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PHYSICAL AND MECHANICAL PROPERTIES

OF ZIRCALOY 2 AND 4

D. B. Scott

Materials and Processes Development

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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Abstract

A literature search was made to find available properties of Zircaloy tubing of importance to the design of fuel elements. A series of laboratory tests was conducted to obtain those properties not available in the existing literature but required for design purposes. The following properties were determined on representative Zircaloy-4 fuel cladding and are presented as a function of temperature.

- 1) Coefficient of thermal expansion, from 70°F to 1850°F in the longitudinal direction, from 70°F to 1200°F in the diametrical direction
- 2) Thermal conductivity, from 70°F to 1450°F
- 3) Specific heat, from 70°F to 1850°F
- 4) Elastic moduli, from 70°F to 1400°F
- 5) Poisson's Ratio, from 70°F to 750°F
- 6) Longitudinal tensile properties, from 70°F to 1400°F
- 7) Longitudinal tensile properties for transient temperature conditions, from 950°F to 1350°F
- 8) Compressive strength and modulus, from 70°F to 1050°F
- 9) Transverse tensile properties, from 70°F to 800°F

Introduction

Zircaloy-2 and Zircaloy-4 are alloys of sponge zirconium, tin, iron, chromium and nickel. They are attractive for use in pressurized and boiling water reactors because of low nuclear cross section, excellent corrosion resistance and structural stability at reactor operating temperatures. They have sufficiently good mechanical properties for use both as a structural material and as a fuel cladding material. However, as the design temperatures have increased, the necessity for knowing higher temperature properties has grown. Of specific importance are the following mechanical and physical properties:

- 1) Short time strength and ductility
- 2) Long time strength and ductility
- 3) Physical properties such as specific heat, coefficient of thermal expansion, Poisson's ratio and thermal conductivity

The purpose of this program* was to assemble information primarily for engineering design on the physical and mechanical properties of Zircaloy-2 and Zircaloy-4. Extensive use was made of the published literature and where published information was not available, tests were initiated to determine the necessary properties. This lack of information was particularly true of Zircaloy-4 tubing for high temperature mechanical properties and was needed both for conventional design purposes and for safety reasons such as a loss of water accident. The data are assembled and as much as possible expressed graphically.

Temperature has a pronounced effect on metal properties. Although the nominal coolant temperatures of water-cooled reactors are on the order of 600°F, the cladding operates at higher temperatures. In addition, the possibility of accidents requires knowledge at

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significantly greater temperatures. As a result, physical properties have been determined for temperatures higher than that of the primary coolant and for short term strength tests to 1400°F.

II. Chemical Composition

Table I Chemical Composition

<u>Alloying Agents</u>	<u>Zircaloy 2</u>	<u>Zircaloy 4</u>
Tin	1.20 to 1.70%	1.20 to 1.70%
Iron	0.07 to 0.20%	0.18 to 0.24%
Chromium	0.05 to 0.15%	0.07 to 0.13%
Nickel	0.03 to 0.08%	-----
Total Iron + Chromium + Nickel	0.18 to 0.38%	0.28 to 0.38%

Table II ASTM Maximum Allowable Impurities in PPM

Aluminum	75
Boron	0.5
Cadmium	0.5
Carbon	270
Chlorine	20
Cobalt	20
Copper	50
Hafnium	200
Hydrogen	25
Lead	130
Manganese	50
Nickel	70 ppm in Zircaloy 4, alloying agent in Zircaloy 2
Nitrogen	80
Silicon	200 ppm for Zircaloy 2, 120 ppm for Zircaloy 4
Titanium	50
Tungsten	100
Uranium	3.5

III. Allotropic Transformation

Zircaloy 2 and Zircaloy 4 are allotropic and will undergo a phase transformation from the room temperature or close packed hexagonal (CPH) phase to an elevated temperature or beta phase (BCC) body-centered cubic, at the following temperatures^{/1}.

Heating: 1499 to 1526°F (alpha to alpha + beta); 1418 to 1823°F (alpha + beta to complete beta structure)

Cooling: 1706 to 1760°F (beta to alpha + beta); 1418 to 1445°F (alpha + beta to complete alpha structure)

In spite of this allotropic change, Zircaloy cannot be heat treated to increase mechanical properties. Cold working, however, is effective in increasing yield, tensile and creep strengths.

IV. Physical Properties

A. Specific Heat

1. Specific heats for Zircaloy-2 and nickel-free Zircaloy 2^{/2}

Table III Specific Heats of Zircaloy-2

<u>Alloy</u>	<u>Temperature, °F</u>	<u>Specific Heat Constant, BTU/#°F</u>
Zircaloy-2	32°-1171°	$0.06805 + 2.3872 \times 10^{-5} T$
	1171°-1495°	$0.08589 + 2.3872 \times 10^{-5} T$
	1782°-1922°	$0.08548 + 2.3872 \times 10^{-5} T$
Nickel Free		
Zircaloy-2	32°-1062°	$0.06880 + 2.0726 \times 10^{-5} T$
	1112°-1495°	$0.08571 + 2.0726 \times 10^{-5} T$
	1782°-1922°	$0.08547 + 2.0726 \times 10^{-5} T$

Both Zircaloy-2 and nickel-free Zircaloy-2 undergo an alpha to alpha plus beta transformation that begins at about 1495°F and continues to about 1782°F. An additional break of .68 BTU/# was noted for Zircaloy-2 at about 1171°F and a break of 0.63 BTU/# was noted for nickel-free Zircaloy-2 between 1060° and 1110°F. Both breaks were thought to be the result of a change in the zirconium-tin solubility. A graph is shown in Figure 1.

Heat contents of Zircaloy-4 were determined by the drop method utilizing an isothermal water calorimeter. The instrument consists of a large Dewar flask containing 12 liters of water, a stirring apparatus, a sensitive thermometer and a copper specimen container. In use, the sample with an attached thermocouple is heated above the testing temperature and then rapidly transferred to the copper specimen container. The stirring apparatus keeps the water circulating and the heat content determined from the corresponding rise in water temperature. A copper standard was encapsulated in vycor as was the Zircaloy. By this means, the effect of the vycor was negated and the heat content of the Zircaloy-4 was determined. The specific heat was the heat content divided by temperature difference and is shown in Figure 2. For best accuracy in measuring the heat content of metals which undergo phase changes, the adiabatic method should be used. However, at the time of test, an adiabatic calorimeter such as the ice calorimeter was not available. Since the specific heat for metals which do not undergo phase changes agrees within 5% for both types of calorimeters (isothermal and adiabatic), it is believed that these results are accurate to about 1050°F. Above this temperature, the zirconium-tin solubility changes and the results are subject to error. This isothermal method was also insensitive to the alpha to beta transformations, thus usage of this graph above 1050°F is questionable.

B. Thermal Conductivity

Thermal conductivity of Zircaloy-2 and nickel-free Zircaloy-2 are given below: 3

INSTANTANEOUS SPECIFIC HEAT OF ZIRCALOY-2 AND
LOW NICKEL ZIRCALOY-2

Figure 1

HEAT CONTENT OF ZIRCALOY-4 86°F TO 1970°F -
DETERMINED BY THE DROP METHOD, WATER CALORIMETER

Figure 2

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Table IV Thermal Conductivity of Zircaloy-2

BTU/Hr-°F-Ft

<u>Temperature, °F</u>	<u>Zircaloy-2</u>	<u>Nickel-free Zircaloy-2</u>
212	7.74	7.86
392	8.38	8.27
572	9.02	8.79
752	9.83	9.48
932	10.64	10.40
1112	11.50	11.62
1292	12.43	13.01
1472	13.35	14.57

Thermal conductivity of Zircaloy-4 has been determined as part of this program by the longitudinal heat flow method. In this method, the thermal conductivity is obtained by measuring the temperature gradients along the length of a specimen of unknown thermal conductivity and a comparison bar of known thermal conductivity and then comparing the results. An Inconel block is used for heating with the bar of Zircaloy-4 inserted into one side. The A nickel comparison bar is mounted on the other end of the Zircaloy and a water-heat sink attached to the free end of the A nickel. The entire assembly is insulated and the insulation heated to prevent heat loss. Thermocouples are mounted along the lengths of the specimen and the standard and the heat conductivity is then compared. The accuracy of this method has been established as within 5%. The results are shown in Figure 3 and a least squares equation of the results from 70°F to 1400°F is:

$$\text{BTU/Hr-}^{\circ}\text{F-Ft} = .00316T + 7.97$$

where T is °F

C. Thermal Expansion

Thermal expansion on rolled Zircaloy-2 plate between 25°C and 800°C may be expressed by the following equations:⁴

$$L_t = L_o (1 + 4.62 \times 10^{-6} T) \text{ Longitudinal direction to rolling}$$

$$L_t = L_o (1 + 8.71 \times 10^{-6} T) \text{ Normal direction to rolling}$$

$$L_t = L_o (1 + 6.85 \times 10^{-6} T) \text{ Transverse direction to rolling}$$

THERMAL CONDUCTIVITY OF ZIRCALOY 4 TUBING

Figure 3

where $T = T - 30^{\circ}\text{C}$

L_t = Length at temperature, inches

L_o = Original length, inches

The average coefficient of expansion of rolled Zircaloy-2 is as follows: 4

Table V Coefficient of Expansion of Zircaloy-2

<u>Direction to Rolling</u>	<u>Average Coefficient of Expansion, In/In ^oF</u>
Longitudinal	2.57×10^{-6}
Transverse	3.65×10^{-6}
Normal	4.84×10^{-6}

Thermal expansion of Zircaloy-4 tubing was determined as part of this program by means of a mechanical-electrical dilatometer. In this instrument, the change in specimen length is transformed into an electrical output which in turn is recorded on a calibrated chart along with the sample temperature. The sample is positioned inside a fused silica tube with an inner fused-silica rod in contact with the sample. The rod is connected to a Statham transducer which measures its motion. By means of these techniques, both of the longitudinal and diametrical coefficients of expansion on Zircaloy were determined and shown in Figures 4 and 5. Mean coefficients of expansion are shown in Figure 6.

D. Density

The density of Zircaloy-2 is 6.55 grams/cc or 0.237 pounds per cubic inch at room temperature. 5

Thermal Expansion of Zircaloy-4 Tubing in Axial Direction

THERMAL EXPANSION OF ZIRCALOY 4 TUBING IN RADIAL DIRECTION
ROOM TEMPERATURE TO 1110 $^{\circ}\text{F}$ SPECIMEN REINFORCED WITH ZIRCALOY
4 RINGS TO PREVENT COLLAPSE - SPECIMEN DEFORMED ABOVE 1110 $^{\circ}\text{F}$

MEAN COEFFICIENT OF THERMAL EXPANSION OF ZIRCALOY 4

Figure 6

E. Emissivity Values

Emissivity values are as follows: ^{/10}

Table VI Emissivity of Zircaloy-2

<u>Temperature °F</u>	<u>Spectral Emissivity</u>	<u>Hole in Tube Method</u>	<u>Wire Loop Method</u>
2192	0.43	0.21	0.22
2372	0.44	0.22	0.22
2552	0.44	0.23	0.23
2732	0.44	0.24	0.24
2912	0.45	0.25	0.25
3092	0.45	0.26	0.25
3182	0.46	0.26	0.26

F. Modulus of Elasticity

The dynamic modulus of elasticity ^{/4,7} for annealed Zircaloy-4 is shown in Figure 7.

Static modulus of Zircaloy-2 in a longitudinal direction are as follows (4):

75°F	13,800,000 psi
600°F	11,400,000 psi

The static modulus for Zircaloy-4 tubing in the 10% cold worked condition was determined in the longitudinal direction from room temperature to 1400°F. In this test, tubes were pulled using special extensometers to carefully record the stress and strain. The change in stress up to the proportional limit is then divided by the change in strain to the proportional limit. Results are shown in Figure 8.

Torsional modulus ^{/8} was determined as

$$G = 5.24 \pm 0.05 \times 10^6 \text{ psi at room temperature.}$$

DYNAMIC MODULUS OF ELASTICITY OF ZIRCALLOY 2 AS A FUNCTION OF TEMPERATURE

STATIC MODULUS OF ELASTICITY VERSUS TEMPERATURE

G. Poisson's Ratio

Poisson's Ratio ^{/9} up to 150°C (332°F) is:

Table VII Poisson's Ratio of Zircaloy-2

Annealed Zircaloy-2	27°C	0.368 - 0.380
	150°C	0.425 - 0.460
Cold Worked Zircaloy-2	27°C	0.382 - 0.406
	150°C	0.392 - 0.432

Additional tests were performed as part of this program to find Poisson's Ratio on Zircaloy-4 tubing from room temperature to 750°F. To obtain Poisson's Ratio four 90° strain gage rosettes were mounted 90° apart around the tube midway on its length. The rosettes were positioned so that one gage of each rosette was in the longitudinal direction and the other gage was in the circumferential direction. The specimen was then loaded in the universal testing machine and Poisson's Ratio calculated from the ratio of strain in the longitudinal direction divided by strain in the circumferential direction. The data are as follows:

Table VIII Poisson's Ratio of Zircaloy-4

<u>Temperature</u>	<u>Poisson's Ratio</u>
70°F	0.296
300°F	0.271
550°F	0.283
680°F	0.245
750°F	0.243

By means of the least squares, this can be written by the following equation:

$$\text{Poisson's Ratio} = 0.301 - 7.03 \times 10^{-5} T$$

where T is in °F

Poisson's Ratio based on the torsional modulus is 0.325 ± 0.015 at room temperature. ^{/8}

V. Mechanical Properties

A. Compression Properties

During this program, axial compression tests were run on Zircaloy-4 10% cold worked tubing from room temperature to 1050°F. Yield strength, proportional limit and compression modulus have been determined and are given in Figure 9. Ultimate compressive strengths could not be determined as the tube would bend rather than buckle.

B. Tensile Properties

Tensile properties are dependent on prior history and previous amount of cold work. Values of 0.2% offset yield and tensile strengths of annealed Zircaloy-2 as a function of temperature are shown in Figures 10 through 12.^{4,9,11} Figures 11 and 12 show the results of a study run at KAPL⁴ to show the correlation of temperature, rolling direction, and hydrogen on the tensile strength of annealed Zircaloy-2.

The salient features are discussed below:

- 1) Both yield and ultimate strengths decrease rapidly with increasing temperature with a plateau evident in the neighborhood of 600°F.
- 2) There is a pronounced effect of directionality on both strength and ductility.
- 3) The effect of hydrogen varies considerably depending on material conditions. Hydrogen (randomly oriented) up to 500 ppm has a moderate strengthening effect on unnotched specimens with both fine and coarse grains, irrespective of direction of rolling. The unnotched ductility may be reduced by as much as 50%, but in no case was it reduced to a value of less than 0.18 in/in strain (expressed as reduction in area). The effects of hydrogen decrease with increasing test temperature.

COMPRESSION PROPERTIES OF ZIRCALLOY-4 TUBING

Figure 9

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TENSILE PROPERTIES OF ANNEALED ZIRCALOY 2 AS A FUNCTION OF TEMPERATURE

Figure 10

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YIELD STRENGTH OF ANNEALED ZIRCALOY 2 AS A FUNCTION OF TEMPERATURE, ROLLING DIRECTION AND HYDROGEN CONTENT (RANDOM ORIENTATION) - REFERENCE 4

Figure 11

ULTIMATE TENSILE STRENGTH OF ANNEALED ZIRCALOY 2 AS A FUNCTION OF TEMPERATURE, ROLLING DIRECTION AND HYDROGEN CONTENT (RANDOM ORIENTATION) - REFERENCE 4

Figure 12

The effect of cold working is to increase the strength of Zircaloy as shown in the accompanying table.¹²

Table IX
Average Conventional Tensile Properties of Zircaloy-2
Containing 0, 10, 20, 40 and 70% Cold Work

All Tests at Room Temperature

% Cold Work and Direction	Strength x 10 ³ psi		Elongation %		% R. A.
	<u>0.2% Yield</u>	<u>Ultimate</u>	<u>Uniform</u>	<u>Total</u>	
Annealed					
Longitudinal	47.9	68.0	16.8	33.0	51
Transverse	54.4	63.1	12.4	34.4	55
10% Cold Work					
Longitudinal	73.4	81.6	2.3	11.3	46
Transverse	69.4	79.9	2.7	11.6	52
20% Cold Work					
Longitudinal	79.2	88.0	2.6	9.6	42
Transverse	73.0	83.9	2.5	9.3	52
40% Cold Work					
Longitudinal	86.0	96.3	3.0	8.7	39
Transverse	80.3	92.4	2.5	8.3	53
70% Cold Work					
Longitudinal	92.8	109.0	3.4	8.6	34
Transverse	85.6	104.0	3.6	7.1	45

As part of this program, elevated temperature tests from room temperature to 1400°F were run in the longitudinal direction on 10% cold worked Zircaloy-4 tubing using conventional methods. The results are shown graphically in Figures 13, 14 and 15. Transverse tensile tests were performed on tab specimens whose lengths were determined by the circumference of the tube. Specimens 1.2 inches by 0.5 inches cut from sections of tubing were flattened and machined into tensile specimens. The specimens were then tested at temperatures from room temperature to 800°F. Results are listed.

Figure 13

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ULTIMATE TENSILE STRENGTH

Figure 15
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Table X Transverse Tensile Tests of Zircaloy-4

<u>Test Temperature</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>
RT	77,150	88,400
300	52,300	63,100
500	44,450	51,600
600	43,050	49,000
680	41,850	45,450
750	37,600	44,850
800	36,900	41,550

Additional tests were run to duplicate a loss of water accident. The tubes were stabilized at 680°F and heated by passing a current through them. The temperature was then suddenly raised to between 950°F to 1350°F and the sample pulled. Generally, the sample was in actual test within two minutes after being stabilized at 680°F. At the location of plastic deformation, localized heating occurred because of reduction in specimen cross section. The specimen temperature at the reduced cross section increased very rapidly with continued loading and this section became much hotter than the rest of the test section. The localized heating effect should be considered when evaluating the data in the plastic range. These data are presented in Figure 16.

Internal pressure tests on 10% cold worked tubing have been run at various temperatures as part of this program. Results are as follows:

Table XI Burst Tests of Zircaloy-4

<u>Temperature</u>	<u>Internal Pressure Tests (Biaxial Stress)</u>	<u>Longitudinal Tensile Tests (Uniaxial Stress)</u>
RT	118,000	85,000
350°F	90,000	65,000
650°F	66,800	45,000
725°F	64,200	40,000

Figure 16

E. D. SK. 322141-B

Other tests run at KAPL^{/13} on annealed tubing have shown the following:

Table XII Burst Tests of Zircaloy-2

<u>Temperature</u>	<u>Internal Pressure Tests (Biaxial Stress)</u>	<u>Longitudinal Tensile Tests (Uniaxial Stress)</u>
RT	99,000	65,000
600°F	37,000	22,000
700°F	31,000	22,000

Little work has been performed on tangential tensile tests on tubing. Room temperature tangential yield stress on Zircaloy-4 tubing was determined as part of the CVTR program.^{/14} Results are as follows:

<u>Condition of Tubing</u>	<u>Longitudinal Yield</u>	<u>Tangential Yield</u>
Annealed	38,900	54,800
10-15% cold worked	66,100	83,500

Studies on the effect of anisotropy on rolled plate made at Oak Ridge^{/15} and Hanford^{/12} showed that anisotropy was affected significantly by the fabrication schedule and the penultimate and final anneals. In particular, increased cold rolling and annealing in the alpha range served to increase anisotropy. Various tubing vendors use different processes such as cold working in heavy increments and stress relieving to desired mechanical properties as opposed to a final 10% cold work. Since both methods of fabrication will affect anisotropy differently, every supplier of tubing will have to be evaluated independently.

C. Creep of Zircaloy

Creep properties of Zircaloy are also dependent on the amount of cold work. Creep rate data for 30% cold worked,^{/5} 15% cold worked,^{/16} and annealed^{/16} Zircaloy-2 are shown in Figures 17, 18 and 19. In addition to the above references, Mehan and Wiesinger^{/4} also performed creep and stress rupture tests. They made the following observations on fully annealed material:

CREEP CURVES OF ANNEALED ZIRCALOY-2

Figure 17

CREEP CURVES OF 15% COLD WORKED ZIRCALLOY-2

Figure 18

CREEP CURVES OF 30% COLD WORKED ZIRCALOY-2

- 1) In general, the creep strength in the direction transverse to rolling is lower than it is in the longitudinal direction. This was surprising in view of the higher yield strength in the transverse direction.
- 2) In both longitudinal and transverse directions, the creep behavior at 600°F is characterized by extremely low creep rates, typical of a strain aging material.
- 3) Zircaloy-2 did not exhibit a minimum creep rate. Mehan and Wiesinger suggested that curves should be cross plotted at constant stress to obtain "faired" strain-time curves and creep rates obtained from the derived curves.
- 4) The effect of 500 ppm hydrogen on the rupture strength and ductility of Zircaloy-2 was negligible.
- 5) The effect of fine grain size was to cause a small reduction in strength at 600°F.
- 6) A limited number of notch rupture tests performed revealed no long-term detrimental effects due to notches on rupture strengths. The notch strength ratio (ratio of notch strength to unnotched strength) is the same as the tensile tests which indicates that the Zircaloy-2 is notch sensitive to long-term as well as short-term loading conditions.

Stress required for various amounts of total deformation for Zircaloy-2 at 600°F and 800°F are shown in Figures 20 and 21.^{/4}

Additional creep tests for AECL^{/17} have shown that with increasing time at test, the creep rate has continued to decrease until tertiary creep is reached. It was estimated that tertiary creep begins at about 2% strain. Creep results are shown in Table XIII.

Tests by Hanford for the PRTR^{/18} have shown that for 15% cold worked Zircaloy-2, a design criteria of 1% creep strain limit at 550°F and 650°F, and 1½% at 750°F was appropriate because minimum creep rates occur at these strains independent of applied stress. These criteria were not valid for annealed Zircaloy as there was no uniquely predict-

STRESS REQUIRED FOR VARIOUS AMOUNTS OF TOTAL DEFORMATION FOR ANNEALED ZIRCALOY-2 TESTED LONGITUDINALLY TO THE ROLLING DIRECTION AT 600°F

Figure 20

STRESS REQUIRED FOR VARIOUS AMOUNTS OF TOTAL DEFORMATION FOR ANNEALED ZIRCALOY-2 TESTED LONGITUDINALLY TO THE ROLLING DIRECTION AT 800°F

Figure 21

able strain at which the "minimum" creep rate behavior of annealed Zircaloy-2 would occur due to strain-age-hardening and overaging, and such behavior must be taken into account in establishing design criteria.

The 15% cold worked condition was preferred to the annealed condition because the creep behavior at all test temperatures was regular and predictable and the strength was anywhere from one and one-half to two times stronger at elevated temperatures.

Additional tests on thermal cycling showed that on samples from rolled sheet, the creep rate was increased by an order of magnitude. On longitudinal samples from the PRTR pressure tubes, the thermal cycling was found to have little effect. This work was performed for Hanford by Battelle and data sheets from monthly progress reports show the creep rate to be steadily decreasing. /19,20,21,22 The data sheet from the last reference (22) is attached.

Creep rupture properties of internally pressurized annealed, Zircaloy-2 tubing was investigated by KAPL. /13 Results are attached.

Table XIII

Long Term Creep Tests on Zircaloy-2 for AECL¹⁷

Source of Material	Stress psi	Temp. °F	Time h	Creep Rate %/hour	Creep Strain %	Total Strain %
Annealed 1 hr. at 750°C	8000	550	8000	1.4×10^{-6}	.054	.104
"	13,500	550	9250	4×10^{-7}	.090	.313
"	13,500	550	17400	8×10^{-7}	.217	.434
"	18,500	570	10000	4.5×10^{-6}	.380	.710
13.1% CW	13,500	550	6900	0	.054	.146
"	13,500	550	16600	2×10^{-7}	.151	.181
"	20,000	550	3121	8×10^{-6}	.120	.340
25.5% CW	13,500	550	7700	4×10^{-6}	.060	.140
+ temper	13,500	550	8250	7×10^{-7}	.074	.201
"	13,500	500	16200	0	.085	.141
"	18,000	570	5400	5×10^{-6}	.070	.170
19.3% CW	16,500	570	4000	2×10^{-6}	.085	.350
+ 3 d at 750°F	16,500	570	3850	3.3×10^{-6}	.145	.525
"	18,000	570	4000	3.7×10^{-6}	.060	.345
"	19,400	570	7600	3×10^{-6}	.320	.755
"	25,000	570	3840	8×10^{-6}	.150	.520
"	13,500	550	2100	1×10^{-6}	.065	.175
"	13,500	550	2040	1.1×10^{-5}	.045	.165
"	13,500	550	1950	2.7×10^{-6}	.028	.136
"	16,500	570	400	-	.026	.168
"	16,500	570	1060	2.4×10^{-5}	.050	.210
"	16,500	570	910	1.9×10^{-5}	.041	.195
"	16,500	570	2550	1.3×10^{-5}	.062	.205
"	16,500	570	2450	1.1×10^{-5}	.072	.220
"	18,000	570	550	-	.030	.195
"	18,000	570	2240	2.1×10^{-5}	.082	.240
"	18,000	570	2380	6×10^{-6}	.050	.210
"	20,000	570	1920	8.3×10^{-6}	.060	.240
"	20,000	570	2220	1.4×10^{-5}	.075	.260
"	25,000	570	3250	7.5×10^{-6}	.115	.360

Table XIV

Current Status of Long-Term Creep Tests on Zircaloy-2 Sheet ^{/24}

Specimen	Temperature °F	Stress psi	Time in Progress hr	Total Deformation, per cent		Tentative Minimum Creep Rate, per cent per hr
				On Loading	At Present	
15 Per Cent Cold-Worked Material						
7-2-1	650	25,000	46,600 ^(a)	0.230	2.300	0.00003
7-4-3	750	12,500	44,200 ^(a)	0.134	3.380	0.00006
Annealed Material						
Zr-A-10	550	22,500	32,154 ^(b)	3.180	4.364	0.0000015
Zr-A-13	550	20,000	32,500 ^(a)	1.511	2.861	0.0000006
Zr-A-14	550	17,500	32,300 ^(a)	1.250	1.968	0.0000002
Zr-A-17	650	17,500	32,100	1.778	3.925	0.000060
Zr-A-25	650	15,000	30,800 ^(a)	0.971	1.715	0.000020
Zr-A-28	650	12,500	23,219 ^(b)	0.321	0.475	0.0000008
Zr-A-16	750	12,500	32,200	0.447	6.725	0.00007
Zr-A-21	750	10,000	31,100 ^(a)	0.113	2.980	0.00006
Zr-A-26	750	9,000	27,803 ^(b)	0.082	0.875	0.00002
Annealed Material - Temperature and Stress Cycled						
Zr-A-36	550	15,000	17,895 ^(b)	0.765	1.192	0.000005
Zr-A-31	550	12,500	21,340 ^(b)	0.170	0.567	0.000003
Zr-A-34	650	15,000	18,822 ^(b)	0.949	1.477	0.000020
Zr-A-32	650	12,500	21,182 ^(b)	0.265	0.776	0.000015
Zr-A-35	650	8,500	18,304 ^(b)	0.063	0.154	0.000004
Annealed PRTR Zircaloy-2 Pressure Tubing						
11-A5-5	450	20,000	11,900	0.242	0.636	0.000003
11-A5-6	450	15,000	4,400	0.046	0.274	0.000003
11-A5-1	550	20,000	18,300	0.444	0.691	0.000006
11-A5-4	550	15,000	15,130 ^(b)	0.187	0.328	0.000002
11-A5-3	550	12,500	16,150 ^(b)	0.129	0.197	0.0000006

(a) Test in progress but only occasional creep readings taken; total strain is estimated.

(b) Test discontinued, final test time.

Table XV

Rupture Conditions for Zircaloy-2 Thin Walled Tubes

<u>Test No.</u>	<u>Pressure History</u>	<u>Wall Thickness in.</u>	<u>Nominal Stress</u>		<u>Local Rupture Strain %</u>				<u>Time to Rupture</u>	<u>Test Temp.</u>
			<u>Axial</u>	<u>Tan.</u>	<u>Axial</u>	<u>Radial</u>	<u>Tan.</u>	<u>Eff.</u>		
1	Increasing	0.0093-0.0100	49,700	98,800	4	-25	21	27	~0.1	Room
2	Increasing	0.0113-0.0122	17,700	35,400	-11	-47	59	62	~0.1	600
3	Constant	0.0132-0.0139	17,200	34,400	-3	-55	58	66	1.8	600
4	Constant	0.0113-0.0121	17,800	35,600	-7	-63	70	77	149	600
5	Constant	0.0132-0.0140	16,750	33,500	-1	-50	51	58	312	600
6	Constant	0.0140-0.0160	15,200	30,400	Did not fail in 1300 hr.					600
7	Increasing	0.0087-0.0093	15,900	31,800	-2	-13	-15	16	~0.9	700
8	Constant	0.0084-0.0092	13,000	26,000	8	-21	13	21	26	700
9	Constant	0.0089-0.0098	12,000	24,000	-1	-26	27	31	3.4	700
10	Increasing	0.0141-0.0172	67,400	0	37	-18	-19	37	~0.1	Room
11	Increasing	0.0120-0.0164	22,700	0	55	-26	-30	56	~0.1	600
12	Increasing	0.0138-0.0167	23,600	0	40	-19	-21	40	~0.1	700

D. Fatigue Properties

Results of tests run on Zircaloy-2 tested in the longitudinal direction to rolling in low-cycle fatigue tests at a frequency of 10 cycles per minute are shown below. ^{/16}

Table XVI Fatigue Strength of Zircaloy-2

<u>Temp., °F</u>	<u>to Failure</u>	<u>Stress Range for Failure, psi</u>		<u>Fatigue Parameter</u>	
		<u>Unnotched</u>	<u>Notched</u>	<u>K_f</u>	<u>q</u>
RT	1 x 10 ³	118,000	87,000	1.36	0.05
RT	5 x 10 ³	92,000	61,000	1.51	0.07
RT	1 x 10 ⁴	83,000	52,500	1.58	0.08
RT	5 x 10 ⁴	66,000	38,000	1.74	0.1
RT	1 x 10 ⁵	62,000	35,000	1.77	0.11
600	1 x 10 ³	70,000	50,000	1.4	0.057
600	5 x 10 ³	54,000	37,000	1.46	0.065
600	1 x 10 ⁴	48,000	33,000	1.46	0.065
600	5 x 10 ⁴	40,000	29,000	1.38	0.055

$$\text{where } K_f = \frac{\text{stress for failure - unnotched}}{\text{stress for failure - notched}}$$

$$q = \text{notch sensitivity factor} = (K_f - 1) / (K_t - 1)$$

and K_t = theoretical stress concentration factor (taken as 8.0)

Graphs showing additional work are shown in Figures 22 and 23. ^{/23,24}

This work performed on annealed Zircaloy-2 was on both axial and bending types of tests at 600°F.

UNNOTCHED AND NOTCHED STRESS FATIGUE PROPERTIES OF VACUUM-MELTED ZIRCALOY-2 BASE-ANNEALED ROLLED PLATE SPECIMENS TESTED TRANSVERSE TO ROLLING DIRECTION. EACH PLOT POINT REPRESENTS ONE SPECIMEN TESTED

Figure 22

SUMMARY OF BENDING STRESS FATIGUE DATA OF ANNEALED ZIRCALOY-2 AT 600°F

E. Impact Properties

Impact tests on subsize Izod specimens of 0.030 inches show the following results: ^{/25}

Table XVII Impact Test Results on Zircaloy-2

<u>Material Condition</u>	<u>Specimen Orientation</u>	<u>Impact Energy (ft-lbs) at</u>			
		<u>Room Temp.</u>	<u>200 F</u>	<u>300 F</u>	<u>550°F</u>
Annealed	Transverse	3.6	4.7	5.7	5.8
Annealed	Longitudinal	2.1	2.5	2.9	4.0
As-extruded	Transverse	2.0	-	5.2	-
As-extruded	Longitudinal	2.1	-	3.6	-

The data shown are the average of three tests each.

Comparisons as to effect of size on the above samples at 300°F are as follows:

<u>Specimen Area</u>	<u>Charpy Impact Energy</u>
.031	4.3 ft-lbs
.062	8.3
.100	15.5

If the above data were extrapolated to full size specimens, the impact energy would be in the range of 20 to 25 ft-lbs.

Results on atmosphere melted Zircaloy-2 ^{/11} are as follows:

Table XVIII Impact Test Results on Zircaloy-2

<u>Test T Test Temp., °C</u>	<u>Quenched from Beta (1010°C), ft-lbs</u>	<u>Aged at 316°C in Oil, ft-lbs.</u>
-190	6	4
0	14	6
100	34	7
200	71	17
300	104	91

Howe²⁵ hydrided Zircaloy-2 by means of anodizing and formed hydride layers on .006 and .012 mm. These hydride layers had no noticeable effect on the impact properties as compared to non-hydrided specimens. Microstructures revealed the presence of cracks in the hydride layer. However, the cracks in the hydride layer did not propagate into the remainder of the specimen, but terminated at the hydride metal interface. Differences were noted as to whether the samples had been heated and slow-cooled to allow hydrides to form or whether the Zircaloy had been fast-cooled to retain hydrogen in solid solution. Graphs to show these effects are shown in Figures 24 and 25.

EFFECT OF A HYDRIDE LAYER ON THE IMPACT PROPERTIES OF STANDARD CHARPY SPECIMENS OF ZIRCALOY-2

EFFECT OF HYDRIDE LAYERS ON THE IMPACT PROPERTIES OF SUB-SIZE ZIRCALOY-2 SPECIMENS

6. Irradiation Behavior of Zircaloy

A. Tensile Properties

The effect of irradiation, generally, is to increase strength and decrease ductility. The amount of change depends on the temperature of test, temperature of irradiation, amount of irradiation, and degree of cold work in the sample. Tabulated results from various experimenters are given in the following tables.

It should be noted that little strengthening can be expected from neutron irradiation above 700°F. Howe^{/26,27} irradiated Zircaloy-2 at 536°F and 716°F and concurrently exposed duplicate samples to equivalent thermal histories. Room temperature tensile tests showed that irradiation damage is annealed out as fast as it forms at irradiation temperatures above 700°F. These tests also showed that time at temperature has as much effect on the mechanical properties as irradiation at temperatures above 700°F.

B. Creep Properties

In-pile creep on 20 percent cold worked Zircaloy-2 has been studied at Hanford Laboratories.^{/34,35} The effect of neutron irradiation on the creep of this material was not large. However, the data showed real differences between in-reactor and out-of-reactor creep.

An increased activation energy was determined which showed the basic creep process is altered during irradiation. The implication of this different activation energy indicates accurate prediction of in-reactor creep behavior from post-irradiation tests is not possible. Secondly, an increase in creep rate during reactor outage is additional evidence that creep processes are altered during irradiation.

Table XIX (Ref. 26)

Room Temperature Tensile Properties of Unirradiated and Irradiated Zircaloy-2

<u>Irradiation History</u>	<u>Condition</u>	<u>Prop. Limit</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Total % Elongation</u>	<u>Hardness Rockwell B</u>
Nonirradiated	Annealed	44,800	51,200	78,500	23.5	87.7
Nonirradiated (536°F)	Annealed	44,300	49,400	76,000	19.6	-
3.6×10^{19} n/cm ² (428°F)	Annealed	60,900	65,600	85,000	19.5	89.5
2.7×10^{20} n/cm ² (536°F)	Annealed	75,700	79,300	91,400	12.7	91.9
Nonirradiated	13.1% C.W.	84,100	88,100	92,900	14.0	90.1
Nonirradiated (536°F)	13.1% C.W.	70,500	74,500	84,300	12.3	-
3.6×10^{19} n/cm ² (428°F)	13.1% C.W.	85,800	90,500	96,700	10.2	93.2
2.7×10^{20} n/cm ²	13.1% C.W.	98,100	102,000	104,100	9.3	95.4
Nonirradiated	Tempered* 25.5% C.W.	72,600	77,100	92,500	15.5	91.2
Nonirradiated (536°F)	Tempered* 25.5% C.W.	70,000	76,000	90,000	13.0	-
3.6×10^{19} n/cm ² (428°F)	Tempered* 25.5% C.W.	83,700	88,100	99,000	11.6	94.2
2.7×10^{20} n/cm ² (536°F)	Tempered*	95,100	99,400	105,800	9.4	95.3

*Tempering was 15 minutes at 800°F. Should actually be considered a short stress relief anneal.

Table XX (Ref. 26)

Tensile Properties of Unirradiated and Irradiated Zircaloy-2 at 536°F

<u>Irradiation History</u>	<u>Condition</u>	<u>Prop. Limit</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Total % Elongation</u>
Nonirradiated	Annealed	18,400	21,900	40,300	29.0
Nonirradiated*	Annealed	21,400	24,300	38,500	21.0
2.7 x 10 ²⁰ n/cm ^{2**}	Annealed	43,300	43,300	46,100	14.4
Nonirradiated	13.1% C.W.	41,000	47,800	48,800	13.0
Nonirradiated*	13.1% C.W.	43,100	45,000	46,800	13.3
2.7 x 10 ²⁰ n/cm ^{2**}	13.1% C.W.	57,700	61,000	62,100	9.0
Nonirradiated	Tempered*** 25.5% C.W.	43,900	47,900	53,100	12.5
Nonirradiated*	Tempered*** 25.5% C.W.	45,100	48,100	52,200	12.7
2.7 x 10 ²⁰ n/cm ^{2**}	Tempered*** 25.5% C.W.	58,600	61,700	62,100	9.0

*Held at 536°F for thermal treatment comparison for duration of irradiation study.

**Irradiated at 536°F.

***Tempering was 15 minutes at 800°F. Should actually be considered a short stress relief anneal.

Table XXI (Ref. 27)

Room Temperature Tensile Properties of Unirradiated and Irradiated Zircaloy-2

<u>Irradiation History</u>	<u>Condition</u>	<u>Prop. Limit</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Total % Elongation</u>
Nonirradiated	Annealed	44,800	51,200	78,500	24
Nonirradiated*	Annealed	44,300	49,400	76,000	20
Nonirradiated**	Annealed	45,400	50,400	73,000	19
9.1×10^{19} n/cm ² ***	Annealed	67,000	72,000	87,000	13
3.6×10^{19} n/cm ²	Annealed	60,900	65,600	85,100	20
7.7×10^{19} n/cm ²	Annealed	63,300	66,600	86,100	16
2.7×10^{20} n/cm ²	Annealed	75,700	79,300	91,400	13
9.5×10^{19} n/cm ²	Annealed	49,400	55,800	76,400	18
Nonirradiated	13.1% C.W.	84,100	88,100	92,900	14
Nonirradiated (536°F)	13.1% C.W.	70,500	74,500	84,300	12
Nonirradiated (716°F)	13.1% C.W.	59,000	62,400	77,800	15
3.6×10^{19} n/cm ² (428°F)	13.1% C.W.	85,800	90,500	96,700	10
2.7×10^{20} n/cm ² (536°F)	13.1% C.W.	98,100	102,000	104,100	9
9.5×10^{19} n/cm ² (716°F)	13.1% C.W.	61,700	67,400	82,800	16
Nonirradiated	Tempered* 25.5% C.W.	72,600	77,100	92,500	16
Nonirradiated	Tempered* 25.5% C.W.	70,000	76,000	90,000	13
Nonirradiated	Tempered* 25.5% C.W.	62,400	65,700	81,800	11
3.6×10^{19} n/cm ² (428°F)	Tempered* 25.5% C.W.	83,700	88,100	99,000	12
2.7×10^{20} n/cm ² (536°F)	Tempered* 25.5% C.W.	95,100	99,400	105,800	9
9.5×10^{19} n/cm ² (716°F)	Tempered* 25.5% C.W.	62,600	67,800	84,400	15

*Tempering was 15 min. at 800 F. Should actually be considered a short stress relief. **Held at indicated Temperature.
 ***Irradiated at indicated temperature.

Table XXII (Ref. 28)

<u>Direction</u>	<u>Treatment</u>	<u>Test Temp.</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Total Elongation</u>
<u>As Received</u>					
Longitudinal	Held 504 hours at 550°F	77°F	81,600	93,500	13.5
Transverse			87,300	90,500	21.7
Longitudinal	A.R. Irradiated	77°F	91,400	105,400	12.0
Transverse	Irr. 527°F-4.1 x 10 ¹⁸ nvt		95,200	98,000	10.0
Longitudinal	A.R. Irradiated	77°F	94,600	101,900	10.4
Transverse	527°F-8.2 x 10 ¹⁸ nvt		94,300	101,300	7.8
Longitudinal	A.R. Irradiated	77°F	93,600	101,200	12.2
Transverse	506°F-8.1 x 10 ²⁰ nvt		88,500	91,300	18.4
<u>After Production Autoclaving</u>					
Longitudinal	Tested 36 hours at 750°F	77°F	75,700	91,900	15.3
Transverse			82,300	85,400	21.3
Longitudinal	36 hours at 750°F	77°F	60,400	93,700	14.3
Transverse	527°F-4.1 x 10 ¹⁸ nvt		89,700	91,700	14.0
Longitudinal	36 hours at 750°F	77°F	71,900	100,200	12.4
Transverse	527°F-8.2 x 10 ¹⁸ nvt		93,100	95,700	11.1
Longitudinal	36 hours at 750°F	77°F	98,700	107,600	12.7
Transverse	506°F-8.1 x 10 ²⁰ nvt		100,000	101,700	12.3
Longitudinal	36 hours in 750°F steam	608°F	48,700	54,200	16.9
Transverse			50,400	51,100	23.2
Longitudinal	36 hours at 750°F	608°F	48,000	51,000	11.2
Transverse	527°F-4.1 x 10 ¹⁸ nvt		50,000	50,000	13.7
Longitudinal	36 hours at 750°F	608°F	55,200	58,900	11.9
Transverse	527°F-8.2 x 10 ¹⁸ nvt		-	-	-
Longitudinal	36 hours at 750°F	608°F	63,300	68,900	10.0
Transverse	506°F-8.1 x 10 ²⁰ nvt		62,500	65,100	9.6

Table XXII (Ref. 28)
Continued

<u>Direction</u>	<u>Treatment</u>	<u>Test Temp.</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Total % Elongation</u>
<u>Recovery Annealed</u>					
Longitudinal	Annealed 1 hr. at 1400°F	77°F	69,700	83,000	18.8
Transverse			76,200	82,600	21.4
Longitudinal	Annealed 1 hr. at 1400°F	77°F	69,200	80,100	15.0
Transverse	527°F-4.1 x 10 ¹⁸ nvt		65,800	83,800	14.7
Longitudinal	Annealed 1 hr. at 1400°F	77°F	104,600	107,500	8.1
Transverse	506°F-8.1 x 10 ²⁰ nvt		94,700	96,400	16.5
Longitudinal	Annealed 1 hr. at 1400°F	608°F	41,500	43,400	21.9
Transverse	Control		33,000	33,200	35.0
Longitudinal	Annealed 1 hr. at 1400°F	608°F	35,100	43,800	18.1
Transverse	527°F-4.1 x 10 ¹⁸ nvt		39,700	41,400	17.5
Longitudinal	Annealed 1 hr. at 1400°F	608°F	-	-	-
Transverse	527°F-8.2 x 10 ¹⁸ nvt		43,200	50,700	13.1
Longitudinal	Annealed 1 hr. at 1400°F	608°F	61,700	62,800	8.5
Transverse	506°F-8.1 x 10 ²⁰ nvt		61,400	62,600	10.7
<u>Recrystallization Annealed</u>					
Longitudinal	Annealed 8 hrs at 1450°F then 36 hrs. at 750°F steam	77°F	52,600	70,400	17.0
Transverse			60,700	70,100	17.2
Longitudinal	Ditto-Irradiated	77°F	80,600	86,200	9.2
Transverse	506°F-8.1 x 10 ²⁰ nvt		87,900	88,300	10.9
Longitudinal	Annealed 8 hrs. at 1450°F	500°F	29,400	38,700	22.4
Transverse	Control		28,700	36,400	28.4
Longitudinal	Ditto-Irradiated	608°F	54,700	54,700	5.4
Transverse	506°F-8.1 x 10 ²⁰ nvt		52,300	52,300	9.3

Table XXIII (Refs. 29, 30)

Post-Irradiation Tensile Properties of Annealed Zircaloy-2

	<u>Tensile Test Temp.</u>	<u>Preirradiated</u>	<u>Irradiated 1 x 10²¹ nvt</u>	<u>Irradiated 6 x 10²¹ nvt</u>
Ultimate Tensile Strength	Room Temp.	68,600	81,500	95,900
	400°F	46,100	71,500	91,000
	600°F	34,600	61,200	73,200
0.2% Yield Strength	Room Temp.	44,300	78,900	93,800
	400°F	31,000	71,500	90,000
	600°F	22,400	61,200	73,200
Total Elong. %	Room Temp.	33.4	12.5	10.1
	400°F	34.9	14.7	11.6
	600°F	35.4	14.5	12.6
Uniform Elong. %	Room Temp.	16.0	2.1	1.3
	400°F	14.2	0.4	0
	600°F	11.7	0	0
Reduction in Area, %	Room Temp.	41.6	29.2	27.5
	400°F	53.3	42.0	39.5
	600°F	59.9	46.7	38.4

Table XXIV (Ref. 31)

Results of Tensile Tests of Irradiated Clad Test Temperature 650°F - Irradiation 545°F

<u>Sample</u>	<u>Material</u>	<u>Integrated Fast Flux</u>	<u>Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Uniform Elong., %</u>	<u>Total Elong., %</u>
Control	Zr-4	0	26,100	35,600	2.1	7.9
#1	Zr-4	2.1×10^{20}	36,600	46,100	1.0	3.8
Control	Zr-2	0	24,700	34,400	3.9	7.8
#1	Zr-2	0.9×10^{20}	29,000	37,100	2.7	9.0
#2	Zr-2	1.4×10^{20}	33,600	42,700	1.4	4.3
#3	Zr-2	2.1×10^{20}	41,500	45,900	0.7	4.6
#4	Zr-2	4.3×10^{20}	39,600	58,800	1.1	2.0

Results of 650°F Tensile Tests of
Clad Irradiated at 545°F

Table XXV (Ref. 32)

<u>Specimen</u>	<u>Fast Flux Exposure</u> <u>x 10²¹</u>	<u>0.2% Offset</u> <u>Yield Strength</u>	<u>Ultimate</u> <u>Tensile Strength</u>	<u>Elongation %</u>	
				<u>Uniform</u>	<u>Total</u>
Control - Zr-2	0	19,700	31,600	14.9	22.8
	0	19,300	30,800	13.7	26.2
Zircaloy-2	1.53	22,600	31,900	10.6	21.1
	1.53	64,200	64,500	0.21	1.5
	1.28	61,600	61,600	0.13	1.3
	1.28	57,000	58,100	0.30	1.8
	0.96	55,900	56,200	0.23	1.9
	0.96	61,700	62,000	0.21	1.4
	1.44	55,200	55,200	0.19	1.3
	1.21	59,700	59,700	0.20	1.6
	1.21	61,200	61,200	0.20	1.6
	0.74	44,400	56,600	0.80	2.3
	1.30	57,200	57,200	0.17	1.7
	1.30	66,000	66,500	0.26	2.1
	0.71	55,200	56,500	0.43	1.6
	0.71	55,200	56,500	0.43	1.6
Zircaloy-4	0.90	52,400	53,000	0.38	1.0
	0.90	56,300	58,500	0.44	2.3
	0.72	55,400	55,400	0.15	1.8
	0.72	53,000	53,000	0.14	1.8
	0.44	52,000	52,000	0.18	1.8
	0.44	57,100	57,100	0.19	1.9

Table XXVI (Ref. 32)

Results of Room Temperature Tensile Tests on Clad Irradiated at 545°F					
	Fast Flux Exposure x 10 ²¹	0.2% Offset Yield Strength	Ultimate Tensile Strength	Elongation % Uniform	Total
Control	0	48,900	70,200	11.2	17.9
Zircaloy-2	0	48,600	71,400	12.3	21.9
Zircaloy-2	1.42	104,000	107,400	0.38	2.0
	1.42	76,700	96,900	1.03	2.8
	1.38	58,700	98,700	2.80	5.1
	1.38	101,000	103,600	0.38	2.8
	0.96	91,400	98,200	0.50	2.1
	1.30	87,400	89,000	0.38	1.9
	1.30	72,000	92,400	1.00	4.1
	1.32	73,100	86,200	0.63	2.0
	1.32	--	92,300	--	-
	0.98	77,600	88,600	--	-
	0.98	77,600	90,900	0.75	4.6
	1.11	66,800	106,000	2.50	5.3
	1.11	69,500	106,300	2.00	5.3
	0.87	92,400	98,000	0.50	2.9
	0.87	78,600	100,000	1.10	5.1
Zircaloy-4	0.85	85,700	97,200	1.63	2.4
	0.85	--	99,300	--	-
	0.82	78,600	90,100	0.55	1.1
	0.82	--	94,000	--	-
	0.56	80,900	96,300	0.75	2.5
	0.56	76,400	93,000	0.88	4.3

Table XXVII (Ref. 33)

Effect of Irradiation at 200°F on Tensile Properties of Zircaloy-4

<u>Condition of Exposure</u>	<u>Test Temp.</u>	<u>0.2% Offset Yield Strength</u>	<u>Ultimate Tensile Strength</u>	<u>Elongation %</u> <u>Uniform</u>	<u>Total</u>	<u>Reduction of Area, %</u>
Zr-4, Annealed, Non-Irradiated	Room	48,100	73,300	15.0	22.9	41.5
Zr-4, Annealed, 1 x 10 ²¹	Room	79,600	90,000	3.7	11.4	36.6
Zr-4, Annealed, 1.4 x 10 ²¹	Room	80,600	90,000	3.6	11.4	32.3
Zr-4, Annealed, Non-Irradiated	300°F	35,100	56,500	13.0	23.9	42.1
Zr-4, Annealed, 1 x 10 ²¹	300°F	67,100	70,800	2.8	12.0	39.1
Zr-4, Annealed, 1.4 x 10 ²¹	300°F	69,000	72,200	2.2	11.6	39.9
Zr-4, Annealed, 2.5 x 10 ²¹	300°F	74,600	76,000	1.1	9.3	37.2
Zr-4, Annealed, Nonirradiated	550°F	21,200	40,600	15.7	27.0	48.0
Zr-4, Annealed, 1.0 x 10 ²¹	550°F	49,200	49,200	0.6	13.7	50.9
Zr-4, Annealed, 1.4 x 10 ²¹	550°F	48,800	49,100	0.6	12.9	45.1
Zr-4, Annealed, 2.5 x 10 ²¹	550°F	59,000	59,000	0.2	10.0	42.4
Zr-4, As-extruded, Nonirradiated	300°F	53,800	73,700	9.3	21.4	50.5
Zr-4, As-extruded, 1 x 10 ²¹	300°F	82,100	87,400	1.5	11.2	49.2
Zr-4, As-extruded, 1.4 x 10 ²¹	300°F	85,800	88,000	0.6	9.4	49.7
Zr-4, As-extruded, 5 x 10 ²¹	300°F	93,800	95,000	0.7	8.8	46.3

During neutron irradiation, steady state creep can be expressed by the following equation^{/34,35}:

$$\epsilon = 2.5 \times 10^{20} \exp 5.31 \times 10^{-4} \sigma_{\text{exp}} - \frac{90,000}{RT}$$

where σ = stress in psi
T = temperature, absolute
 ϵ = creep rate
R = gas constant

A family of curves is presented in Figure 26 to show plastic creep strain as a function of Dorn's coefficient which includes both time and temperature. The stresses shown vary from 20,000 to 35,000 psi.

PLASTIC CREEP STRAIN, PERCENT

TOTAL CREEP STRAIN MEASURED IN REACTOR FOR 20% COLD
WORKED ZIRCALOY 2 - REFERENCE 34, 35

Figure 26

VII. Discussion and Recommendations

Various physical and mechanical properties of Zircaloy-2 and Zircaloy-4 have been presented suitable for design. Finished tubing was used as much as possible to determine these properties. Thus, if any anisotropy were present, it would be taken into account. Care should be exercised in using these data. The user of these data should insure that the fabrication parameters used in making these tubes give comparable results to other fabrication parameters and heat treatments.

Not included in this study were the effects of hydrides and their orientation on the mechanical properties of Zircaloy. It is known that applied tensile stress during hydriding will cause precipitation of hydrides perpendicular to the direction of stress. The interaction between hydriding and mechanical properties was beyond the scope of this search and was not examined.

From the reports of Howe^{/26,27} it is apparent that creep will occur on Zircaloy cladding exposed to irradiation above 700°F. Biaxial creep was beyond the scope of this report.

There has been a dearth of information for Zircaloy irradiated in the cold worked condition and at elevated temperatures. The tests of Howe^{/26,27} appears to be the only work performed above 600°F. Additional work in this area is recommended.

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