Zr	
1.5	Sn

ZIRCALOY-2

1. GENERAL

This alloy is used for reactor fuel cladding because of its excellent corrosion resistance, its structural stability at reactor operating temperatures, and its low thermal neutron absorption cross section. It is available in form of strip, wire, forgings and tubing.

1.01 Commercial Designation. Zircaloy-2.

1.02 Alternate Designations. None.

1.03 Specifications. Table 1.03.

TABLE 1.03

AMS	Form	Military
-	Strip	MIL-Z-19859A

1.04 Composition. Table 1.04.

TABLE 1.04

Source	(1)					
	Percent		Impurities			
	Min	Max	Element	ppm*	Element	ppm*
Tin	1.20	1.70	Aluminum	75	Manganese	50
Iron	0.07	0.20	Boron	0.5	Molybdenum	-
Chromium	0.05	0.15	Cadmium	0.5	Nitrogen	-
Nickel	0.03	0.08	Carbon	270	Average	80
Iron	-	-	Cobalt	20	Individual	100
+ Chromium	-	-	Copper	50	Silicon	120
+ Nickel	0.18	0.38	Hafnium	200	Titanium	50
Zirconium	Balance		Lead	130	Tungsten	100
			Magnesium	20	Vanadium	-
					Uranium	3.5
					U 235	0.025

* Maximum ppm, weight basis.

1.05 Heat Treatment

1.051 Anneal.

1.0511 1550 F, 15 min to 1 hr, in vacuum, air cool or furnace cool.

1.0512 "Base anneal". 1380 F, 20 hr in vacuum, furnace cool.

1.052 Solution treat. 1850 F, 1 hr, water quench.

1.053 Age solution treated condition, 1300 F.

1.06 Hardenability. Hardening of this alloy is obtained primarily by cold work, although quenching from the beta range, about 1850 F, also increases the strength. Effect of cold reduction on tensile properties, Fig. 1.06.

1.061 Effect of cold work, hot work and size on hardness of plate, Table 1.061.

TABLE 1.061*

Source	(16, p.3)						
Alloy	Zr-1.5Sn						
Form	Plate						
Condition							
Size - in	0.50	0.25	0.05				
Hot W %	50	75	95	95	95	95	95
C W %	-	-	0	10	25	40	60
Rolling Plane DPH	183	188	193	228	231	243	256
L, cross-sect DPH	168	-	182	203	216	215	224

* Avg. of 5 readings for 20 kg load, 15 sec.

1.07 Forms and Conditions Available

1.071 Alloy is available in the full commercial range of sizes for sheet, strip, plate, bar, tubing and ingots.

1.08 Melting and Casting Practice. Consumable electrode double vacuum melt.

1.09 Special Considerations

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range. Pure zirconium, 3360 to 3370 F.

2.012 Phase changes. Alloy is subject to transformation from beta to alpha on cooling. Begin 1705 to 1760 F, end 1420 to 1445 F. Begin of transformation on heating 1500 to 1525 F, end 1785 to 1820 F.

2.013 Thermal conductivity, Fig. 2.013.

2.014 Thermal expansion, 3.6×10^3 ksi, in per in per F, (5).

2.0141 Room temperature to 1290 F, 3.6×10^{-6} in per in per F.

2.0142 Thermal expansion for pure zirconium, Fig. 2.0142.

2.015 Specific heat. Pure zirconium, 0.067 Btu per (lb F). Zircaloy-2, estimated, 0.077 Btu per (lb F).

2.02 Other Physical Properties

2.021 Density. 0.237 lb per cu in. 6.55 gr per cu cm, (5).

2.022 Electrical resistivity, Fig. 2.022, (5).

2.023 Magnetic properties.

2.03 Chemical Properties

2.031 Corrosion resistance.

2.0311 In general the corrosion resistance of Zircaloy-2 is similar to that of zirconium. It has been found that the corrosion rate decreases with increasing total iron, nickel and chromium content.

2.0312 Pure zirconium has good resistance to strong alkalies and molten caustic, as well as to liquid metals such as sodium, potassium and sodium-potassium alloy. It is extremely resistant to most acids except hydrofluoric and hot concentrated sulfuric or phosphoric. Severe embrittling attack is caused by ferric and cupric chlorides.

2.0313 Zircaloy-2 has good resistance to liquid sodium, potassium and sodium-potassium alloys, provided that these metals are low in oxygen.

2.0314 The corrosion resistance of Zircaloy-2 in water and steam up to 850 F is better than that of commercially pure zirconium, provided that its nitrogen content does not exceed 0.01 percent. Specifications for Zircaloy-2 require that strip specimens exposed to 1500 psi steam for 14 days shall show the following: a) a continuous black lustrous temper film, b) freedom from corrosion products, c) freedom from stains, cracks, streaks and blisters, and, d) a weight gain of 0.18 to 0.38 mg per sq cm. Weight gain due to corrosion in water and steam at elevated temperatures, Fig. 2.0314.

2.0315 Zircaloy-2 clad uranium can be stretched in water by about 5 percent and in molten sodium by about 2 percent before the cladding cracks.

2.032 Oxidation resistance. Pure zirconium will absorb and hold in solution large quantities of oxygen, nitrogen and hydrogen at relatively low temperatures, beginning below 390 F, 750 F and 390 F respectively. The rates of reaction increase with increasing temperature. Nitrogen cannot be removed. Some oxygen can be removed by heating in molten calcium. Hydrogen can be eliminated by heating above 1470 F in vacuum.

2.04 Nuclear Properties

2.041 Thermal neutron absorption cross section of zirconium is 0.18, and of Zircaloy-2, 0.22 to 0.24, (5).

2.042 Irradiation effects on Zircaloy-2 are similar to those on commercially pure Zirconium.

2.043 The effects of fast neutron irradiation on mechanical properties of zirconium are greatest for the annealed condition and decrease with increasing cold work. The different mechanical characteristics are changed as follows.

2.0431 The hardness of the annealed condition may increase by 20 to 40 percent, that of cold worked material by 5 to 15 percent. Annealing at 660 F eliminates this effect.

2.0432 The increase in tensile strength may be 10 to 15 percent. The yield strength of the annealed condition has been found to be increased by up to 60 percent of its value, that of material cold rolled 20 percent by 18 percent and that of material cold rolled 50 percent by 13 percent.

2.0433 The elongation may be reduced by about 35 percent, for both annealed and cold worked material. Reduction in area also appears to be reduced, according to limited data.

2.0434 The impact strength was found to be substantially unchanged after exposures of 3 to 6×10^9 nvt at tempera-

Zr
1.5 Sn

ZIRCALOY-2

tures below 240 F.

2.0435 The fatigue strength appeared to be not affected, according to limited data.

2.0436 Creep was considerably slowed down by exposure to 3×10^{12} nvt at 500 F, but little affected by exposure to 6×10^{12} nvt at 930 F.

2.0437 The microstructure was observed to remain the same after exposure to 10^{19} nvt at 135 to 200 F. Evidence of recrystallization, associated with twinning, was present, when exposed to 2×10^{20} nvt at 360 to 465 F.

2.045 Physical properties of commercially pure zirconium are affected by irradiation as follows.

2.0451 Density does not change significantly.

2.0452 The electrical resistivity at -320 F is increased by about 25 percent by exposure to 10^{19} nvt. Annealing at 750 to 1100 F causes nearly complete recovery.

2.046 Zircaloy-2 in the annealed condition showed effects of irradiation on the tensile tests similar to, but less pronounced than those of commercially pure zirconium. The impact strength of material containing 0.002 percent (20 ppm) hydrogen increased by irradiation at 300 F, while material containing 0.010 percent exhibited embrittlement.

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Military specified mechanical properties, Table 3.011.

TABLE 3.011

Source		(1)
Alloy		Zr-1.5Sn
Form		Strip
Condition		Annealed
F_{tu}, min -ksi	L	31*
	T	29*
F_{ty}, min -ksi	L	15*
	T	18.4*
e(2 in), min-percent	L	24*
	T	35*
Hardness		
RB		98
R15T		92
R30T		80
R15N		68
BHN (500 kg)		158
BHN (3000 kg)		200

* Tested at 600 F

3.02 Mechanical Properties at Room Temperature. See 3.03 also.

3.03 Mechanical Properties at Various Temperatures

3.031 Short time tension properties.

3.0311 Effect of test temperature on tensile properties of annealed strip, Fig. 3.0311.

3.0312 Effect of test temperature on tensile properties of sheet in various conditions, Fig. 3.0312.

3.0313 Effect of low and elevated temperature on hot and cold rolled sheet, Fig. 3.0313.

3.0314 Effect of true strain on nominal tensile strength of sheet, Fig. 3.0314.

3.0315 True strain curves at 482 F for cold rolled sheet, Fig. 3.0315.

3.0316 Effect of cold work on ductility of sheet, Fig. 3.0316.

3.0317 Effect of cold work on tensile properties of sheet, Fig. 3.0317.

3.032 Short time properties other than tension.

3.0321 Effect of test temperature on hardness, Fig. 3.0321.

3.0322 Compression properties, Table 3.0322.

TABLE 3.0322

Source	(1)			
Alloy	Zr-1.5Sn			
Condition	As Rolled		Base Annealed	
Test Temp - F	RT	500	RT	500
F_{cu}, * typ - ksi	184	183	115.2	110.7

* Averages of vacuum and inert atmosphere arc melted Zircaloy-2 at 25 percent strain.

3.0323 Effect of test temperature on impact strength of alloy in various conditions, Fig. 3.0323.

3.033 Static stress concentration effects.

3.04 Creep and Creep Rupture Properties

3.041 Creep rupture curves at 300 to 932 F for annealed and cold worked sheet, Fig. 3.041.

3.042 Stress for 1 percent total deformation at 932 F in 1000 hr, 5 ksi and 10,000 hr, 2 ksi.

3.05 Fatigue Properties

3.051 Fatigue strength at various temperatures, Table 3.051.

TABLE 3.051

Source	(2)									
Alloy	Zr-15Sn									
Condition	Temp F	Method	Stress Ratio		Stress Concentration	Fatigue Strength - ksi at Cycles				
			A	R		10^4	10^5	10^6	10^7	10^8
Annealed	RT	-	-	-	Smooth	-	-	-	-	37.3
Base ann	600	-	-	-	Smooth	-	-	-	-	28.0
					Notched	-	-	-	-	9
ST + age	600	-	-	-	Smooth	-	-	-	-	27.5
					Notched	-	-	-	-	11
Degassed	500	Tension			Smooth	-	24	20	-	-
500 ppm	500	- tension	0.82	0.1	Notched	-	-	19	-	-
H_2					Notched	-	-	19	19	-
Source	(4)									
Condition	Temp F	Method	Stress Ratio		Stress Concentration	Fatigue Strength - ksi at Cycles				
			A	R		10^4	10^5	10^6	10^7	10^8
Base ann	600	-	-	-	Smooth	35	32	29.5	29	28.5
					Notched K = 3.5	32.5	22 -	13	10	9
Anneal	600	-	-	-	Smooth	-	36.5	29.5	27.5	27
					Notched K = 3.5	37	24	15.5	11.5	11

3.052 Strain cycling curves for bar, Fig. 3.052.

3.06 Elastic Properties
3.061 Modulus of elasticity of Zircaloy-2 and Zirconium at room and elevated temperatures, Fig. 3.061.
3.062 Modulus of rigidity. Hot rolled or base annealed 5,240 ksi.
3.063 Poisson's ratio. 0.37 to 0.41.

4. FABRICATION

4.01 Forming and Casting
4.011 General. Zircaloy-2 can be formed by all common methods, if special precautions are taken and careful attention is paid to details of suitable techniques.
4.012 Forging. Starting temperature 1700 F maximum, finishing temperature 750 F minimum. Forging of cast material should begin with small reductions. The oxide layer, which is formed on heating and forging, acts as a lubricant. Finish working should be within the alpha range since finishing in the beta or alpha + beta field may result in stringers of intermetallic compounds. Forged material is usually annealed at 1450 to 1500 F.

4.02 Machining
4.021 General. Alloy is adaptable to all standard machining operations. Since turnings present a fire hazard, cutting tools should be kept sharp, and a lubricating coolant is recommended.
4.022 Grinding should be done with extreme care, preferably on an endless belt. Zirconium particles have a tendency to reweld to the ground surface, causing reduction in corrosion resistance.

4.03 Welding. Ductile welds can be made in thin sheets by using the inert gas shielded tungsten arc or consumable electrode methods with direct current. Welding of thicker sections should be done in a gas tight box with an inert gas atmosphere. Any pick up of nitrogen should be prevented to avoid reduced corrosion resistance.

4.04 Heating and Heat Treating. Should be done in a vacuum or inert gas atmosphere.

4.05 Surface Treating. Scale removal from forged material can be effected only by grinding, shot blasting or other mechanical processes, followed by pickling in sulfuric acid and in nitric-hydrofluoric acid solution.

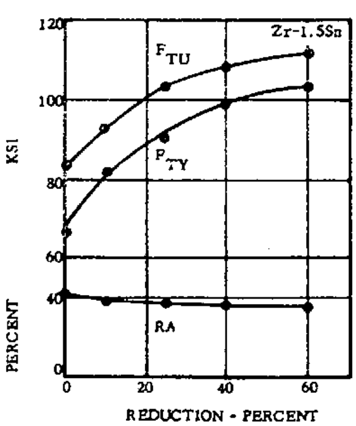

FIG. 1.06 EFFECT OF COLD REDUCTION ON TENSILE PROPERTIES (7)

Zr
1.5 Sn

ZIRCALOY-2

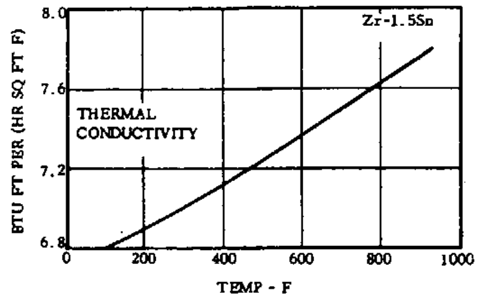

FIG. 2.013 THERMAL CONDUCTIVITY (1)

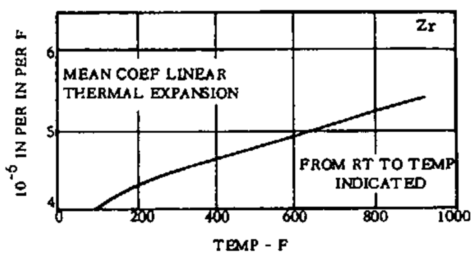

FIG. 2.0142 THERMAL EXPANSION FOR PURE ZIRCONIUM (7)

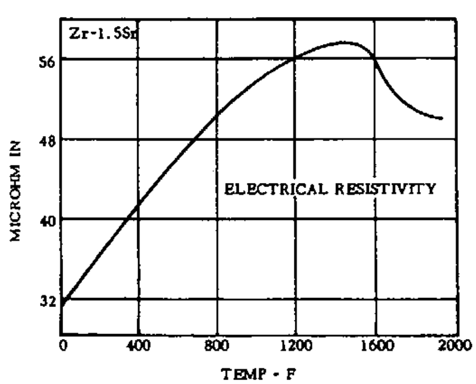

FIG. 2.022 ELECTRICAL RESISTIVITY (3)

Zr
1.5 Sn

ZIRCALOY-2

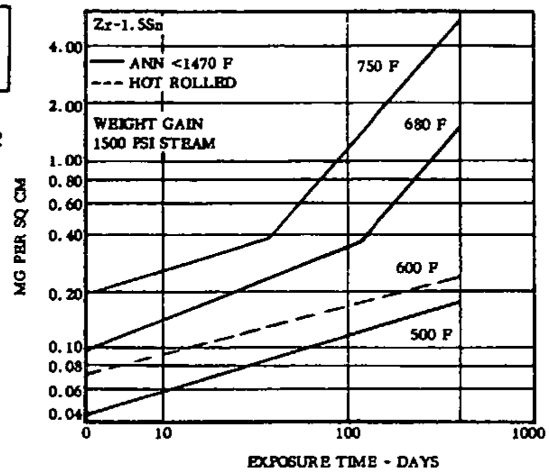

FIG. 2.0314 WEIGHT GAIN DUE TO CORROSION IN WATER AND STEAM AT ELEVATED TEMPERATURES (1)

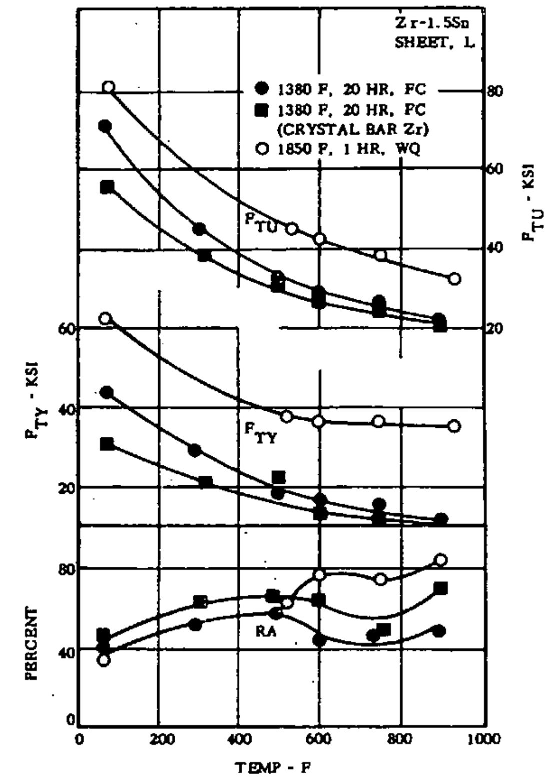

FIG. 3.0312 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET IN VARIOUS CONDITIONS (7)

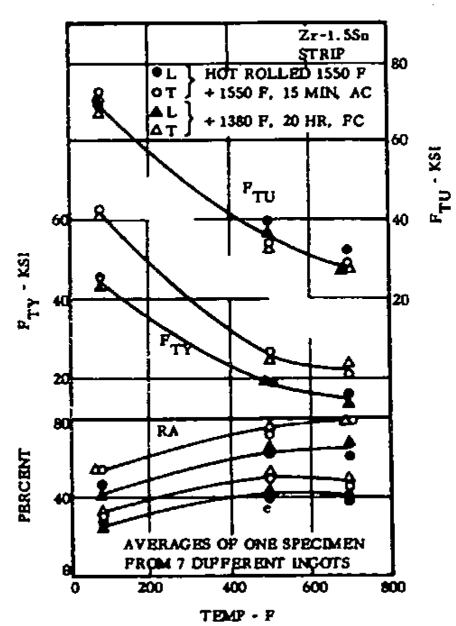

FIG. 3.0311 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED STRIP (1)

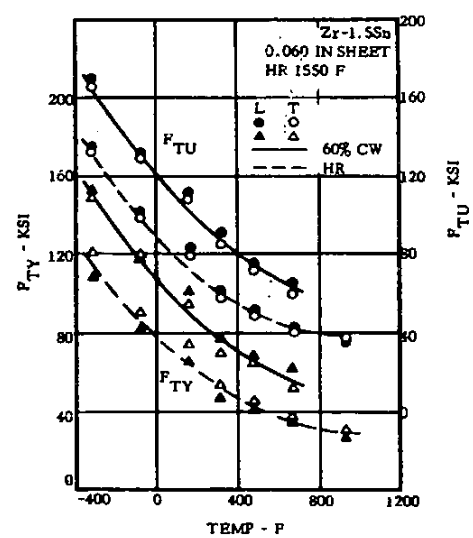

FIG. 3.0313 EFFECT OF LOW AND ELEVATED TEMPERATURE ON HOT AND COLD ROLLED SHEET (6, p.3)

Zr
1.5 Sn

ZIRCALOY-2

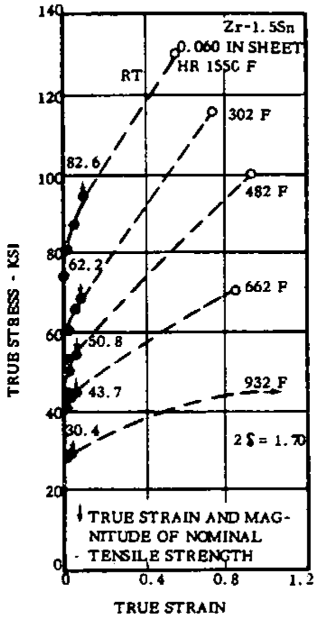

FIG. 3.0314 EFFECT OF TRUE STRAIN ON NOMINAL TENSILE STRENGTH OF SHEET (6, p. 7)

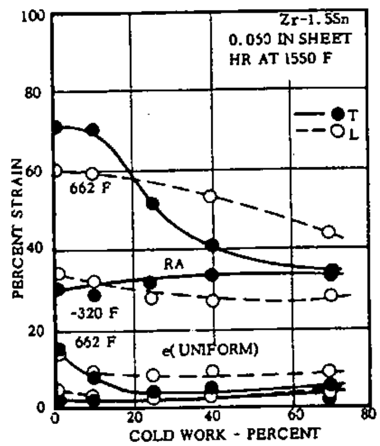

FIG. 3.0316 EFFECT OF COLD WORK ON DUCTILITY OF SHEET (6, p. 5)

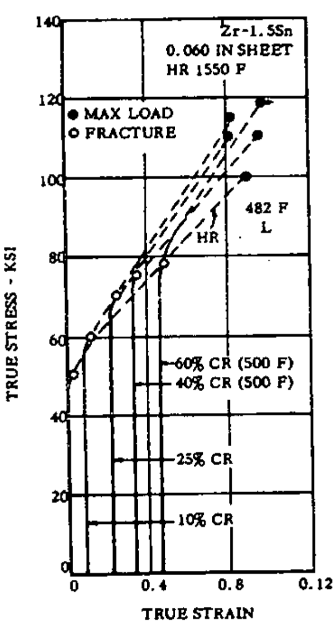

FIG. 3.0315 TRUE STRAIN CURVES AT 482 F FOR COLD ROLLED SHEET (6, p. 4)

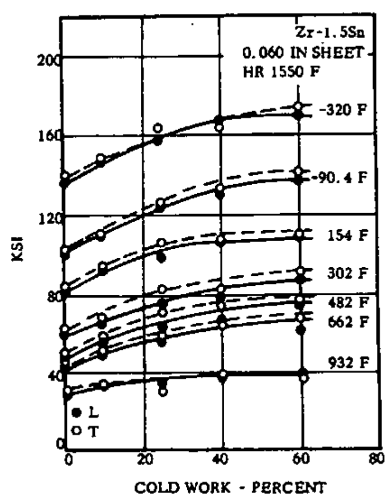

FIG. 3.0317 EFFECT OF COLD WORK ON TENSILE PROPERTIES OF SHEET (6, p. 3)

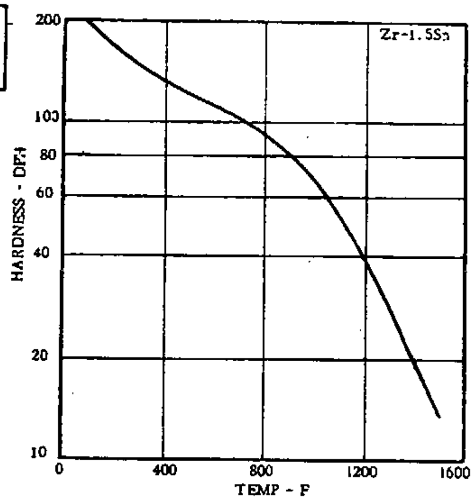

FIG. 3.0321 EFFECT OF TEST TEMPERATURE ON HARDNESS (4)

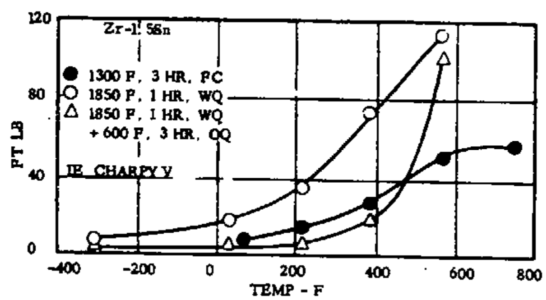

FIG. 3.0323 EFFECT OF TEST TEMPERATURE ON IMPACT STRENGTH OF ALLOY IN VARIOUS CONDITIONS (7)

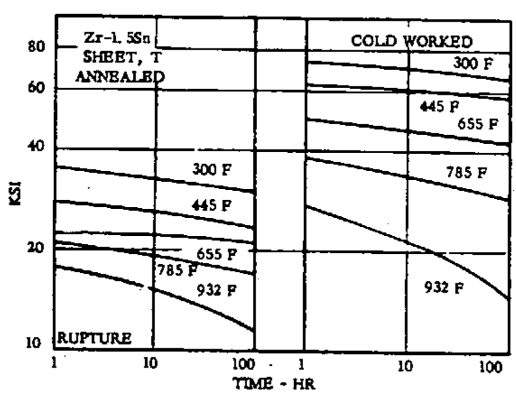

FIG. 3.041 CREEP RUPTURE CURVES AT 300 TO 932 F FOR ANNEALED AND COLD WORKED SHEET (1)

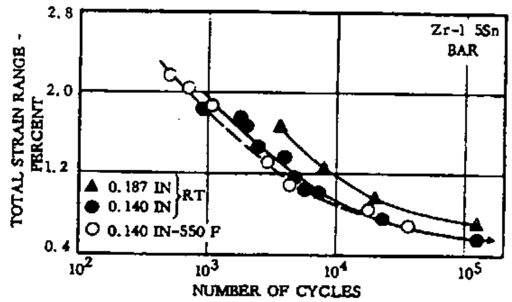

FIG. 3.052 STRAIN CYCLING CURVES FOR BAR (1)

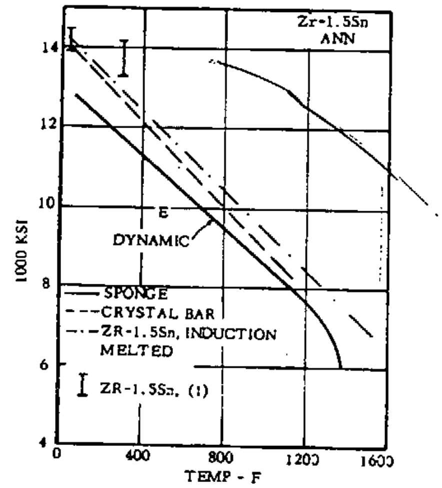

FIG. 3.061 MODULUS OF ELASTICITY OF ZIRCALOY-2 AND ZIRCONIUM AT ROOM AND ELEVATED TEMPERATURES (1)

REFERENCES

1 Rubenstein, L. S., "Properties of Zircaloy-2, " Nucleonics Data Sheet No. 30, Nucleonics Vol. 17, No. 3, (March 1959)

2 Knolls Atomic Power Laboratory, "Handbook", General Electric Co., (1955)

3 Goldsmith, A., Waterman, T. E. and Hirschhorn, "Thermophysical Properties of Solid Materials, Vol. 1-Elements(Melting Temperature Above 1000 F)", Armour Research Division, WADD, (Aug. 1960)

4 Westinghouse Electric Co., "Materials Manual", Bettis Plant, (May 1957)

5 Superior Tube Co., "Preliminary Data on Zirconium, Zircaloy-2, Zircaloy-4 Seamless", Memo No. 112, (1956)

6 Forscher, F., "Effect of Cold Work on the Mechanical Properties of Zircaloy-2, " Westinghouse Atomic Power Div., Paper No. 57-NESC-9, (March 11-14, 1957)

7 Knolls Atomic Power Laboratory, General Electric Co., (1955)