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DESTRUCTIVE EVALUATION OF
IRRADIATED ZIRCALOY SHEATHING

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DESTRUCTIVE EVALUATION OF IRRADIATED ZIRCALLOY SHEATHING

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ABSTRACT

The effect of irradiation on the ability of Zircaloy-sheathed oxide fuel tubes to withstand sheath strains during reactor service was determined by mechanical burst, weld-shear, and bend tests. The ductility of the sheath was not affected by irradiation exposures up to approximately 10^{20} fast nvt, and increases in the weld-shear strength were observed.

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DESTRUCTIVE EVALUATION OF IRRADIATED ZIRCALOY SHEATHING

INTRODUCTION

Thin-walled Zircaloy tubing is used at the Savannah River Laboratory as sheath material for tubular oxide fuel elements fabricated by vibratory and swage compaction. During irradiation the sheath must withstand, without failure, strains produced by internal gas pressure and by differential thermal expansion between the oxide core and the sheath. It is therefore desirable to know the effect of irradiation on the ability of the sheath to withstand these strains. This report describes tests made to determine the effects of irradiation on the strength and ductility of the sheathing from experimental Zircaloy-sheathed oxide fuel elements irradiated in the SRP production reactors in 1960 through 1962.

Early irradiation failures by brittle fracture of the outer sheath after exposures of about 10^{20} fast nvt were attributed to local hydriding of the sheaths and massive deposits of hydride at the sheath-core interface.⁽¹⁾ Subsequent improvements in fabrication eliminated the hydriding problem; however, some concern remained as to the effect of irradiation per se on the ductility of the sheathing.

A number of investigations⁽²⁻⁵⁾ of the mechanical properties of Zircaloy have been made: Pankaskie and Knecht⁽²⁾ determined the properties of thin-walled tubing for the Plutonium Recycle Test Reactor; Rittenhouse and Picklesimer⁽³⁾ measured the tensile properties and strain behavior of Zircaloy plates with differing preferred orientations; Burton⁽⁴⁾ determined the effect of hydrogen on the tensile properties of Zircaloy-2; and Green, White, and Isserow⁽⁵⁾ studied the factors affecting the ductility of tubular Zircaloy-clad fuel elements. Other investigators determined the effect of irradiation on the tensile properties of Zircaloy and indicated that some irradiation embrittlement did occur.^(6,7)

However, studies by Sturcken and Duke⁽⁸⁾ and Rittenhouse and Picklesimer⁽³⁾ have shown that the strain behavior of Zircaloy is markedly affected by its preferred orientation (texture) and that the texture is controlled by fabrication techniques. These studies indicated that information previously developed on tubing of different sizes, manufactured by different techniques, and fabricated into fuel elements by different processes will not necessarily furnish the data required for the work at the

Savannah River Laboratory. Therefore, the effect of irradiation on the mechanical stability of the Zircaloy sheath used at SRL was investigated.

SUMMARY

The effect of irradiation on the ability of Zircaloy-sheathed oxide fuel tubes to withstand sheath strains produced during reactor service was determined by mechanical burst, weld-shear, and bend tests. The ductility of the sheath was not affected by irradiation exposures up to approximately 10^{20} fast nvt and increases in the weld-shear strength were observed.

DISCUSSION

DESCRIPTION OF ELEMENTS AND IRRADIATIONS

Description of Sheath

The Zircaloy tubing used as sheath material was commercially fabricated by extrusion of copper-jacketed billets at 788°C. The tubing was drawn to size at room temperature with intermediate anneals at 650°C. After the final drawing to a wall thickness of about 30 mils, the tubing was etched in a HNO₃-HF mixture, vacuum annealed at 650°C, and stretch straightened. Standard Zircaloy-2 tubing was used for the SPRO-5 assembly and low-nickel Zircaloy-2 for the SPRO-12 and -13 assemblies. Nominal compositions of these alloys are given in the following table.

<u>Compositions of Zircaloy-2, wt %</u>					
<u>Grade</u>	<u>Sn</u>	<u>Fe</u>	<u>Cr</u>	<u>Ni</u>	<u>Zr</u>
Standard	1.2-1.7	0.07-0.20	0.05-0.15	0.03-0.08	Bal
Low-Ni	1.2-1.7	0.18-0.29	0.07-0.13	0.007-Max	Bal

Element Design and Fabrication

The tubular elements were 1-1/2 to 2 feet long, with outside diameters of approximately 2-1/4 inches and inside diameters of approximately 1-1/2 inches. The irradiation assemblies consisted of five or six tubes, stacked vertically in ribbed aluminum housing tubes. The elements were fabricated

by vibratory compaction or by vibratory compaction followed by cold swaging as described in DP-515, -665, and -715^(10, 11, 12). Specific details for individual assemblies are given in Table I and Figure 1.

TABLE I

Fabrication Details of Elements for the SPRO Assemblies

	SPRO Assembly No.	Fabrication Technique	
		Vibratory ^(a)	Swaged ^(b)
No. of tubes per assembly	5	0	6
	12	3	3
	13	2	3
Oxide density after vibratory compaction, % ^(c)	5	-	72
	12	82	80
	13	86	84
Oxide density after swaging, % ^(c)	5	-	91
	12	-	90
	13	-	92
No. of swaging passes	5	-	7
	12	-	2
	13	-	2
Reduction in cross-sectional area of inner sheath, %	5	-	16
	12	0	9
	13	0	9
Reduction in cross-sectional area of outer sheath, %	5	-	14
	12	0	7
	13	0	7

(a) Vibratory compaction alone.

(b) Vibratory compaction followed by cold swaging.

(c) Oxide densities are listed as % theoretical.

The end plug design for the SPRO-5 assembly differed from the plug design for the SPRO-12 and -13 assemblies (Figure 2). The weld configuration was redesigned for the latter two assemblies to obtain greater assurance of satisfactory closures.

The end plugs for the SPRO-5 assembly were welded under conditions that led to oxygen and nitrogen contamination of the weld. This condition was remedied for the SPRO-12 and -13 assemblies by welding in a dry box to provide better control of the atmosphere; both of these assemblies were welded under similar conditions except that the SPRO-13 welds were made at higher powers to increase weld penetration.

Irradiation Conditions

The assemblies were irradiated in a Savannah River Plant (SRP) reactor to exposures up to approximately 10^{20} fast nvt at coolant temperatures below 100°C.

FIG. 1 DIMENSIONS OF FUEL ELEMENTS FOR THE SPRO-5, -12, AND -13 ASSEMBLIES

a. SPRO-5 Elements

b. SPRO-12 and -13 Elements

FIG. 2 WELD DESIGNS FOR THE SPRO-5, -12, AND -13 ELEMENTS

EXPERIMENTAL PROCEDURES

It was impractical to machine tensile specimens from the irradiated sheaths. Therefore, standard tensile tests were made only on unirradiated sheaths, and weld-shear, mechanical burst, and bend tests were performed directly on irradiated elements, and on companion unirradiated elements for comparison.

The tensile tests on the unirradiated sheaths were performed at strain rates between 0.02 and 0.04 inch/inch/minute. Load-elongation data were recorded by an autographic recorder with a microformer-type extensometer. The ultimate tensile strength and the 0.2% offset yield strength were estimated from the load-elongation curves and pretest specimen measurements. The elongation and reduction in area were determined from measurements made directly on the samples.

Weld-shear tests were made by rupturing the fusion weld at the end plugs by pulling the inner sheath while restraining the end plug. The apparatus for the weld-shear test is shown schematically in Figure 3. The outer sheath was removed from the test section after the oxide core had been pickled from the tube in a nitric acid bath. The weld-shear strength was expressed as load required to rupture the weld.

FIG. 3 APPARATUS FOR WELD-SHEAR TESTS

Mechanical burst tests were performed on ring sections of the outer sheath by forcing a tapered steel mandrel through an aluminum liner contained in the sheath (Figure 4). The elongations, both maximum and uniform, were determined by measuring the diametral increases on the aluminum liner after sheath fracture. The diameter of the liner was measured every 30 degrees around the circumference. The maximum diametral increase was reported as maximum elongation, and the minimum diametral increase was reported as minimum elongation. To determine the accuracy of this type of measurement, minimum and maximum elongations on several specimens were determined from increases in the grid spacing of 1/4-inch grid lines scribed on the aluminum liner and on the test specimen. The elongations obtained from all three measurements were quite similar; therefore, diametral measurements, being the easiest to obtain, were used.

Mechanical bend tests were performed on longitudinal strips to determine the minimum radius of bend that a specimen could accommodate without rupture. It had been expected that the preirradiation strips could be bent double without failure and only the irradiated strips could be tested to fracture. However, both types readily accommodated a radius of curvature of 1/8 inch, the limit of the test equipment, without fracture.

FIG. 4 APPARATUS FOR MECHANICAL BURST TESTS

EXPERIMENTAL RESULTS

Preirradiation Tensile Tests

The room temperature tensile properties of the as-received tubing (Table II) were not affected by vibratory compaction; however, swage compaction increased the sheath strength and decreased its ductility.

TABLE II

Room Temperature Tensile Properties of Unirradiated Sheathing^(a)

Assembly Number	Type and Condition of Sheathing	Orientation	0.2% Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, %	Reduction in Area, %
SPRO-5 ^(b)	Outer	Long.	61,000	87,000	16	43
	As-received	Circum.	80,000	89,000	12	56
	Outer	Long.	91,000	95,000	7	39
	Swaged	Circum.	78,000	102,000	6	39
	Inner	Long.	43,000	68,000	25	48
	As-received	Circum.	-	-	-	-
	Inner	Long.	71,000	77,000	14	32
	Swaged	Circum.	-	-	-	-
SPRO-12 and -13 ^(c)	Outer	Long.	48,000	76,000	23	33
	As-received	Circum.	48,000	83,000	16	44
	Outer	Long.	58,000	80,000	10	18
	Swaged	Circum.	57,000	90,000	6	24
	Outer	Long.	45,000	77,000	21	35
	As-received	Circum.	49,000	78,000	16	44
	Outer	Long.	50,000	72,000	24	35
	Vibrated	Circum.	48,000	78,000	15	44
	Inner	Long.	45,000	75,000	24	35
	As-received	Circum.	-	-	-	-

(a) Each value the average of at least three specimens.

(b) Zircaloy-2

(c) Low-Ni Zircaloy-2

As expected, the tensile elongation of the sheath varied inversely with the sheath strength. However, in similar sheathing, the circumferential elongation was always less than the longitudinal elongation, but the reduction in area in the circumferential direction was always greater than in the longitudinal direction. This behavior indicated that the amount of uniform elongation was less in the circumferential direction than in the longitudinal direction and that the circumferential strain was localized. Furthermore, circumferential specimens necked equally in width and thickness, and longitudinal specimens necked predominantly in width.

Preferred orientation measurements^(a) of the tubing showed that the poles of the basal (0001) planes were predominantly oriented in the circumferential direction.

The strain behavior described above is consistent with this texture and the slip systems for zirconium observed by Rappaport⁽⁹⁾.

These tensile properties indicated that the unirradiated sheath was very suitable for reactor service and contained sufficient ductility to accommodate any strain that should occur during irradiation.

Weld-Shear Tests

The results of the pre- and postirradiation weld-shear test are given in Table III.

TABLE III
Weld-Shear Strengths of Inner Sheath Welds

<u>Assembly Number</u>	<u>Element Number</u>	<u>Type</u>	<u>Condition</u>	<u>Weld Shear Strength, lb</u>	
					Avg
SPRO-5	Z-93	Swaged	Unirradiated	8900	8300
	Z-93	Swaged	Unirradiated	8900	
	Z-96B	Swaged	Unirradiated	8200	
	Z-96B	Swaged	Unirradiated	7300	
	Z-90A	Swaged	Irradiated	8100	8100
SPRO-12	Z-186A	Swaged	Unirradiated	5000	6200
	Z-186B	Swaged	Unirradiated	7100	
	Z-178A	Vibrated	Unirradiated	7100	
	Z-181A	Vibrated	Unirradiated	5500	
	Z-184A	Swaged	Irradiated	7500	6600
	Z-184A	Swaged	Irradiated	5600	
SPRO-13	Z-207C	Swaged	Unirradiated	6700	7600
	Z-211B	Vibrated	Unirradiated	7600	
	Z-208C	Swaged	Unirradiated	7200	
	Z-207C	Swaged	Unirradiated	8300	
	Z-210B	Vibrated	Unirradiated	8300	
	Z-207B	Swaged	Irradiated	7600	8500
	Z-207B	Swaged	Irradiated	8900	
	Z-210D	Vibrated	Irradiated	9000	

The preirradiation tests revealed that the welds in companion tubes to the SPRO-12 assembly were the weakest, fracturing at the average load of 6200 pounds. The welds in companion tubes to the SPRO-13 assembly fractured at an average load of 7600 pounds, while the SPRO-5 companion tubes had an average weld strength of 8300 pounds.

The differences in weld strength in the SPRO-12 and -13 assemblies were due to differences in welding procedure, rather than weld design or sheath properties. The average weld penetration for the SPRO-12 companion tubes was approximately 26 mils with an average minimum penetration of 23

mils. The 26-mil penetration was approximately 14% less than the average inner sheath thickness of 30 mils. Therefore, the average weld strength would have been 14% higher, 7200 pounds instead of 6200 pounds, if complete penetration had been achieved. Subsequently, the welding power was increased to achieve an average penetration equal to the sheath thickness in the welds for the SPRO-13 assembly. The average weld strength for the SPRO-13 companion tubes, 7600 pounds, is very close to the calculated average strength of 7200 pounds that would have been obtained in the SPRO-12 assembly if complete penetration had been obtained.

The high weld strength of the SPRO-5 companion tubes was attributed to oxygen and nitrogen contamination of the sheath during the welding operation. Oxygen and nitrogen have been shown⁽¹³⁾ to increase the tensile strength of Zircaloy, and there was no reason to assume that similar increases should not occur in weld-shear test.

The welds of the irradiated tubes of the SPRO-13 assembly were significantly stronger than those for the unirradiated companion tubes, showing that irradiation may increase the strength of the welds. There were no statistically significant differences in the pre- and postirradiation strengths of welds from tubes in the SPRO-5 and -12 assemblies.

The stress at weld failure on the inner sheath of unirradiated SPRO-13 companion tubes averaged 48,000 psi. This value closely approximates the yield strength of longitudinal section of Zircaloy tubing used to fabricate the fuel elements and indicates that the weld-shear stress represents the stress required to cause localized yielding in the adjacent sheath. In fact, the welds fractured with almost no macroscopic deformation in the sheath, except in the heat-affected zone.

This lack of ductility should not affect the serviceability of the fuel element, however, because the internal pressure required to produce a stress large enough to cause weld failure, ~4000 psi at room temperature, is far greater than the pressure required to cause element failure by collapse of the inner sheath, ~1500 psi at room temperature.

Mechanical Burst Tests

The irradiation exposures of these assemblies did not noticeably affect the ductility of the outer sheath. The ductility values for most of the irradiated sections were

nearly equal to those for unirradiated companion sections fabricated in the same manner, as shown in Table IV. The uniform and total circumferential elongations show that the vibratory compacted elements were more ductile than the swaged elements, both before and after irradiation.

TABLE IV
Mechanical Burst Tests of Sheathing

<u>Assembly Number</u>	<u>Condition</u>	<u>Total Elongation, %</u>	<u>Minimum Elongation, %</u>
SPRO-5	Unirradiated, swaged	27	21
		26	20
	Irradiated, swaged	27	21
		27(a)	19
		18(a)	13
SPRO-12	Unirradiated, vibratory	19(a)	14
	Unirradiated, vibratory	35	30
		37	34
	Irradiated, vibratory	36	32
		20(a)	17
	Unirradiated, swaged	27	20
		28	25
	Irradiated, swaged	27	19
		15(a)	12
		10(a)	9
SPRO-13	Unirradiated, vibratory	36	31
		37	34
		38	32
	Irradiated, vibratory	36	29
		36	32
		37	27
	Unirradiated, swaged	27	21
		29	23
	Irradiated, swaged	27	24
		30	27
		29	28

(a) Premature failure due to improper positioning of specimen.

In several tests, failure of the irradiated sections began prematurely by tearing at the specimen edges. These premature failures were probably caused by improper positioning of the specimen during testing and did not represent an

effect of irradiation damage, although the possibility exists that irradiation increased the notch sensitivity of the metal and thus contributed to the premature failures.

The specimens, both irradiated and unirradiated, developed an elliptical shape during deformation because variations in sheath thickness produced higher stresses at the thinner sections and caused the deformation to be localized in these regions.

The mechanical burst tests showed that there was sufficient ductility in the irradiated sheath to withstand sheath strains produced by internal gas pressure buildup and by differential thermal expansion of the oxide core and the sheath.

CONCLUSIONS

The results of these tests indicate that large diameter tubular elements should not fail by either sheath rupture or weld separation due to irradiation embrittlement. In this event, calculations⁽¹⁴⁾ have shown that the limiting stress should be that stress required to cause sheath collapse. The tests also showed that the irradiation exposures, up to approximately 10^{20} fast nvt, had no noticeable effect on the sheath ductility, as measured by mechanical burst tests.

These conclusions would be invalid, however, if severe hydriding, such as was previously observed in the SPRO test series⁽¹⁾, were present.

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