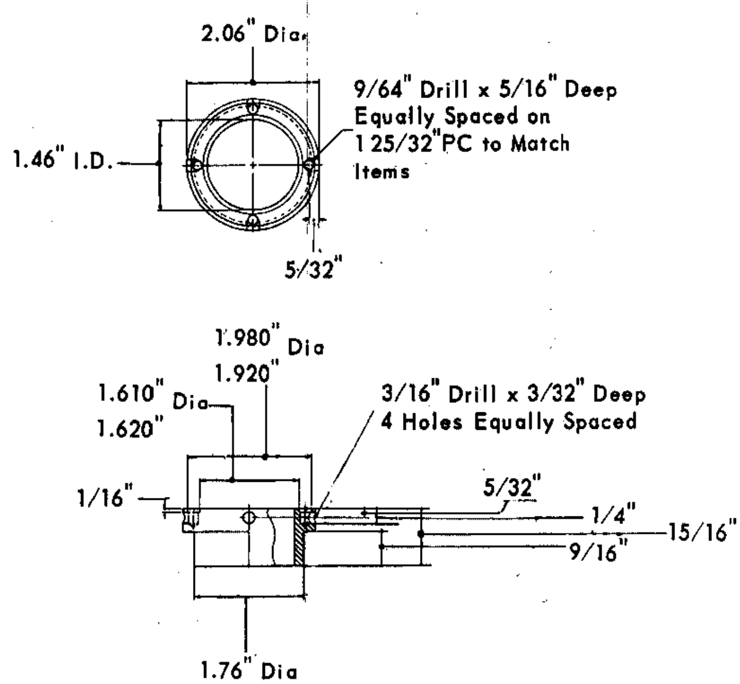
LOW NICKEL

ZIRCALOY-2



STUD

304 SS



END PLUG 304 SS

FIG. A-3 PERMANENT END PLUGS

APPENDIX IV
DIMENSIONS OF TEST FUEL AND ALTERNATES

Dimension, inches	Vibrated		Swaged	
	ZE-191	ZE-195	ZE-196	ZE-197
	(Alternate)	(Test fuel)	(Alternate)	(Test fuel)
Outer diameter				
Average	2.065	2.065	2.061	2.060
Range	0.009	0.015	0.004	0.007
Inner diameter				
Average	1.474	1.474	1.467	1.465
Range	0.005	0.006	0.007	0.009
Bow, single throw	0.010	0.018	0.008	0.014
Wall thickness				
Micrometer - tube ends				
Average	0.296	0.296	0.295	0.295
Max eccentricity	0.006	0.005	0.012	0.015
Magnetic wall thickness tester[a]				
Excluding ends				
Average	-	-	0.298	0.298
Max Eccentricity	-	-	0.011	0.012
Difference of average diameters	0.296	0.296	0.297	0.298
Max circumferential variation of UO_2 loading-densitometer, %	8.1	11.0	5.3	4.3
Cladding thickness, mils				
Outer sheath				
Average	25	28	30	30
Minimum	22	25	27	28
Inner sheath				
Average	31	33	32	31
Minimum	28	32	31	29

(a) A magnetic reluctance instrument[11] which measured the gap (wall thickness) between the tube OD and a steel mandrel positioned in the bore of the tube. Wall thickness measurements were made on swaged tubes only; techniques for vibrated tubes were not available.

APPENDIX V
TENSILE PROPERTIES OF OUTER SHEATHS[(a)]
(Not autoclaved)

Sheath Condition	Orientation	Yield Strength, 1000 psi	Ultimate Strength, 1000 psi	Elongation to Fracture, %	Reduction in Area, %
As-received	Longitudinal				
	Average	46	76	20	33
	Range	43 - 50	72 - 78	15 - 25	27 - 38
As-received	Circumferential				
	Average	48	81	16	44
	Range	46 - 52	76 - 84	15 - 17	41 - 48
Vibratory compacted	Longitudinal				
	Average	45	71	23	32
	Range	44 - 45	71 - 72	21 - 24	0
Vibratory compacted	Circumferential				
	Average	41	73	14	43
	Range	37 - 45	0	0	40 - 46
Swaged	Longitudinal				
	Average	55	81	12	22
	Range	52 - 58	80 - 81	11 - 13	20 - 25
Swaged	Circumferential				
	Average	55	89	6.3	29
	Range	0	88 - 89	0	27 - 32

(a) Values were determined for a minimum of two samples, and as many as six.