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THERMAL-STRESS-FATIGUE BEHAVIOR OF ZIRCONIUM AND ZIRCONIUM ALLOYS

Final Report

By
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October 31, 1961

Advanced Technology Laboratories
Division of American-Standard
Mountain View, California

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Final Report

THERMAL-STRESS-FATIGUE BEHAVIOR OF
ZIRCONIUM AND ZIRCONIUM ALLOYS

ATL Job 4036

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FOREWORD

This final report is submitted by Advanced Technology Laboratories (ATL) in fulfillment of the requirements of Contract AT(04-3)-250, Project Agreement No. 6, with the U. S. Atomic Energy Commission, Division of Reactor Development. The report covers the study of the thermal-stress-fatigue behavior of zirconium and zirconium alloys conducted during the period January 1959 through October 1961.

SUMMARY

The thermal-stress-fatigue behavior of zirconium and Zircaloy-2 was investigated under a variety of experimental conditions. The external variables taken into consideration were: 1) temperature change, 2) mean temperature, 3) environment (atmosphere), and 4) reverse loading. Material variables studied were cold work and prestraining. In addition, constant-temperature strain cycling was performed in which the following variables were examined: 1) temperature, 2) environment, 3) cold working, 4) specimen size, 5) prestraining, and 6) strain rate.

Ideally, it is desirable to arrive at an equation which can be used to predict fatigue failure under any circumstances. However, the interplay among the variables in thermal stress results in an equation so general in nature as to be no more accurate for predicting fatigue failure than would be extrapolation of constant-temperature strain-cycling fatigue data (especially at low cycles to fatigue). The biggest uncertainty in thermal-stress fatigue is the amount of plastic strain in each cycle. Even in fixed-temperature strain cycling where plastic strain is more easily assessed, a general equation for fatigue life led to poor predictions at low cycles-to-failure conditions. However, a number of equations of the form $N^n \epsilon_p = K$ (N = cycles to failure, ϵ_p = plastic strain per cycle, n and K = constants) were derived and found useful for fixed operating conditions.

The effect of each variable on fatigue life has been illustrated. Since an appreciable number of variables were studied, the program has yielded useful data which approximates many design conditions often encountered. Thus the results will be of value to anyone required to estimate, with little extrapolation, thermal-stress cycling or strain-cycling fatigue life of zirconium and Zircaloy-2.

INTRODUCTION

In the field of reactor design, the phenomenon of thermal stress invariably plagues the designer with uncertainties. Fortunately, thermal stresses are self-correcting in that the deformation they cause reduces the initiating stress. While this self-correcting feature tends to reduce the possibility of failure by stress rupture, a new consideration is made necessary if the temperature change is cyclic. That is, the deformation that relieves the initial thermal stress causes a new thermal stress when the temperature is brought back to its original value--usually room temperature. Thus the designer is confronted with predicting thermal-stress-fatigue life.

Previous experimentation with thermal-stress fatigue has resulted in the unanimous conclusion that this type of fatigue is more harmful than the conventional type of fatigue would be under equivalent conditions. Realization of the number of variables that affect thermal-stress-fatigue life is in itself discouraging to anyone attempting to extrapolate conventional fatigue data to conditions of cyclic thermal stress. Clearly, some base-line data (obtained by thermal-stress cycling) is necessary to substantiate predictions of thermal-stress-fatigue life.

Two of the materials most commonly used in nuclear reactor cores are zirconium and Zircaloy-2, primarily because of their inherent corrosion resistance and low thermal-neutron-absorption cross section. Depending on the reactor's use, the temperature variations can be small and often, large and seldom, or combinations thereof. All temperature variations will cause thermal stress, hence fatigue. It is desirable, therefore, to study thermal-stress fatigue of zirconium and Zircaloy-2 under a variety of conditions, preferably those most closely approximating the majority of reactor operating conditions.

PREPARATION OF TEST SPECIMENS

A. Materials

The test specimens used in this investigation were fabricated from reactor-grade zirconium and Zircaloy-2 seamless tubing supplied by the Bridgeport Brass Company in conjunction with the Wah Chang Company and Mallory-Sharon Metals Corporation. For continuity of test results, an attempt was made to obtain all specimens of a given material from a single melt. In the case of zirconium, all specimens were fabricated from melt M-262, which was forged, extruded, and drawn to a final nominal tubing size of 0.5" ID $\times$ 0.030" wall. The result was a final total cold working of 20.6% reduction in area. It was not possible to fabricate all Zircaloy-2 specimens from a single melt due to supply difficulties. Instead, test specimens were obtained from three selected melts of essentially equivalent properties. For most of the tests, Zircaloy-2 specimens were fabricated from M-250 and M-251 (tubing size 0.5" ID $\times$ 0.030" wall), with M-402 (0.5" ID $\times$ 0.040" wall) being used for certain special-purpose tests. These three melts were all formed by processes similar to those used on zirconium, but with a total cold work of 27% reduction in area.

Complete chemical and physical analyses by Bridgeport Brass Testing Laboratories, including autoclave and corrosion results, are given in Tables C-I and C-II (Appendix C). In addition, the tensile properties for the specific melts used in the investigation were verified by Advanced Technology Laboratories, employing the same specimen geometry as used for fatigue testing. Results for all applicable temperatures in several types of environments are presented in Table C-III. Partial verification of autoclave corrosion tests were also carried out by ATL for the principal melts of Zircaloy-2. Under test conditions equivalent to those used by Bridgeport Brass Company, weight gains of 28.3 mg/dm² and 29.9 mg/dm² were obtained for M-250 and M-251, respectively. These results are comparable with those of Bridgeport Brass Company as listed in Table C-II.

The finished specimens for the annealed series of tests were given alpha-phase heat treatments, which were carried out in a high-vacuum annealing furnace at ATL under the following conditions:

Material	Melt No.	Temperature (°C)	Time at Temperature (hr)	Pressure at Temperature (mm Hg)
Zirconium	M-262	600	48	} furnace-cooled 10 ⁻⁵ " "
Zircaloy-2	M-250, M-251	725	24	
Zircaloy-2	M-402	Not annealed		

These treatments were determined by metallographic examination and by measurement of hardness (DPH) decrease with time at the annealing temperature. An example of hardness decrease versus annealing time for zirconium M-262 may be seen graphically in Figure 1.

Photomicrographs of zirconium and Zircaloy-2 as received and after annealing are presented in Figure 2.

B. Test-Specimen Fabrication

Test specimens of the configuration shown in Figure 3 were fabricated from three sections: the tubular center section (consisting of the test material) and the two flanges or boss ends. The center section is cut in 2.31-inch lengths from one of the previously described zirconium or Zircaloy-2 tubing lots. This piece is then fusion-arc-welded in argon to the end pieces, which have been machined to shape from 1.25-inch-diameter bar stock of the same material used for the tube. The specimens are then precision-machined and honed to the specifications shown in Figure 3 (0.020-inch wall thickness for strain-cycling experiments and 0.010-inch wall thickness for thermal-stress-fatigue work).

HARDNESS VERSUS ANNEALING TIME AT 600°C
FOR ZIRCONIUM M-262

FIGURE 1

a. Zircaloy-2, M-251, as received,
27% cold-worked (M-250 similar)

150×

b. Zircaloy-2, M-251, after annealing
treatment (M-250 similar)

150×

c. Zirconium, M-262, as received,
20.6% cold-worked

150×

d. Zirconium, M-262, after annealing
treatment

150×

ZIRCONIUM AND ZIRCALOY-2 MICROSTRUCTURES

FIGURE 2

CODE LETTER	I. D.
A	.5106 DIA .5110
B	.5136 DIA .5140

4. ENDS "A" SHOULD BE PERPENDICULAR TO CENTER LINE.
3. O.D. & I.D. TO BE PARALLEL WITHIN .001
2. GRIND ALL OVER - $\sqrt{32}$ FINISH EXCEPT AS NOTED.
1. MATERIAL - ZIRCONIUM OR ZIRCALLOY-2

NOTE:

TEST SPECIMEN CONFIGURATION

FIGURE 3

DESCRIPTION OF TEST EQUIPMENT

A. Thermal-Stress-Fatigue Apparatus

1. Configuration

The basic layout of the thermal-stress-fatigue apparatus is shown in Figure 4, while Figures 5 and 6 show some of the actual equipment.

The test chamber is a rectangular framework of heavy steel plates which can be completely enclosed for inert-atmosphere operation. Within the framework is mounted a 5000-lb capacity Baldwin SR4 load cell (item 28, Figure 4), into which is screwed the load-cell shaft and the lower specimen-grip assembly (item 41). The upper end of the specimen is held by the upper grip assembly to a hollow shaft or screw (item 12), which is free to slide through the upper plate of the framework. This shaft can be firmly constrained in any vertical position by means of a lock nut (item 11) and a hold-down screw (item 39) mounted on top of the framework. Each specimen-grip assembly consists of a heavy ring (item 4) within which the specimen (item 3) is contained by a small split ring (item 5). This assembly is then screwed to either the upper shaft or the load-cell shaft.

Combination cooling-water and power leads (item 40) encircle the shafts and are clamped to the grip assemblies by means of lock nuts (item 8). These power/water leads are sufficiently flexible to allow small movements of the upper shaft with negligible constraint. The leads exit through insulators (item 17) in the side plates and are connected to the power supply through a bus bar (item 18) and to the cooling-water supply. Forced cooling of the specimen is accomplished by admitting compressed gas into the gas tube (item 13), then down the center of the upper shaft through the specimen, and finally releasing it from an opening below the lower grip assembly.

The base plate of the framework, and hence the load cell and the lower grip assembly, are electrically isolated from the rest of the apparatus by a sheet of formica (item 29) and sleeved bushings (item 32).

2. Operation

In operation, the test specimen is first fixed in the two grip assemblies. The lower grip is tightened firmly to the load-cell shaft and the lower power lead brought up and secured with a lock nut. The upper shaft, which is free to move vertically, is

1	Baseplate	14	Tube Connector	28	Load Cell, Baldwin SR4
2	Side Plate, Left	15	O-ring	29	Insulation, Formica
3	Test Specimen	16	Side Plate, Right	30	Screw
4	Ring, Specimen Holder	17	Power-Input Insulation	31	Washer
5	Split Ring	18	Power-Lead Bar	32	Bushing, Nylon
6	Cooling Ring	19	Screw	33	Screw
7	Washer, Brass	20	Nut	34	O-ring
8	Nut, Lock, Thin	21	Cooling-Ring Base	35	O-ring
9	Upper Plate	22	Copper Tubing	36	Screw
10	Washer	23	O-ring	37	O-ring Spacer
11	Nut, Lock, Thick	24	O-ring	38	Hold-Down Jig
12	Upper Shaft
(Adjustable Screw)	25	Screw	39	Hold-Down Screw
13	Gas Tube	26	Solid Screw	40	Cooling-Water & Power Lead
		27	Nut	41	Grip Assembly

THERMAL-STRESS-FATIGUE APPARATUS SCHEMATIC

FIGURE 4

THERMAL-STRESS-FATIGUE APPARATUS
TEST CHAMBER

FIGURE 5

THERMAL-STRESS-FATIGUE APPARATUS INSTALLATION

FIGURE 6

brought into tight contact with the top of the specimen by means of the upper grip assembly. The upper power lead is then connected.

Applying a voltage across the specimen from a high-current, low-voltage, step-down transformer heats the specimen to the desired test temperature by means of its own resistance. A plot of the resultant temperature distribution versus specimen gage length is shown in Figure 7. The upper shaft is free to move vertically with the expansion or contraction of the specimen until it is mechanically constrained by the hold-down screw and lock nut. When the desired temperature range is reached, the specimen is rigidly constrained by this means and alternately heated and cooled between set limits as determined by the settings of the power-control circuit. In this manner, cyclic uniaxial loading of the specimen is obtained whereby the linear thermal expansion and contraction are converted into tensile or compressive strain according to the following relationship:

$$\epsilon_t = \alpha(\Delta T)l_e - (\text{load-cell deflection}), \quad (1)$$

where ϵ_t is the total strain change, α is the average coefficient of expansion of the material, ΔT is the temperature change, and l_e is the effective gage length of the specimen. The value for l_e is determined by measuring the expansion and contraction of the specimen between the temperature limits before constraint is imposed and dividing this value by $\alpha(\Delta T)$. The result is, in effect, a correction factor for any variance in ΔT over the measured gage length, l_e .

Ideally, all thermal expansion is converted to strain; however, in practical operation, any deflection inherent in the test apparatus must be subtracted. It was found that movements within the apparatus were extremely negligible in the "constrain" position except in the load cell, where movement is inherent. Under these circumstances, approximately 88% of total thermal expansion is converted to strain.

Temperature is measured by spot-welding 30-gage Chromel/Alumel thermocouples to the center of the specimen. The readings thus obtained may be read directly or recorded.

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MEASURED TEMPERATURE DISTRIBUTION ALONG
THERMAL-STRESS-FATIGUE SPECIMEN
FOR SEVERAL TEMPERATURE LEVELS

FIGURE 7

Stress levels present in the test specimen are accurately determined by measurements obtained from the previously calibrated load cell. The reading may be either taken directly with a Baldwin SR4 Type M strain indicator or recorded continuously with an Offner Dynograph Type MR six-channel recorder. A typical temperature-load recording taken on the Offner is shown in Figure 8. In addition, a two-axis recording of stress change per cycle versus temperature change may be made, using a Mosely Model 3 X-Y recorder.

The temperature cycle is controlled in four stages: a) heat up (rapid heating by applying high currents), b) high hold (sustained at the high temperature), c) cool (time or forced gas-cooled, as required), d) low hold (sustained at the low temperature). This sequence is regulated by relays and electric timers, as shown in Figure 9. Power is obtained from a 3-kva step-down transformer, using a voltage stabilizer and 110-vac input. (Power circuit is shown in Figure 10.)

Because of the direct applicability of this study to reactor design considerations, the criterion for failure was considered to be the point at which a crack or leak started. The continuous temperature record maintained by the strip-chart recorders provides an extremely sensitive means of determining this failure. With the onset of a minute crack, the plateau of the high-temperature hold period begins to drop because of the area reduction and corresponding resistance increase of the specimen. Since voltage remains constant, the current through the specimen drops with the rise in resistance, resulting in the observed drop in specimen temperature (provided, of course, the thermocouple is not located in the region of area reduction, where a temperature increase actually occurs in a ductile failure).

In some specimens, conditions are such that cracks will not occur; instead, the specimen gage length will merely approach a barrel shape and no further change will occur. In these cases, when the bulge reaches 4% of specimen diameter, failure is considered to have occurred. The diameters of the specimens while in test were determined by photographing, followed by measurement of the enlarged (10×) projected image.

TYPICAL THERMAL-STRESS-FATIGUE CYCLE
 TEMPERATURE AND EQUIVALENT LOAD VERSUS TIME
 SPECIMEN 252-9
 (CURVALINEAR RECORDING)

FIGURE 8

TIME SEQUENCE:

T1			T2			T3			T4		
TD4 R	TD1 O		TD1 R	TD2 O		TD2 R	TD3 O		TD3 R	TD4 O	
C1 R	C1 E		TD2 E	C2 E		TD3 E	C3 E		TD4 E	C1 R	
TD1 E	C4 E			C5 E			C6 E			C2 R	
	C7 E			C8 E			C9 E			C3 R	

LIGHT LABELS:

L1: Heat Up (red)
 L2: High Hold (amber)
 L3: Cool (green)
 L4: Low Hold (white)
 L5: Power Circuit On (red)
 L6: (Use label for S1) (red)

LEGEND:

E = Energized
 O = Operated after time delay
 R = Restored
 + = Normally open relay contacts
 / = Normally closed relay contacts

THERMAL-STRESS-FATIGUE APPARATUS CONTROL CIRCUIT

FIGURE 9

THERMAL-STRESS-FATIGUE APPARATUS
POWER CIRCUIT

FIGURE 10

B. Strain-Cycling Apparatus

1. Configuration

The strain-cycling apparatus consists of a vertically mounted cylindrical structure of heavy steel within which a Baldwin SR4 load cell (5000-lb capacity) is placed in one end and a movable shaft in the opposite end.

The test specimen, similar to those used in the thermal-stress-fatigue apparatus, is then clamped between the shaft and the load cell by means of suitable grips. The specimen can then be strain-cycled by a double-acting 8-inch-diameter hydraulic cylinder mounted below and applying force to the movable shaft. The amount of travel is regulated within the desired limits by large micrometer lock nuts mounted on the shaft and bearing against the lower sections of the structure. A cutaway view and an exploded view illustrating the gripping mechanisms are shown in Figure 11.

2. Operation

In operation, the specimen is first joined with the grip assemblies, each consisting of an outer lock ring and an inner split ring. The combined pieces are then mounted in the machine and the lower movable shaft brought up until the end surfaces of the specimen are in contact with it and the load-cell shaft. The grip lock rings, having been seated in position, are given a quarter turn which interlocks them with a set of tension sleeves. These tension sleeves are free to slide vertically about the shafts until tightened with Marman clamps against Belleville springs (Figure 11). The amount of force brought to bear against the tension sleeves, and hence the grips, is regulated by tension wheels, which can be seen at the extreme ends of the test section. Gripping forces up to 4500 pounds can be obtained rapidly by this means with no twisting movements on the specimen and a high degree of positive holding power against either tension or compression.

For inert-atmosphere or high-vacuum operation, the test section is enclosed by a suitable chamber, entirely O-ring sealed.

The lower movable shaft is held in accurate alignment by a bearing sleeve. The actuating hydraulic cylinder is supplied by a reservoir and a hydraulic pump. By controlling the inflow and outflow of the cylinder with precision micrometer valves, any given strain rate can be set up. Solenoid valves in conjunction with suitable relays

and timers control the cycling of the machine. The specimen is heated by inserting a cartridge-type heater through the center of the lower movable shaft and thence into the interior of the specimen. A reasonably even temperature distribution can be obtained in this way, as shown in Figure 12. A schematic diagram of the control circuits and heater circuits is shown in Figure 13. Photographs of the strain-cycling equipment are shown in Figures 14, 15, and 16.

Specimen temperatures are recorded on a multipoint recorder from five Chromel/Alumel thermocouples distributed along the gage length. Strain amplitudes, which are easily read by a dial indicator mounted on the grips, may be regulated to ± 0.0001 inch by the previously mentioned lock nuts.

Load records are obtained from the Baldwin load cell. Since failure does not affect the temperature, these records provide a means for determining specimen failure. That is, a slight change in the magnitude of either the tension or compression load from the previous-cycle load during hold time indicates the presence of a minute crack. An example of a typical load cycle and an equivalent strain cycle versus time may be seen in Figure 17. This sketch illustrates the yield-point, load-relaxation, and sustained-load levels.

CUTAWAY AND EXPLODED VIEWS OF STRAIN-CYCLING APPARATUS

FIGURE 11

MEASURED TEMPERATURE DISTRIBUTION ALONG
STRAIN-CYCLING SPECIMEN FOR
SEVERAL TEMPERATURE LEVELS

FIGURE 12

STRAIN-CYCLING APPARATUS
CONTROL AND POWER CIRCUITS

FIGURE 13

STRAIN-CYCLING APPARATUS
TEST SECTION

FIGURE 14

STRAIN-CYCLING APPARATUS
ACTUATING MECHANISMS

FIGURE 15

STRAIN-CYCLING APPARATUS INSTALLATION

FIGURE 16

a. Strain Versus Time

b. Load Versus Time

TYPICAL STRAIN AND LOAD VERSUS TIME (AT HALF LIFE)
REPRESENTATION OF STRAIN CYCLING

FIGURE 17

RESULTS AND DISCUSSION

The results of the experimental work completed on zirconium and Zircaloy-2 can be divided into two main groups: 1) fatigue induced by constrained thermal cycling, 2) fatigue induced by elevated-temperature strain cycling. A discussion of each group follows, as well as of the relationship between strain cycling and thermal-stress cycling.

It should be realized, however, that the large amount of data collected can be grouped in many ways other than that presented in this section. The actual data are tabulated in Appendix C, Tables C-IV through C-VII.

A. Fatigue Induced by Constrained Thermal Cycling

This type of fatigue was studied by determining the effects of 1) temperature change and mean temperature, 2) test environment, 3) prior cold work, 4) reverse loading, and 5) prestraining. Each of these parameters is discussed below, followed by some comments on plastic-strain damage.

1. Effect of Temperature Change (ΔT) and Mean Temperature (T_m)

The effect of ΔT on cycles to failure (N) for annealed zirconium tested in air is shown in Figure 18* (T_2 = high temperature of thermal cycling). This curve, as well as the equivalent curves for annealed Zircaloy-2 in Figure 19, is similar to the well-known curves of stress versus cycles to failure ($S-N$), since ΔT is, to a first approximation, proportional to stress. Both differ from ferrous-alloy $S-N$ curves in that they do not indicate an endurance limit; however, this is typical of most non-ferrous alloys. If points of the same mean temperature (T_m) are connected by a dotted line as shown in Figure 19, more information is obvious. It is seen that as T_m increases, the number of cycles to failure decreases for the same ΔT (e.g., in going from point A to point B).

Effects of thermal cycling on zirconium during fatigue testing are shown in Figure 20. A measurable bulge developed early in the test, and progressive oxidation was apparent. Similar effects were noted on Zircaloy-2 when cycled under identical

* All illustrations referenced in this section appear at the end of the section.

conditions; Figure 21 shows a Zircaloy-2 specimen tested at a mean temperature only 25°C higher than the zirconium. Oxidation occurs more rapidly on Zircaloy-2 at this mean temperature.

It was stated previously that the curves of ΔT versus N are similar to conventional S-N curves. S-N data for the tests graphed in Figures 18 and 19 are plotted in Figure 22. It should be noted that total stress change, $\Delta\sigma_t$, as plotted in this graph, is taken at the half life of the tests (i. e., $\Delta\sigma_t$ at $N/2$ is plotted versus N). Unlike conventional S-N curves, where stress is cycled about a mean value, the thermal-cycling experiments are of such a nature that the mean value of σ changes throughout the test. The effect of a higher mean temperature is very pronounced in Figure 22, as shown by the " ΔT Equal" notation. (See Figure 19 for the same effect.)

2. Effect of Test Environment

The effect of oxidation on thermal-stress-fatigue life can be ascertained by comparing the above-described tests with tests run in argon. The argon used was 99.999% pure and was passed over zirconium chips at 900°C prior to its entering the fatigue-test chamber. Figure 23 shows ΔT versus cycles to failure for annealed zirconium and Zircaloy-2 tested both in air and in argon. Fatigue life is greater in argon than in air, which is to be expected from observation of the difference in oxidation rates in air and in argon. However, this type of data is difficult to relate because of variation in oxide thickness along the length of the specimen due to the temperature gradient. At high temperatures (600°C), most specimens exhibit a pronounced bulge or collapsing in the failure region, which in turn causes a hot spot by reducing the cross-sectional area generating heat. These effects are shown in Figures 24 and 25. The actual variation in oxide thickness is illustrated in Figures 26 and 27. Comparison of these two figures makes it immediately apparent that increasing the temperature increases the oxidation rate (or oxide thickness) and that the difference in oxide thickness between Zircaloy-2 cycled in air and in argon is small. Note in Figures 27a and b that oxide apparently does not form on the inside of the tubular specimen that is cycled in argon. Since no tests were force-cooled, the argon flow (hence the supply of oxygen) through the inside of the tube is much less than the flow on the outside of the tube. Thus oxidation is proportionally less. When the specimen is cycled in air, even the small flow through the center of the tubes due to convection provides sufficient oxygen (see Figures 26a and b).

The difference in oxidation rates between zirconium and Zircaloy-2 in the absence of stress is illustrated in Figure 28. The extent of stress corrosion or stress-corrosion cracking could not be ascertained because of the variation in oxide thickness on any given thermal-stress specimen.

3. Effect of Prior Cold Work

During the course of the program, cold-worked zirconium and Zircaloy-2 were tested to compare with the annealed condition. Time permitted only one degree of cold work to be investigated, namely, 27% for Zircaloy-2 and 20.6% for zirconium (% reduction in area). In Figure 29, the difference in fatigue life between annealed and cold-worked zirconium and Zircaloy-2 tested in air is shown. It can be seen that at $T_2 = 500^\circ\text{C}$, the cold-worked Zircaloy-2 material appears the best, regardless of ΔT . At $T_2 = 600^\circ\text{C}$, a crossover is noted; i.e., at low strains (low ΔT) cold-worked material is superior to annealed material, while at high strains (high ΔT) the annealed material is superior. This latter effect has been noticed by Coffin¹ in his studies on 347 stainless steel.

Figure 29 provides interesting data when metallurgical structures are taken into consideration. It will be recalled that cold-worked Zircaloy-2 has a smaller grain size than the annealed material (see Figure 2); hence at temperatures above the so-called equicohesive temperature, the large-grain-size (annealed) material could be stronger than the small-grain-size (cold-worked) material. In going from a T_2 of 500°C to a T_2 of 600°C in Figure 29, it is seen that for the same ΔT , the annealed material becomes stronger, or more fatigue resistant, than the cold-worked material (tests in argon show the reverse trend). However, no general conclusion can be drawn as to the actual equicohesive temperature because of the cross-over tendency between annealed and cold-worked material evident in Figure 29.

The data in Figure 29 for zirconium indicates little difference between the cold-worked and annealed conditions. If grain size, cold work, and equicohesive temperature are considered, an explanation is possible. It is noticed that cold-worked zirconium has a larger grain size than annealed zirconium (see Figure 2); therefore,

1. Superscripts indicate references in Appendix B.

the testing of zirconium indicated in Figure 29 must have taken place well below the equicohesive temperature, since cold-worked large-grain-size material is approximately equivalent to annealed small-grain-size material.

Returning to the cross-over effect mentioned by Coffin and noticed in this program, it was found by Coffin that when data of this type are replotted as total stress change (instead of ΔT) versus cycles to failure, cold-worked material is always better than annealed. It should be noted that Zircaloy-2 tested in argon does not show the same difference between annealed and cold-worked materials, as can be seen in Figure 30. Here, cold-worked material is superior at a $T_2 = 600^\circ\text{C}$, while annealed material is slightly superior at a $T_2 = 500^\circ\text{C}$.

Following the suggestion by Coffin that total stress change should be plotted versus cycles to failure to eliminate the data crossover resulted in Figure 31, which indicates that the crossover is still present; i.e., annealed zirconium and Zircaloy-2 have a longer fatigue life than cold-worked material at certain stresses in both air and argon (see also Figure 32). It is worthwhile to compare the results of the present study with results in reference 1, since the degree of prior cold work is of the same order in both programs.

It is noted that in all reference 1 data, prior-cold-worked specimens exhibited a strain-softening effect upon thermal cycling, the degree of softening increasing with increasing ΔT (hence increasing total strain). However, such is not the case in the current program. Figure 33 shows strain hardening occurring in both the annealed and cold-worked Zircaloy-2 at low strain in air (at $T_2 = 600^\circ\text{C}$). The cold-worked material begins to strain-soften with increasing ΔT , yet this effect is only an initial one and is followed by strain hardening after further cycling. When tested in argon at low strains ($T_2 = 600^\circ\text{C}$), both the annealed and the cold-worked materials initially strain-harden; however, both materials strain-soften permanently at high total strains, as shown in Figure 34. When Zircaloy-2 is cycled in air at $T_2 = 500^\circ\text{C}$, both annealed and cold-worked materials tend to strain-harden, as seen in Figure 35.

When zirconium is tested in air at $T_2 = 500^\circ\text{C}$, the annealed materials tends to strain-harden and the cold-worked material to strain-soften (see Figure 36). When zirconium is tested in argon, both annealed and cold-worked materials strain-harden (see Figure 37).

Thus, no general conclusion is reached as to whether zirconium or Zircaloy-2 will strain-harden or strain-soften. It has been shown that mean temperature of cycling and test environment are also involved in the strain-hardening/softening phenomenon. Prediction of correct results would indeed be fortuitous.

4. Effect of Reverse Loading

Some interesting results were obtained when the thermal-stress-fatigue specimens were clamped at the low temperature of the cycle rather than at the high temperature, as in the previous summations. Reverse loading (that is, making the specimen go into initial compression at the high temperature instead of initial tension at the low temperature) was performed on cold-worked Zircaloy-2 in air and the results plotted in Figures 38, 39, and 40. Figures 38 and 39 indicate that specimens have a shorter life under reverse loading than under normal loading at low ΔT but have a longer life at high ΔT . Figure 40 shows that cold-worked Zircaloy-2 strain-hardens, whether under normal or reverse loading, at a T_2 of 500°C .

The load-cycling history of normal- and reverse-loading tests was illustrated by feeding load into the Y coordinate of an X-Y recorder and specimen temperature into the X coordinate. X-Y graphs were taken on the majority of specimens tested; however, these graphs are not to be confused with the more conventional hysteresis loops found on a cyclic stress-strain plot. In thermal-stress cycling, it is impossible to graph strain, because the ends of the specimens do not move during the test. Since strain is proportional to $\alpha(\Delta T)\ell_e$, it can be loosely assumed that temperature-load as X-Y coordinates, respectively, would indicate a hysteresis loop if one actually existed. It has been found that the width of the hysteresis loop due to plastic strain is overshadowed by the width caused by a difference in specimen temperature profile on heating and cooling. This latter effect is illustrated in Figure 41, where X-Y data were taken on a specimen cycling between 500 and 100°C . Depending on the heating and cooling rates (and therefore specimen temperature profile at any given temperature), it is possible to get a wide hysteresis loop (indicating large plastic strain) or a loop shaped like a figure 8.

Figure 42 shows X-Y plots of cold-worked Zircaloy-2 cycled between 500 and 200°C in both reverse- and normal-loading tests. Ignoring for the present the possibility of unequal specimen temperature profiles, the reverse-loading curves indicate that plastic strain occurred during the first cycle. However, close examination reveals that the hysteresis loop and tensile load were not caused solely by $\alpha(\Delta T)\ell_e$ plastic strain, but also by load relaxation at constant temperatures, shown by the vertical-line segment of cycle 1. This vertical line is easily explained in the first cycle (Figure 42a), where relaxation is occurring at a high temperature and high load. (All thermal-stress fatigue tests were run with a 3-minute hold at T_2 and a 6-second hold at T_1 .) Some relaxation is also evident at low temperature (but at high load) in Figure 42b, and no doubt it contributed to the width of the apparent hysteresis loop.

If it is assumed that the "effective" proportional limit^{*} was exceeded during the first cycle of the reverse-loaded specimen and that the relaxed load is roughly equal to the proportional limit, it is theorized that the same amount of "internal plastic strain" occurs during relaxation as occurs from the effective proportional limit to the maximum load. In other words, the specimen undergoes the equivalent internal strains depicted in Figure 43. Obviously, such a diagram could not be obtained directly from thermal-stress-fatigue or strain-cycling experiments. From a comparison of Figure 43 with Figure 42, it appears that allowing relaxation to occur is equivalent to increasing the ΔT of cycling.

The relaxation phenomenon has been termed "anelastic strain," a phenomenon that is a function of vibration frequency (ΔT cycling rate) and temperature and that can result from several physical conditions, such as grain boundaries, interstitial solute atoms, and twin boundaries. Labeling relaxation "anelastic strain" implies that it would not cause a decrease in fatigue life³ and would also be contrary to Coffin's¹ explanation for a decrease in fatigue life with increasing hold time. It is certain that the relaxation occurring is damaging in nature; therefore it is plastic, not anelastic strain.

* See Figure 51.

The X-Y plots obtained from most specimens tested have been described as being of small value for plastic-strain measurement, if a different specimen temperature profile exists during heating as compared to cooling. However, they do give a close load-strain approximation if each side of the loop is considered individually. For instance, it is noticed that no straight lines exist on these loops because of the variation in Young's modulus with temperature. Nevertheless, points of inflection should occur, and possibly small segments approaching a straight line, when the effective proportional limit is exceeded upon cooling of a normally loaded specimen. This phenomenon is illustrated in Figure 44. The theoretical loop of Figure 44 has been closely approximated by actual X-Y data, as shown in Figure 45.

The effects of reverse loading are closely related to the effects of prestraining normally loaded specimens. The latter are discussed in the following section.

5. Effect of Prestraining

Prestraining experiments were conducted on Zircaloy-2 cycling from 500°C to 100°C. The results, and comparison data, are shown in Figure 46. Prestraining is seen to increase fatigue life at $\Delta T = 400^\circ\text{C}$, just as the life of reverse-loaded specimens increased (at high ΔT) over the life of normally loaded specimens. The fatigue lives plotted in Figure 46 are so close together as to make the previous statement strictly conditional, and further experimentation might result in a different conclusion.

It is instructive to plot high-hold load versus cycles for some of the specimens shown in Figure 46, as is done in Figure 47. Here, all high-temperature loads, whether initially tension, compression, or zero, end up in compression and approach the same value. The fact that both normal and reverse loading result in a compressive stress at T_2 is common to all specimens thermally cycled, indicating that plastic strains in tension and compression tend to become equal.

The increase in σ_2 (compressive stress at T_2) after equilibration of plastic strain could be explained by oxide formation in cracks effecting an increase in specimen length on cooling only, as seen in Figure 48. It was shown previously that $\Delta\sigma_t$ also increases after plastic-strain equilibration; hence low-temperature stress remains relatively constant or decreases slightly as would be expected. Figure 49 shows the opening and closing of cracks caused by thermal cycling.

6. Plastic-Strain Damage

There is a tendency when reporting fatigue data to relate the plastic strain per cycle to the fatigue life. In particular, it has been found that the relationship

$$N^n \epsilon_p = K \quad , \quad (2)$$

where ϵ_p = plastic strain per cycle (heating and cooling), and n and K = material constants, is a fair approximation of the fatigue characteristics of ductile metals.¹ Orowan⁴ and McCutchan and Murphy⁵ have proposed models illustrating the stress-strain curve for normal cycling. These models, which are applicable to tests in which the load is at first in tension or compression only, are based on the fact that regions of high stress occur in a material under an over-all low stress. This condition is necessary because plastic strain occurs at over-all stress values far below the tensile-test yield strength. The problem, then, is in determining the plastic strain per cycle in thermal-stress specimens.

Coffin⁶ describes a method of calculating ϵ_p wherein the stress is assumed not to exceed the mean-temperature yield strength. ATL devised another way to measure plastic strain per cycle, as seen in Figure 50. Here, the relaxed stress approaches the proportional limit, allowing measurement of plastic strain during thermal cycling as follows:

$$\alpha(\Delta T) \ell_e \left(\frac{\text{Relaxed Stress at } T_2}{\text{Young's Modulus at } T_2} + \frac{\text{Relaxed Stress at } T_1}{\text{Young's Modulus at } T_1} \right)$$

= Total Plastic Strain per Cycle.

As seen in Tables C-IV and C-V (Appendix C), this method yields negative plastic strain at low ΔT . Coffin's method also resulted in negative plastic strain when applied to ATL data, and the first thought would be that ℓ_e was in error, since it is used in both methods. Even using the actual length of the test specimens in the calculations does not prevent negative calculated values of ϵ_p at low ΔT variations.

As mentioned previously, plastic strain can be measured only under closely controlled heating and cooling conditions in thermal-stress fatigue. However, it can be roughly calculated as a function of temperature during thermal cycling by taking into

account the dependence of Young's modulus on temperature. Experimentally, it was found that the equation

$$Y = aT + b$$

represented closely the actual tensile-test data. Since

$$\Delta\epsilon = \alpha(\Delta T)l \text{ (no relaxation),}$$

or $d\epsilon = \alpha l(dT)$

and $\frac{\Delta\sigma}{\Delta\epsilon} = Y,$

a differential equation for stress in the elastic region can be written as

$$\frac{d\sigma}{d\epsilon} = Y ;$$

$$\int_{\sigma_1}^{\sigma_2} d\sigma = \int_{T_1}^{T_2} (aT + b) \alpha l(dT) ;$$

from which is obtained

$$\sigma \left| \begin{matrix} \sigma_2 \\ \sigma_1 \end{matrix} \right| = \frac{\alpha l a T^2}{2} \left| \begin{matrix} T_2 \\ T_1 \end{matrix} \right| + b \alpha l T \left| \begin{matrix} T_2 \\ T_1 \end{matrix} \right| ,$$

which simplifies to

$$\Delta\sigma = \alpha l(\Delta T) (aT_m + b)$$

By holding T_m constant and slowly increasing ΔT , a curve can be drawn; when this curve deviates from a straight line, the conditions of elasticity are no longer valid, i. e., plastic strain is occurring.

During the course of the current program, a specimen was kept at a constant T_m and ΔT was slowly increased. This was done by clamping at T_2 , cycling by ΔT a few times, then recording σ_2 and σ_1 before and after relaxation. Then $\Delta\sigma_t$ was plotted versus $\alpha l(\Delta T) (aT_m + b)$, as shown in Figure 51. Here, it is seen that "elastic" stress is operative only with $\Delta T < 300^\circ\text{C}$ when $T_m = 400^\circ\text{C}$. It must be pointed out that in Figure 51 plastic strain occurs mostly in tension only, since the specimen was cycled only a few times at each successive ΔT . The relaxed stress values are also shown, along with actual half-life data from previous fatigue testing. Even though Figure 51 shows that the specimen is undergoing only elastic strain at ΔT 's less than

300°C, fatigue failure can result at a ΔT less than 100°C. Since a ductile failure occurs with ΔT as low as 100°C, it is further apparent that the effective proportional limit is even lower than that shown in Figure 51. In all probability there is no proportional limit in fatigue, and plastic strain per cycle indeed becomes an illusive quantity to calculate.

With the above arguments in mind, it was decided not to attempt to calculate the values of K and n in equation 2.

B. Fatigue Induced by Elevated-Temperature Strain Cycling

This type of fatigue was studied by determining the effects of 1) temperature, atmosphere, and cold work; 2) specimen size; 3) prestraining; 4) strain rate; and 5) prior strain cycling. Each parameter is discussed below, followed by comments on plastic-strain damage. All the data gathered is presented in Tables C-VI and C-VII (Appendix C).

1. Effects of Temperature, Atmosphere, and Cold Work

Figures 52 and 53 show fatigue life as a function of temperature for zirconium and Zircaloy-2 in both air and argon. As can be seen in both illustrations, the annealed material has a longer life at all temperatures. Unlike Zircaloy-2, zirconium tested in air exhibits a clear superiority over zirconium tested in argon. Actual comparison of the two graphs shows that Zircaloy-2 has a longer fatigue life than does zirconium. Strain softening is evident at all temperatures for both the annealed and the cold-worked material (except annealed Zircaloy-2 tested at 400°C), as seen in Figures 54 and 55. When metallurgical structure is taken into account, Figure 52 indicates that the zirconium was strain-cycled well below the equicohesive temperature, as concluded in Section A.3. From Figure 54, it is evident that the annealed large-grain-size Zircaloy-2 is better (at and below 500°C) than the cold-worked small-grain-size material, regardless of the environment. This data is similar to the thermal-stress-fatigue data of Figure 30, and the only conclusion reached is the detrimental effects of cold work (prestrain) on the strain-cycling fatigue life of Zircaloy-2 at large strains per cycle.

In practically all strain-cycled specimens, there was a characteristic failure region, which was shown by metallography to be removed from the region of weld-affected metal (Figure 56). The region of failure is illustrated in Figures 57 and 58.

Another common phenomenon occurring in strain cycling was that of necking near the ends, as illustrated in Figures 58a and 59 (see arrows). This necking occurred in the first few cycles and was noticeable on specimens cycled at and below 400°C. When necking took place, failure would occur in this region. At 500°C, there was no end necking, and ductile failure occurred in the center of the specimens.

The cause of the necking is tentatively attributed to complex end stresses and to the specimen being slightly softer in the neck region than in the center (see Figure 56). When cycling at 500°C, the center of the specimen is 50 to 60°C hotter than the region where necking would normally take place. As seen from the tensile test data in Table C-III, there is a large change in ductility from 400 to 500°C. Clearly, the center of the specimen is much more ductile than the ends when cycling at 500°C; thus no necking occurs and the stresses are relieved by buckling, as shown in Figure 60.

2. Effect of Specimen Size

Short-gage-length specimens of Zircaloy-2 were used in experiments to determine the effect of size on fatigue. These specimens were 1 inch in gage length, compared to the 2-inch gage length used for all other specimens. However, all specimens were of the same over-all length. Results of this very brief study are summarized in Figure 61. By comparing this curve to Figure 53, it is seen that the short-gage-length specimens have longer fatigue lives than do the longer gage-length specimens.

This finding corroborates the above explanation given for failure occurring at the ends in most strain-cycling tests; since the wall thickness at the ends is greater in short-gage-length specimens, the ends can withstand more force. On the other hand, the test volume in short-gage-length specimens is one-half that in normal-gage-length specimens; therefore the fatigue lives should be related as shown by the expression

$$\frac{N_1}{N_2} = \left(\frac{V_2}{V_1} \right)^{1/\eta}$$

where $1/\eta$ is a material constant relating the number of large flaws to the number of small flaws.⁷ This equation lessens the value of the complex end-stress explanation given previously. It would also be expected from the above equation that the cyclic

stress accompanying a given $\Delta l/l$ would be less in a short-gage-length specimen. This is, in fact, shown in Figure 62. It should be mentioned that short-gage-length specimens were machined from a new, different melt of Zircaloy-2 which could have been more ductile than previous melts; hence the explanation for Figure 62 may not be entirely a result of the above relationship.

3. Effect of Prestraining

In addition to cold-work effects, the effect of prestraining at test temperature was investigated. This prestrain is obviously additional cold work. The severity of a constant prestrain is dependent on the temperature, but it would be expected that any prestrain would decrease fatigue life (see Figure 53). Contrary to this observation is the phenomenon of the cyclic-stress drift. That is, regardless of prestrain, the tensile and compressive stresses after the first few cycles terminate roughly equidistant (algebraically) from zero (see Figure 63). Thus fatigue life will probably decrease, reading from top to bottom in Figure 63, since progressively more initial plastic strain is required to cause cycling about zero. This theory is confirmed by Figure 64. The scatter in data for the few tests run in this series of experiments is such as to make a definite statement of optimum prestraining conditions risky at present. However, there is an indication that fatigue life can be increased by selective prestraining.

4. Effect of Strain Rate

In conventional tensile testing, yield strength increases as the rate of loading increases (see next section). Also, the effect of strain rate is operative in strain cycling at lower temperatures, in that fatigue life increases with increasing strain rate for both zirconium and Zircaloy-2, and the rate effect is greater at lower test temperatures (ref. Figure 65).

At low test temperatures, an increase in strain rate effects an increase in elastic deformation, hence a decrease in plastic deformation when the total deformation is held constant as in strain cycling. It is known that the less plastic deformation per cycle, the longer the fatigue life. Thus this series of experiments substantiates predicted results.

5. Effect of Prior Strain Cycling on Tensile Testing

In order to ascertain the effects of prior strain cycling on tensile-test properties, it is advisable to include in this section all tensile-test data. Although a complete study of short-time tensile data was made in the early stages of the program, only a small amount of the data has been plotted. However, all results are tabulated in Appendix C (Table C-III).

Figures 66 through 69 plot the yield strengths of Zircaloy-2 and zirconium at two different strain rates and also the percent elongation to fracture. In Figure 66, Zircaloy-2 conforms to usual results with respect to yield strength increasing with increasing strain rate. Conversely, zirconium (Figure 67) does not show a significant trend of yield strength as a function of strain rate. The results agree to a large extent with the fatigue test results shown in Figure 65.

It should be mentioned that erratic results in short-time tensile tests are a common occurrence. In fact, in reference 8, the tensile-test data were plotted on semilogarithmic paper to smooth out the curves.

When the true-stress true-strain data are plotted on log-log graph paper, straight lines result. This leads to the equation for stress:

$$\sigma = \sigma_0 \epsilon_p^m$$

where m = strain-hardening exponent,

σ_0 = stress where true strain equals 1.

This equation is valid only in the plastic region. The values of m and σ_0 have been tabulated with the tensile-test data (Table C-III). It will be noticed that plastic strain hardening was not apparent for cold-worked Zircaloy-2 in both air and argon nor for cold-worked zirconium in argon. These results conform more or less with the fatigue results, where strain softening was apparent after a few cycles.

A brief series of short-time tensile tests was performed on Zircaloy-2 specimens that had previously undergone strain cycling at 500°C. In addition, these specimens had been cold-worked the standard amount. Both the specimen cycled for 1/2 normal fatigue life and the one cycled for 3/4 normal fatigue life (at 500°C) gave a short-time tensile-test yield strength of 56,000 psi, a value well in excess of the yield strength of cold-worked Zircaloy-2 at 500°C. The elongation to fracture for

specimens previously strain cycled is appreciably less than the corresponding values for merely cold-worked Zircaloy-2. Whether or not this is a true indication of the effect of prior strain cycling is debatable on the grounds of insufficient data. In reference 1, prior thermal cycling resulted in a wide spread in fracture ductility during tensile testing, leading to the conclusion that "prior cycling does not produce an appreciable effect on the bulk structural properties..." The trend in this program, as well as in reference 1, was for prior cycling to cause a reduced fracture ductility upon tensile testing.

6. Plastic-Strain Damage

In the section on thermal-stress cycling, it was stated that fatigue damage could sometimes be summarized in the relationship

$$N^n \epsilon_p = K$$

where n and K are characteristics of the material in question. The above relationship resulted when it was noticed that as plastic strain per cycle decreased, the total plastic strain during fatigue testing ($N\epsilon_p$) increased. This is illustrated in Figure 70 for thermally cycled, annealed 347 stainless steel. It should be noted that both curves were drawn through the points representing plastic strain in tensile testing. Had these points been omitted from the graph and the lines drawn through fatigue data alone, entirely different equations would have been obtained. With this in mind, the summation of data concerning plastic strain per cycle is given in Figures 71 through 74. These graphs also include equations of the curves but omit tensile-test data.

With the large number of variables taken into consideration in this program, Figures 71 through 74 show that the very useful equation relating plastic strain per cycle to fatigue life can result in misleading predictions of fatigue life. The equations of over-all trend, if used for prediction of fatigue life, could easily result in either overestimation or underestimation of cycles to failure by an appreciable margin. In low-cycle fatigue, such uncertainty is prohibitive; however, in the range of 10^7 cycles, the error is more tenable.

C. Relationship Between Strain Cycling and Thermal-Stress Cycling

In reference 9, a comparison between strain cycling and thermal-stress cycling was made by strain cycling at a temperature equal to the mean temperature in thermal-stress cycling and keeping the total strain in both tests equal. From the limited amount of data collected, it was concluded that, under equivalent conditions, strain-cycling tests lasted four times longer than thermal-cycling tests. Since the ATL program undertook the investigation of such a large number of variables, it was realized that strain cycling under equivalent conditions would take too long. Therefore, to speed up data acquisition, the total strain per cycle was made to be at least twice as great in strain cycling as in thermal-stress cycling.

By comparing Figures 75 through 77, it is seen that strain cycling results in a shorter fatigue life than thermal-stress cycling, the difference becoming less with increasing equivalent temperature and ΔT . This can be expected, since the plastic strain per cycle is at least four times greater in strain cycling, with the difference becoming less with increasing equivalent temperature and ΔT .

It is particularly interesting to note that the difference between thermal-stress-cycling fatigue life and equivalent-temperature strain-cycling fatigue life is less with Zircaloy-2 than with zirconium. This point is clarified by plotting total plastic strain to failure at equivalent temperatures, as shown in Figures 78 and 79. * It is seen that on the basis of total plastic strain to failure, strain cycling at a greater plastic strain per cycle (yet at a temperature less than reached in thermal-stress cycling) puts strain and thermal-stress cycling on a more or less equal basis regarding total plastic strain. In fact, with Zircaloy-2, total plastic strain is greater in strain cycling than in thermal-stress cycling. This verifies the conclusion stated in reference 9. That is, other things being equal, strain cycling at a temperature equal to the mean temperature in thermal-stress cycling results in a longer fatigue life or a greater total plastic-strain-to-failure capability.

* As indicated in Figure 17, strain cycling was conducted with a 3-minute hold at the end of each strain. This differs from the hold-time scheme used in thermal-stress cycling.

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED ZIRCONIUM TESTED IN AIR

FIGURE 18

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED ZIRCALOY-2 TESTED IN AIR

FIGURE 19

a. After 3,287 cycles
No noticeable bulge

b. After 6,700 cycles
0.010" bulge

c. After 10,869 cycles

d. After 15,760 cycles
0.018" bulge

ANNEALED ZIRCONIUM CYCLING BETWEEN 500°C AND 400°C IN AIR

FIGURE 20

ANNEALED ZIRCALOY-2 CYCLING BETWEEN 500°C AND 450°C IN AIR

FIGURE 21

TOTAL STRESS CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR

FIGURE 22

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR AND IN ARGON

FIGURE 23

a. Initially

b. After 82 cycles

c. After 88 cycles

INFRARED PHOTOGRAPHS OF
COLD-WORKED ZIRCALOY-2 CYCLING BETWEEN 700°C AND 500°C IN AIR

FIGURE 24

INFRARED PHOTOGRAPH OF
ANNEALED ZIRCALLOY-2 CYCLING BETWEEN 600°C AND 300°C IN AIR

FIGURE 25

a. Region of failure

100×

b. 3-1/8" from region of failure

100×

PHOTOMICROGRAPHS OF ANNEALED ZIRCALOY-2 AFTER 894 CYCLES
BETWEEN 600°C AND 300°C IN AIR

FIGURE 26

100×

100×

PHOTOMICROGRAPHS OF ANNEALED ZIRCALLOY-2 AFTER 1532 CYCLES
BETWEEN 600°C AND 300°C IN ARGON

FIGURE 27

TEMPERATURE VERSUS PERCENT WEIGHT GAIN FOR
ZIRCONIUM AND ZIRCALLOY-2
AFTER 210 DAYS AT TEMPERATURE INDICATED

FIGURE 28

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED AND COLD-WORKED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR

FIGURE 29

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR ANNEALED AND COLD-WORKED ZIRCALLOY-2 TESTED IN ARGON

FIGURE 30

TOTAL STRESS CHANGE VERSUS CYCLES TO FAILURE FOR
ANNEALED AND COLD-WORKED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR

FIGURE 31

TOTAL STRESS CHANGE VERSUS CYCLES TO FAILURE FOR ANNEALED AND COLD-WORKED ZIRCALOY-2 TESTED IN ARGON

FIGURE 32

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR ANNEALED AND COLD-WORKED ZIRCALOY-2 TESTED IN AIR AT $T_2 = 600^\circ\text{C}$

FIGURE 33

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR
ANNEALED AND COLD-WORKED ZIRCALOY-2 TESTED IN ARGON AT $T_2 = 600^\circ\text{C}$

FIGURE 34

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR
ANNEALED AND COLD-WORKED ZIRCALOY-2 TESTED IN AIR AT $T_2 = 500^\circ\text{C}$

FIGURE 35

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR
ANNEALED AND COLD-WORKED ZIRCONIUM TESTED IN AIR AT $T_2 = 500^\circ\text{C}$

FIGURE 36

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR
 ANNEALED AND COLD-WORKED ZIRCONIUM TESTED IN ARGON AT $T_2 = 500^\circ\text{C}$

FIGURE 37

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE
FOR COLD-WORKED ZIRCALOY-2 TESTED IN AIR AT $T_2 = 500^\circ\text{C}$
UNDER REVERSE LOADING AND NORMAL LOADING

FIGURE 38

TOTAL STRESS CHANGE VERSUS CYCLES TO FAILURE
FOR COLD-WORKED ZIRCALOY-2 TESTED IN AIR AT $T_2 = 500^\circ\text{C}$
UNDER REVERSE LOADING AND NORMAL LOADING

FIGURE 39

TOTAL STRESS CHANGE VERSUS THERMAL CYCLES FOR
 COLD-WORKED ZIRCALOY-2 TESTED IN AIR AT $T_2 = 500^\circ\text{C}$
 UNDER REVERSE LOADING AND NORMAL LOADING

FIGURE 40

X-Y PLOT OF TEMPERATURE-LOAD DURING
THERMAL-STRESS CYCLING FROM 500°C TO 100°C

FIGURE 41

a. Reverse Loading - Cold-Worked Zircaloy-2 Tested in Air (Specimen 248)

b. Normal Loading - Annealed Zircaloy-2 Tested in Argon (Specimen S-139)

LOAD-TEMPERATURE PLOTS OF COLD-WORKED AND ANNEALED ZIRCALOY-2
DURING THERMAL-STRESS CYCLING BETWEEN 500°C AND 200°C
UNDER REVERSE LOADING AND NORMAL LOADING

FIGURE 42

2 LESS DAMAGING THAN 1

LOAD VERSUS "EQUIVALENT INTERNAL PLASTIC STRAIN"

FIGURE 43

REPRESENTATION OF A THEORETICAL HYSTERESIS LOOP
CAUSED BY THERMAL-STRESS CYCLING

FIGURE 44

ACTUAL X-Y (TEMPERATURE-LOAD) RECORDED DATA OF THERMAL-CYCLING TESTS

FIGURE 45

TEMPERATURE CHANGE VERSUS CYCLES TO FAILURE FOR
COLD-WORKED ZIRCALOY-2 TESTED IN AIR
(EFFECT OF PRESTRAIN)

FIGURE 46

σ_2 VERSUS THERMAL CYCLES FOR COLD-WORKED ZIRCALOY-2 TESTED IN AIR
 $(\sigma_2 = \text{COMPRESSIVE STRESS AT } T_2 = 500^\circ\text{C})$

FIGURE 47

- a. Cold-worked zirconium tested in air. $T_2 = 500^\circ\text{C}$
(Note deformation twins)

- b. Cold-worked Zircaloy-2 tested in air. $T_2 = 500^\circ\text{C}$

PHOTOMICROGRAPHS OF COLD-WORKED ZIRCONIUM AND
ZIRCALOY-2 SPECIMENS AFTER THERMAL CYCLING

FIGURE 48

Cycle 5175 at high hold temperature (T_2)

Cycle 5175 at low hold temperature (T_1)

PHOTOMICROGRAPHS OF COLD-WORKED ZIRCALLOY-2
AT HIGH AND LOW HOLD TEMPERATURES DURING
THERMAL CYCLING BETWEEN 500°C AND 100°C

FIGURE 49

LOAD VERSUS STRAIN AT DIFFERENT STRAIN RATES AND TEMPERATURES
FOR ANNEALED AND COLD-WORKED ZIRCALOY-2

FIGURE 50

FIGURE 51

TEMPERATURE VERSUS CYCLES TO FAILURE
FOR ANNEALED AND COLD-WORKED ZIRCONIUM TESTED IN AIR AND IN ARGON

FIGURE 52

TEMPERATURE VERSUS CYCLES TO FAILURE
FOR ANNEALED AND COLD-WORKED ZIRCALOY-2 TESTED IN AIR AND IN ARGON

FIGURE 53

TOTAL STRESS CHANGE VERSUS CYCLES FOR
 COLD-WORKED ZIRCONIUM AND ZIRCALLOY-2 TESTED IN AIR

FIGURE 54

TOTAL STRESS CHANGE VERSUS CYCLES FOR
ANNEALED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR

FIGURE 55

DPH = 218

DPH = 224

DPH = 186

DPH = 172

DPH = 134

METALLOGRAPHY OF A ZIRCALOY-2 STRAIN-CYCLING SPECIMEN
AFTER WELDING (NO ANNEALING)
(150× - DPH with 200-gram load)

FIGURE 56

a. Annealed, tested at 400°C in air

b. Cold-worked, tested at 400°C in air

c. Cold-worked, tested at 100°C in argon

STRAIN-CYCLED ZIRCONIUM SPECIMENS TESTED IN AIR AND IN ARGON

FIGURE 57

a. Cold-worked, tested at 500°C in argon

b. Annealed, tested at 300°C in argon

c. Cold-worked, tested at 100°C in air

STRAIN-CYCLED ZIRCALOY-2 SPECIMENS TESTED IN AIR AND IN ARGON

FIGURE 58

STRAIN-CYCLED COLD-WORKED ZIRCALOY-2 SPECIMEN
ILLUSTRATING END NECKING

FIGURE 59

a. Tested in argon

b. Tested in air

COLD-WORKED ZIRCALOY-2 SPECIMENS TESTED AT 500°C

FIGURE 60

TEMPERATURE VERSUS CYCLES TO FAILURE
FOR COLD-WORKED ZIRCALOY-2 TESTED IN AIR
(EFFECT OF GAGE LENGTH)

FIGURE 61

TOTAL STRESS CHANGE VERSUS CYCLES FOR
COLD-WORKED ZIRCALOY-2 TESTED IN AIR

FIGURE 62

CYCLIC TENSILE AND COMPRESSIVE STRESS VERSUS CYCLES FOR
COLD-WORKED ZIRCALOY-2 STRAIN CYCLING AT 400°C

FIGURE 63

TEMPERATURE VERSUS CYCLES TO FAILURE
FOR COLD-WORKED ZIRCALOY-2 WITH AND WITHOUT PRESTRAIN

FIGURE 64

TEMPERATURE VERSUS CYCLES TO FAILURE
FOR COLD-WORKED ZIRCONIUM AND ZIRCALOY-2 TESTED IN AIR
AT DIFFERENT STRAIN RATES

FIGURE 65

YIELD STRENGTH VERSUS TEMPERATURE FOR
ZIRCALOY-2 SHORT-TIME TENSILE-TESTED IN AIR

FIGURE 66

YIELD STRENGTH VERSUS TEMPERATURE FOR
ZIRCONIUM SHORT-TIME TENSILE-TESTED IN AIR

FIGURE 67

PERCENT ELONGATION VERSUS TEMPERATURE
FOR ZIRCALOY-2 SHORT-TIME TENSILE-TESTED IN AIR

FIGURE 68

PERCENT ELONGATION VERSUS TEMPERATURE
FOR ZIRCONIUM SHORT-TIME TENSILE-TESTED IN AIR

FIGURE 69

TOTAL PLASTIC STRAIN VERSUS CYCLES TO FAILURE FOR
THERMALLY CYCLED, ANNEALED, 347 STAINLESS STEEL
($T_m = 350^\circ\text{C}$)

FIGURE 70

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ZIRCONIUM STRAIN-CYCLED IN ARGON AND VACUUM

FIGURE 71

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ZIRCONIUM STRAIN-CYCLED IN AIR

FIGURE 72

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ZIRCALOY-2 STRAIN-CYCLED IN ARGON

FIGURE 73

PLASTIC STRAIN PER CYCLE VERSUS CYCLES TO FAILURE FOR
ZIRCALOY-2 STRAIN-CYCLED IN AIR

FIGURE 74

$$\text{MAXIMUM RATIO (PER CYCLE)} \frac{\text{TOTAL STRAIN TSF}}{\text{TOTAL STRAIN SC}} = \frac{0.0026}{0.010}$$

CW = COLD-WORKED
 Ann. = ANNEALED
 SC = STRAIN CYCLING
 TSF = THERMAL-STRESS CYCLING

FATIGUE LIFE OF ZIRCONIUM TESTED BY STRAIN CYCLING AND
 THERMAL-STRESS CYCLING AT 400°C EQUIVALENT TEMPERATURE
 STRAIN RATE IN BOTH CASES = 0.001 IN./IN.-SEC

FIGURE 75

$$\text{MAXIMUM RATIO (PER CYCLE)} \frac{\text{TOTAL STRAIN TSF}}{\text{TOTAL STRAIN SC}} = \frac{0.0026}{0.010}$$

CW = COLD-WORKED
 Ann. = ANNEALED
 SC = STRAIN CYCLING
 TSF = THERMAL-STRESS CYCLING

FATIGUE LIFE OF ZIRCALLOY-2 TESTED BY STRAIN CYCLING AND
 THERMAL-STRESS CYCLING AT 400°C EQUIVALENT TEMPERATURE
 STRAIN RATE IN BOTH CASES = 0.001 IN./IN.-SEC

FIGURE 76

$$\text{MAXIMUM RATIO (PER CYCLE)} \frac{\text{TOTAL STRAIN TSF}}{\text{TOTAL STRAIN SC}} = \frac{0.0026}{0.010}$$

CW = COLD-WORKED
 Ann. = ANNEALED
 SC = STRAIN CYCLING
 TSF = THERMAL-STRESS CYCLING

FATIGUE LIFE OF ZIRCONIUM AND ZIRCALOY-2 TESTED BY STRAIN CYCLING AND
 THERMAL-STRESS CYCLING AT 500°C EQUIVALENT TEMPERATURE
 STRAIN RATE IN BOTH CASES = 0.001 IN./IN.-SEC

FIGURE 77

CW = COLD-WORKED
Ann. = ANNEALED
TSF = THERMAL-STRESS CYCLING

SC = STRAIN CYCLING
 T_e = EQUIVALENT TEMPERATURE

TOTAL PLASTIC STRAIN TO FAILURE FOR
THERMAL-STRESS AND STRAIN-CYCLED ZIRCONIUM
STRAIN RATES IN SC AND TSF ARE EQUAL

FIGURE 78

CW = COLD-WORKED
 Ann. = ANNEALED
 TSF = THERMAL-STRESS CYCLING
 SC = STRAIN CYCLING
 T_e = EQUIVALENT TEMPERATURE

TOTAL PLASTIC STRAIN TO FAILURE FOR
 THERMAL-STRESS AND STRAIN-CYCLED ZIRCALLOY-2
 STRAIN RATES IN SC AND TSF ARE EQUAL

FIGURE 79

CONCLUSIONS

A. Thermal-Stress Cycling

The thermal-stress-fatigue experiments on zirconium and Zircaloy-2 have led to the following conclusions.

1. Fatigue life decreases with increasing temperature change (ΔT) and mean temperature (T_m) for all cases tested.
2. Graphs of ΔT versus cycles to failure (N) are similar to the S-N curves obtained in conventional fatigue data. However, no endurance limit is evident.
3. Fatigue life is increased by testing in argon instead of air. The effect is more prominent at lower ΔT (hence higher mean temperature).
4. At high strains per cycle, there is a tendency for cold-worked material to have a shorter fatigue life than annealed material. However, the reverse is true at low strains per cycle.
5. Prior cold work does not necessarily increase the total stress change per cycle that a specimen can withstand at a given fatigue life.
6. Cold-worked material shows a tendency to strain-soften during fatigue only when tested in argon at high T_m and low strain per cycle. Generally, no predictions can be made as to whether a material will strain-harden or soften during thermal-stress fatigue.
7. Reverse loading decreases fatigue life at high strains per cycle and increases fatigue life at low strains per cycle. At half life, both normally loaded and reverse-loaded specimens have the same compressive and tensile stresses exerted on them by changing temperature, other things being equal.
8. The large number of variables studied precludes a serious attempt to reduce fatigue-life data to an equation of the form $N^n \epsilon_p = K$ (ϵ_p = plastic strain per cycle; n and K = constants). Furthermore, no satisfactory way of determining ϵ_p is evident at low total strain per cycle.
9. Generally speaking, Zircaloy-2 has a greater thermal-stress-fatigue life than zirconium.

b. Strain Cycling

Strain-cycling data on zirconium and Zircaloy-2 lead to the following conclusions:

1. Annealed material yields a longer fatigue life at all temperatures.
2. Fatigue life of strain-cycled zirconium tested is increased by testing in air instead of argon. This is not true for Zircaloy-2.
3. Generally, all material strain-softens during cycling.
4. Specimen size influences fatigue life in that complex end stresses present in the gage length can cause premature failure.
5. Prestraining results affect fatigue life in such a way that it is advisable to establish the optimum prestrain before conducting normal cycling. This phenomenon is associated with the initial plastic strain necessary to bring compressive and tensile stresses to relatively equal magnitude (and opposite sign).
6. After only a few cycles, the compressive and tensile stresses become relatively equal and opposite in magnitude, resulting in a rapid closing of the hysteresis loop.
7. Fatigue life increases with increasing strain rate, thus elucidating the fact that the plastic strain per cycle decreases with increasing strain rate.
8. Fatigue life in strain cycling can be reduced to an equation of the form

$$N^n \epsilon_p = K$$

The many variables taken into consideration greatly affect n and K factors and lead to erroneous predictions if just one equation is written. Over-all trends result in the indicated range of n and K listed below:

$$n = 0.2 \text{ to } 0.38.$$

$$K = 0.02 \text{ to } 0.048.$$

c. General

The relationship between strain cycling and thermal-stress cycling at equivalent temperatures is summarized as follows:

Strain cycling at a strain per cycle of roughly four times that incurred in thermal-stress cycling at an equivalent temperature leads to approximately the same amount of total plastic strain to failure. Restated, this means that other things being equal

(equivalent temperature, strain per cycle), strain-cycling fatigue life is approximately four times greater than thermal-stress fatigue life.

It is furthermore concluded that a sufficient number of variables were studied in the program to make the results very useful to reactor designers and others interested in the fatigue life of zirconium and Zircaloy-2. This approach was adopted to prevent the necessity for extrapolation by designers faced with set operating conditions other than those normally listed in fatigue data.

APPENDIX A

LIST OF SYMBOLS

α	=	coefficient of linear thermal expansion (in. /in. -°C)
a	=	constant = slope of Young's modulus versus temperature curve
b	=	constant = intercept of Young's modulus versus temperature curve
c	=	constant
ϵ	=	strain (elastic)
ϵ_e	=	elastic strain per complete cycle
ϵ_p	=	plastic strain per complete cycle
ϵ_t	=	total strain change
K	=	constant = intercept of plastic strain to failure versus cycles-to-failure on log-log paper
l	=	specimen length
l_e	=	effective specimen gage length
l_o	=	measured specimen gage length
n	=	constant = slope of plastic strain to failure versus cycles to failure on log-log paper
N	=	cycles to failure
m	=	constant = strain-hardening exponent
σ_o	=	constant = stress where true strain equals 1
σ	=	stress (psi)
σ_2	=	stress at temperature T_2 (psi)
σ_1	=	stress at temperature T_1 (psi)
} in thermal-stress fatigue data		
σ_2	=	stress when specimen is at its original length
σ_1	=	stress when specimen is at its extended length
} in strain-cycling data		
σ_t	=	$\sigma_1 + \sigma_2$

T = temperature ($^{\circ}\text{C}$)

T_1 = low temperature of thermal cycling ($^{\circ}\text{C}$)

T_2 = high temperature of thermal cycling ($^{\circ}\text{C}$)

T_m = mean temperature of thermal cycling = $\frac{T_2 + T_1}{2}$

ΔT = temperature change during thermal cycling

Y = Young's modulus

V = volume of metal in gage length

APPENDIX B

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TABLE C-I
MANUFACTURER'S CHEMICAL ANALYSIS
OF ZIRCONIUM AND ZIRCALOY-2

Element	Melt No.			
	Zirconium, M-262 (ppm)	Zircaloy-2, M-250 (ppm)	Zircaloy-2, M-251 (ppm)	Zircaloy-2, M-402 (ppm)
Sn	None	1.44%	1.41%	1.56%
Fe	360	1410	1285	1410
Cr	<25	740	720	1130
Ni	<25	584	556	552
Hf	<45	<45	<45	<100
B	<0.5	<0.5	<0.2	<0.5
Co	<5	<5	<5	<5
Cd	<0.5	<0.5	<0.2	<0.5
Mn	<10	<10	<10	<10
W	<20	<20	<20	<20
Al	<30	<30	<30	<30
Mg	<15	<15	<15	<15
Zn	<10	<10	<10	<10
H ₂	25	16	16	15
N ₂	33	40	55	65
Cu	<10	30	20	27
Pb	<15	<15	<15	<15
Si	35	<30	<30	66
Ti	<20	<20	<20	38
Mo	<20	<20	<20	<30
V	<20	<20	<20	<20
C	214	322	242	236
O ₂	920	1280	1160	1800

TABLE C-II
MANUFACTURER'S PHYSICAL ANALYSIS
OF ZIRCONIUM AND ZIRCALOY-2

Material	Hardness R_B	Tensile Test			Burst Test		Corrosion Test	Cold Work
		Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Yield Point (psi)	Burst Pressure (psi)	Weight Gain (mg/dm ²)	Final Cold Work (%)
Zirconium M-262	84.0	83,300	80,125	8	7,500	8,500	46.7-51.9**	20.6
Zircaloy-2 M-250	95.0	100,250	-	10	9,750	11,500	29.34-30.27*	27
Zircaloy-2 M-251	95.0	102,270	-	10	9,500	11,750	27.89-29.61*	27
Zircaloy-2 M-402	100	115,665	108,325	-	-	-	20.4*	25

* In water for 14 days at 750°F

** In water for 14 days at 680°F

TABLE C-III
SHORT-TIME TENSILE TEST DATA*

Melt No.	Temperature (°C)	Atmosphere	Strain Rate (in./in./sec)	Yield Strength (.2%) (psi)	Ultimate Strength (psi)	Elongation (%)	Strain-Hardening Exponent, m	Stress, σ_o
<u>Zirconium (Annealed 48 hr at 600°C in vacuum, furnace cooled)</u>								
M-262	500	Air	.0001	5,700	9,250	43.5	-	-
	400	"	.0001	8,700	12,320	17	.117	18,500
	300	"	.0001	7,730	17,700	20	.133	25,000
	200	"	.0001	15,670	26,000	35	-	-
	100	"	.0001	25,825	39,700	27	-	-
	Room Temp.	"	.0001	29,000	53,000	18	.137	75,000
M-262	600	Air	.001	4,075	6,850	84	-	-
	500	"	.001	8,640	12,364	37	-	-
	400	"	.001	7,800	14,700	-	.160	23,500
	300	"	.001	9,440	14,700	-	.160	24,000
	200	"	.001	16,710	29,075	30.5	-	-
	100	"	.001	20,250	42,290	25	-	-
	Room Temp.	"	.001	29,900	56,250	18	.126	77,000
M-262	600	Argon	.001	4,850	7,190	91	-	-
	500	"	.001	8,430	12,890	33	-	-
	400	"	.001	6,835	14,450	34.5	-	-
	300	"	.001	10,840	20,430	35.5	-	-
	200	"	.001	18,360	31,970	30	-	-
	100	"	.001	22,540	45,080	22	-	-
	Room Temp.	"	.001	25,615	54,770	20	-	-

* Specimen geometry same as in fatigue tests.

TABLE C-III
(cont.)

Melt No.	Temperature (°C)	Atmosphere	Strain Rate (in./in./sec)	Yield Strength (.2%) (psi)	Ultimate Strength (psi)	Elongation (%)	Strain-Hardening Exponent, m	Stress, σ_o
<u>Zirconium (Cold-Worked)</u>								
M-262	600	Air	.0001	5,254	5,495	58	-	-
	500	"	.0001	15,050	15,450	36	.0133	16,700
	400	"	.0001	23,550	24,550	14	.024	27,000
	300	"	.0001	31,200	36,900	6	.118	75,000
	200	"	.0001	45,000	46,500	6	.0179	50,000
	100	"	.0001	59,970	60,860	7.5	-	-
	Room Temp.	"	.0001	63,100	72,000	6	.0585	90,000
M-262	600	Air	.001	6,680	7,940	67	-	-
	500	"	.001	24,400	25,400	13	.0346	29,000
	400	"	.001	25,700	28,600	7	.0520	35,000
	300	"	.001	35,000	40,900	5	.0718	58,000
	200	"	.001	38,600	49,900	6	.096	76,000
	100	"	.001	64,190	66,800	6.9	-	-
	Room Temp.	"	.001	66,000	75,300	6	.101	110,000
M-262	600	Argon	.001	7,890	9,060	62	-	-
	500	"	.001	20,435	20,925	17	-	-
	400	"	.001	32,400	32,960	4.5	-	-
	300	"	.001	-	40,530	7.0	-	-
	200	"	.001	34,520	44,110	7.5	-	-
	100	-	-	-	-	-	-	-
	Room Temp.	Argon	.001	71,250	75,260	5.5	-	-

TABLE C-III
(cont.)

Melt No.	Temperature (°C)	Atmosphere	Strain Rate (in./in./sec)	Yield Strength (.2%) (psi)	Ultimate Strength (psi)	Elongation (%)	Strain-Hardening Exponent, m	Stress, σ_o
<u>Zircaloy-2 (Annealed 24 hr at 725°C in vacuum, furnace cooled)</u>								
M-251	600	Air	.0001	-	-	-	-	-
	500	"	.0001	10,900	23,050	22	.161	35,000
	400	"	.0001	12,325	25,950	24.9	.213	46,000
	300	-	-	-	-	-	-	-
	200	Air	.0001	27,000	43,750	18	.128	60,000
	100	-	-	-	-	-	-	-
	Room Temp.	Air	.0001	41,600	72,800	17	.200	118,000
M-251	600	Air	.001	12,450	16,920	53	.086	21,500
	500	"	.001	13,000	23,300	21	.120	34,000
	400	-	-	-	-	-	-	-
	300	"	.001	19,400	34,800	25	.157	52,000
	200	"	.001	29,550	47,000	25	.112	62,500
	100	-	-	-	-	-	-	-
	Room Temp.	"	.001	53,400	84,200	17	.133	120,000
<u>Zircaloy-2 (27% Cold Worked)</u>								
M-251	600	Air	.0001	12,075	12,300	45	.0227	13,500
	500	"	.0001	19,450	23,600	39	.0866	32,000
	400	"	.0001	36,410	39,400	13	-	-
	300	"	.0001	52,900	55,800	5	-	-
	200	"	.0001	56,100	67,250	10	-	-
	100	"	.0001	64,140	66,780	9.0	-	-
	Room Temp.	"	.0001	89,400	97,400	18	-	-

TABLE C-III
(concl.)

Melt No.	Temperature (°C)	Atmosphere	Strain Rate (in./in./sec)	Yield Strength (.2%) (psi)	Ultimate Strength (psi)	Elongation (%)	Strain-Hardening Exponent, m	Stress, σ_o
<u>Zircaloy-2 (27% Cold Worked)</u>								
M-251	600	Air	.001	15,290	18,365	47.5	.068	24,000
	500	"	.001	-	-	-	-	-
	400	"	.001	-	-	-	-	-
	300	"	.001	58,170	58,810	7.5	-	-
	200	"	.001	-	-	-	-	-
	100	"	.001	88,640	92,520	8.0	-	-
	Room Temp.	"	.001	-	-	-	-	-
M-251	600	Argon	.001	17,765	18,800	50.5	.058	23,000
	500	"	.001	33,240	33,600	22.5	-	-
	400	"	.001	47,920	48,750	7.5	-	-
	300	"	.001	58,170	59,225	7.5	-	-
	200	"	.001	68,145	70,640	8.5	-	-
	100	"	.001	64,975	71,310	9.5	-	-
	Room Temp.	"	.001	92,240	101,660	8	-	-
M-250	600	Air	.001	17,495	19,190	40.0	-	-
	600	"	.001	15,460	17,770	-	.036	20,800
	500	"	.001	30,750	33,100	22.0	-	-
	400	"	.001	37,670	38,480	5.5	-	-
	300	"	.001	54,020	55,320	6.5	-	-
	200	"	.001	68,560	71,050	11.0	-	-
	100	"	.001	82,270	86,980	10.5	-	-
	Room Temp.	"	.001	89,750	101,110	8.0	-	-
M-250	500	Air	.001	56,000	84,000	5	-	-
	500	"	.001	56,000	83,000	15	-	-

TABLE C-IV
THERMAL-STRESS-FATIGUE DATA FOR ZIRCONIUM

Specimen No.	ΔT	N	$T_{avg.}$	At Half Life			ϵ_e	ϵ_p	ϵ_t
	(°C)					σ_2	σ_1	σ_t	($\times 10^{-6}$ in./in.)
	(°C)		(°C)	(psi)	(psi)	(psi)	($\times 10^{-6}$ in./in.)	($\times 10^{-6}$ in./in.)	($\times 10^{-6}$ in./in.)
<u>Annealed, $T_2 = 500^\circ\text{C}$, Air</u>									
S-544	400	1,257	300	4,775	17,930	22,700	1,875	515	2,392
S-543	300	2,590	350	2,100	12,900	15,000	1,280	540	1,820
S-545	200	5,380	400	5,565	5,395	10,960	1,080	-87	1,167
S-552	100	17,850	450	4,925	1,700	6,620	695	-90	606
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Air</u>									
525	400	1,253	300	4,100	17,900	22,000	1,810	480	2,290
524	300	1,483	350	4,520	10,540	15,060	1,525	200	1,730
522	200	3,404	400	-	-	9,500	975	220	1,180
520	100	18,500	450	4,410	1,765	6,175	648	-188	460
<u>Annealed, $T_2 = 500^\circ\text{C}$, Argon</u>									
S-546	400	2,960	300	5,635	16,560	22,195	1,860	450	2,310
S-548	300	3,110	350	4,800	11,200	16,000	1,430	310	1,740
S-551	200	>5,800	400	3,245	7,320	10,565	1,005	122	1,127
S-550	100	20,550	450	4,140	2,365	6,505	682	-90	592
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Argon</u>									
527	400	2,200	300	7,550	16,950	24,500	2,100	130	2,230
528	300	2,772	350	7,200	9,955	17,155	1,590	115	1,705
529	200	6,700	400	5,035	6,690	11,725	1,135	-50	1,803
531	100	21,700	450	5,755	800	6,550	700	-115	585

TABLE C-IV
(concl.)

Specimen No.	ΔT (°C)	N	$T_{avg.}$ (°C)	At Half Life			ϵ_e ($\times 10^{-6}$ in./in.)	ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)
				σ_2 (psi)	σ_1 (psi)	σ_t (psi)			
<u>Cold-Worked, $T_2 = 600^\circ\text{C}$, Air</u>									
532	500	153	350	1,630	(17,370)	(19,000)	(1,515)	(1,540)	3,056
533	400	269	400	2,850	12,915	15,765	1,405	1,065	2,470
535	300	445-480	450	3,290	10,830	14,100	1,365	470	1,835
536	200	1,480	500	3,455	6,680	10,135	1,075	152	1,227
537	100	1,760	550	3,065	3,260	6,325	725	-108	617
<u>Cold-Worked, $T_2 = 600^\circ\text{C}$, Argon</u>									
538	500	480	350	4,165	14,611	18,780	1,615	1,315	2,930
661	400	525	400	3,445	11,175	14,620	1,515	795	2,310
540	300	608	450	2,420	8,305	10,725	1,037	790	1,828
656	200	3,225	500	3,155	5,225	8,380	895	325	1,220
650	100	4,125	550	3,425	1,930	5,350	625	-5	620

TABLE C-V
THERMAL-STRESS-FATIGUE DATA FOR ZIRCALOY-2

Specimen No.	ΔT (°C)	N	$T_{avg.}$ (°C)	At Half Life			ϵ_e ($\times 10^{-6}$ in./in.)	ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)
				σ_2 (psi)	σ_1 (psi)	σ_t (psi)			
<u>Annealed, $T_2 = 500^\circ\text{C}$, Air</u>									
S-117	400	3,250	300	5,800	20,000	25,800	2,120	160	2,280
S-118	300	4,328	350	3,200	14,800	18,000	1,550	190	1,740
S-119	200	7,577	400	6,000	4,000	10,000	1,000	170	1,170
S-124	100	6,300	450	5,000	-1,500	6,500	700	-150	550
S-123	50	7,768	475	7,500	4,500	3,000	1,265	-940	325
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Air</u>									
253	400	35-3900	300	5,500	19,000	24,500	2,000	600	2,600
105	400	2,900	300	5,700	17,000	22,700	1,900	460	2,360
109	300	4,115	350	8,950	9,050	18,000	1,700	30	1,730
107	200	15,347	400	11,200	1,500	12,700	1,350	-200	1,150
106	100	13,579	450	9,300	2,900	6,400	715	-165	550
<u>Annealed, $T_2 = 500^\circ\text{C}$, Argon</u>									
S-127	400	4,028	300	6,890	15,180	22,000	1,890	390	2,280
S-139	300	6,890	350	5,485	11,135	16,620	1,510	105	1,616
S-140	200	11,994	400	3,525	7,250	10,775	1,025	120	1,144
S-150	100	>40,000	450	7,300	-1,800	5,500	600	-50	550
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Argon</u>									
135	400	3,077	300	7,000	14,500	21,500	1,850	530	2,380
137	300	7,167	350	5,500	11,000	16,500	1,490	130	1,620
134	200	8,000	400	5,650	6,630	12,280	1,190	-30	1,160
136	100	35,500	450	9,260	-3,930	5,330	615	-65	550

TABLE C-V
(cont.)

Specimen No.	ΔT (°C)	N	$T_{avg.}$ (°C)	At Half Life			ϵ_e ($\times 10^{-6}$ in./in.)	ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)
				σ_2	σ_1	σ_t			
				(psi)	(psi)	(psi)			
<u>Annealed, $T_2 = 600^\circ\text{C}$, Air</u>									
S-120	500	580	350	9,700	24,400	34,100	3,010	-190	2,820
S-128	400	321	400	4,900	16,220	21,100	1,950	530	2,480
S-129	300	802	450	7,050	13,950	21,000	2,100	-270	1,830
S-130	200	802	500	6,600	5,100	11,700	1,300	-100	1,205
S-138	100	859	550	7,650	-1,100	6,550	810	-160	650
<u>Cold-Worked, $T_2 = 600^\circ\text{C}$, Air</u>									
165	500	300	350	7,100	24,000	31,100	2,680	145	2,825
166	400	371	400	4,000	21,000	25,000	2,200	80	2,280
168	300	494	450	8,000	13,500	21,500	2,150	-320	1,830
170	200	723	500	8,150	6,500	14,650	1,630	-420	1,207
172	100	898	550	7,130	350	7,480	910	-275	633
<u>Annealed, $T_2 = 600^\circ\text{C}$, Argon</u>									
S-238	500	538	350	5,120	22,330	27,450	2,290	530	2,820
S-240	400	545	400	6,180	14,360	20,530	1,930	330	2,260
S-239	300	779	450	4,600	11,500	16,100	1,600	180	1,780
S-242	200	3,941	500	7,100	5,920	13,020	1,445	-210	1,235
S-241	100	4,925	550	9,450	-2,830	6,620	850	-260	590
<u>Cold-Worked, $T_2 = 600^\circ\text{C}$, Argon</u>									
164	500	694	350	6,800	23,000	29,800	2,570	680	3,250
167	400	603	400	7,000	16,500	23,500	2,200	320	2,317
169	300	802	450	6,030	12,150	18,180	1,820	-30	1,790
171	200	5,223	500	9,050	5,570	14,620	1,645	-490	1,156
173	100	~8,520	550	10,315	-2,890	7,420	1,140	-590	550

TABLE C-V
(concl.)

Specimen No.	ΔT (°C)	N	$T_{avg.}$ (°C)	At Half Life			ϵ_e ($\times 10^{-6}$ in./in.)	ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)
				σ_2	σ_1	σ_t			
				(psi)	(psi)	(psi)			
<u>Cold-Worked, $T_2 = 700^\circ\text{C}$, Air</u>									
254	400	55	500	5,700	15,100	20,800	2,150	180	2,330
256	300	96	550	5,690	11,980	17,670	1,970	-810	1,160
251	200	80	600	2,960	11,100	14,060	1,605	-395	1,210
257	100	130	650	4,020	1,637	5,660	760	-	-
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Air, Reverse Load</u>									
245	400	4,350	300	6,000	20,700	26,700	2,210	195	2,405
248	300	7,275	350	7,200	11,000	18,200	1,675	65	1,740
244	200	7200-7608	400	7,400	5,700	13,100	-	-	1,170
246	100	6450-9540	450	-	-	6,600	-	-	623
<u>Cold-Worked, $T_2 = 500^\circ\text{C}$, Air, Prestrain</u>									
249*	400	4,000	300			25,800	-	131	2,330
250†	400	4,250	300			24,600	-	95	2,156
252‡	400	5,000	300			24,100	-	225	2,270

* Prestrain: 12,000 psi tension

† Prestrain: 4,000 psi compression

‡ Prestrain: 7,500 psi compression

TABLE C-VI
STRAIN-CYCLING DATA FOR ZIRCONIUM
(Melt M-262)

Specimen No.	Test Temp. (°C)	N	Strain Rate (sec)	Area (in. ²)	Gage Length (in.)	Hold Time (min)	At Half Life			ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)	Atmos- phere
							σ_2	σ_1	σ_t			
							(psi)	(psi)	(psi)			
573	500	127	.001	.0335	2	3	7,132	6,381	13,513	3,547	5,000	Air
569	500	31	.001	.0335	2.00	3	8,209	6,903	15,112	8,375	10,000	Air
590	500	35	.001	.0335	2.00	3	7,552	6,797	14,349	8,457	10,000	Air
S-557	500	66	.001	.0335	2.00	3	4,478	3,731	8,209	9,117	10,000	Air
514	500	29	.0001	.0308	2.313	3	7,792	6,494	14,286	8,444	9,980	Air
516	500	33	.0001	.0314	2.326	3	10,072	6,446	16,518	8,234	10,000	Vac.
578	500	14	.001	.0335	2.00	3	9,440	4,154	13,594	7,820	10,000	Argon
579	500	17	.001	.0333	2.00	3	8,129	4,559	12,688	8,536	10,000	Argon
576	400	1,083	.001	.0333	2.00	3	13,138	12,950	26,088	2,143	5,000	Air
509	400	42	.0001	.0308	2.316	3	17,005	15,625	32,630	6,821	10,020	Air
526	400	16	.0001	.0175	2.297	3	13,590	16,626	30,216	6,998	9,960	Air
570	400	32	.001	.0335	2.00	3	14,254	14,440	28,694	7,187	10,000	Air
591	400	5	.001	.0335	2.00	3	13,971	14,349	28,320	7,241	10,000	Air
S-558	400	120	.001	.0335	2.00	3	9,515	8,582	18,097	8,226	10,000	Air
507	400	5,000	.0001	.0327	2.244	3	15,474	14,700	30,174	2,031	4,990	Vac.
517	400	95	.0001	.0304	2.284	3	15,813	18,309	34,122	7,075	10,042	Vac.
519	400	1	.0001	.0381	2.286	3	7,969	12,086	20,055	21,874	23,840	Vac.
588	400	24	.001	.0335	2.00	3	15,104	12,084	27,188	7,334	10,000	Argon
S-567	400	106	.001	.0333	2.00	3	10,713	7,218	17,931	8,242	10,000	Argon
S-568	400	133	.001	.0333	2.00	3	11,776	6,306	18,082	8,377	10,000	Argon

TABLE C-VI
(concl.)

Specimen No.	Test Temp. (°C)	N	Strain Rate (sec)	Area (in. ²)	Gage Length (in.)	Hold Time (min)	At Half Life			ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)	Atmos- phere
							σ_2	σ_1	σ_t			
							(psi)	(psi)	(psi)			
518	300	78	.0001	.0307	2.270	3	24,723	25,630	50,353	5,505	10,000	Vac.
575	300	3,071	.001	.0333	2.00	3	16,742	16,366	33,108	2,094	5,000	Air
587	300	188	.001	.0333	2.00	3	17,455	21,321	38,776	6,538	10,000	Air
592	300	30	.001	.0335	2.00	3	18,125	20,920	39,045	6,514	10,000	Air
S-559	300	1,080	.001	.0335	2.00	3	12,761	12,239	25,000	7,768	10,000	Air
510	300	71	.0001	.0302	2.261	3	21,937	22,310	44,247	6,049	10,000	Air
582	300	76	.001	.0333	2.00	3	22,033	20,134	42,167	6,235	10,000	Argon
S-562	300	835	.001	.0335	2.00	3	14,198	10,573	24,771	7,988	10,000	Argon
585	200	309	.001	.0335	2.00	3	24,067	28,433	52,500	5,697	10,000	Air
584	200	458	.001	.0335	2.00	3	23,993	23,880	47,873	6,076	10,000	Air
593	200	245	.0001	.0333	2.00	3	26,212	26,592	52,804	5,671	10,000	Air
S-565	200	1,492	.001	.0335	2.00	3	15,672	15,037	30,709	7,483	10,000	Air
511	200	76	.0001	.0310	2.225	3	22,581	24,597	47,178	6,193	10,020	Air
586	200	200	.001	.0333	2.00	3	27,503	26,212	53,715	5,597	10,000	Argon
S-564	200	1,332	.001	.0333	2.00	3	17,095	14,815	31,910	7,385	10,000	Argon
594	100	871	.001	.0333	2.00	3	28,941	30,218	59,159	5,718	10,200	Air
S-566	100	2,064	.001	.0333	2.00	3	20,533	20,571	41,104	6,886	10,000	Air
513	100	614	.0001	.0306	2.285	3	29,820	29,820	59,640	5,502	9,980	Air
583	100	1,013	.001	.0335	2.00	3	31,342	31,115	62,457	5,269	10,000	Argon
S-563	100	1,710	.001	.0333	2.00	3	21,653	18,006	39,659	6,996	10,000	Argon

TABLE C-VII
STRAIN-CYCLING DATA FOR ZIRCALOY-2

Specimen No.	Melt	Test Temp. (°C)	N	Strain Rate (sec)	Area (in. ²)	Gage Length (in.)	Hold Time (min)	At Half Life			ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)	Atmos- phere	Prestrain (in./in.)
								σ_2 (psi)	σ_1 (psi)	σ_t (psi)				
132	251	500	17-52	.0001	.0182	2.125	3	16,484	14,766	31,250	6,040	9,400	Air	
142	"	500	31	.0001	.0352	2.240	3	16,077	13,269	30,500	6,700	10,080	Air	
149	"	500	5	.001	.0331	2.263	3	15,106	11,518	26,624	21,787	24,740	Air	
152	"	500	54	.001	.0335	2.288	3	14,888	12,239	27,827	7,000	9,960	Air	
157	"	500	1,374	.001	.0336	2.249	3	13,021	14,695	27,716	2,040	5,020	Air	
161	"	500	84	.001	.0343	2.230	3	17,493	14,577	32,070	11,521	14,930	Air	
204	250	500	20	.001	.0327	2.000	3	15,558	15,061	30,619	11,708	15,000	Air	
207	"	500	23	.001	.0331	2.00	3	16,805	15,558	32,353	16,520	20,000	Air	
212	"	500	155	.001	.0333	2.00	3	15,465	14,264	39,729	6,853	10,050	Air	
218	"	500	234	.001	.0328	1.016	3	15,282	14,253	29,535	6,824	10,000	Air	
230	"	500	75	.001	-	-	3	14,165	12,271	86,436	7,158	10,000	Air	
S-194	"	500	165	.001	.0333	2.00	3	12,387	11,561	23,948	7,525	10,000	Air	
174	"	500	29	.001	.0334	2.167	3	18,028	9,469	27,497	7,044	10,000	Argon	
223	"	500	21	.001	.0351	1.986	3	18,452	12,470	30,922	16,675	20,000	Argon	
225	"	500	44	.001	.0334	2.013	3	17,119	12,923	29,542	11,823	15,000	Argon	
S-189	"	500	59	.001	.0330	2.128	3	12,190	6,747	18,937	7,964	10,000	Air	
133	251	400	10-20	.0001	.0179	2.125	3	23,743	26,187	49,930	9,215	14,110	Air	
143	"	400	154	.0001	.0330	2.241	3	28,030	28,030	56,060	4,700	10,040	Air	
153	"	400	458	.001	.0333	2.263	3	25,150	26,464	51,614	4,390	9,940	Air	
158	"	400	2	.001	.0327	2.261	3	21,904	29,625	51,529	18,459	23,520	Air	
159	"	400	51	.001	.0343	2.255	3	26,057	29,155	55,212	12,839	18,000	Air	
185	250	400	213	.001	.0329	2.196	3	26,684	24,377	51,061	4,994	10,000	Air	
217	"	400	1,615	.001	.0337	1.014	3	19,659	23,331	42,990	5,786	10,000	Air	
205	"	400	120	.001	.0331	2.00	3	23,695	25,911	79,606	5,137	10,000	Air	.005*
206	"	400	623	.001	.0335	2.00	3	26,508	26,961	53,469	4,758	10,000	Air	.005**

* 1st stroke tension

** 1st stroke compression

TABLE C-VII
(cont.)

Specimen No.	Melt	Test Temp. (°C)	N	Strain Rate (sec)	Area (in. ²)	Gage Length (in.)	Hold Time (min)	At Half Life			ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)	Atmos- phere	Prestrain (in./in.)
								σ_2	σ_1	σ_t				
								(psi)	(psi)	(psi)				
S-197	250	400	689	.001	.0333	2.00	3	20,908	20,495	41,403	5,941	10,000	Air	
178	"	400	338	.001	.0340	2.115	3	27,532	25,374	52,906	4,813	10,000	Argon	
222	"	400	1-8	.001	.0345	1.988	3	24,933	28,013	52,946	14,930	20,000	Argon	
S-190	"	400	634	.001	.0330	2.150	3	22,847	18,630	41,477	5,934	10,000	Argon	
145	251	300	400	.0001	.0320	2.236	3	30,660	31,570	62,230	4,630	10,170	Air	
154	"	300	814	.001	.0343	2.258	3	28,061	28,061	56,122	5,220	10,000	Air	
182	250	300	2	.001	.0335	2.201	3	31,115	40,707	71,822	18,587	10,000	Air	
186	"	300	693	.001	.0325	2.160	3	31,216	34,797	66,013	4,106	10,000	Air	
208	"	300	837	.001	.0335	2.00	3	28,769	29,030	57,799	4,939	10,000	Air	.005**
228	"	300	785	.001	.0340	7.980	3	28,200	30,500	58,700	4,760	10,000	Air	.005*
S-216	"	300	2,000	.001	.0333	2.00	3	20,646	21,059	41,705	6,277	10,000	Air	
181	"	300	1,253	.001	.0324	2.168	3	32,796	29,673	62,469	4,513	10,000	Argon	
S-188	"	300	1,854	.001	.0319	2.140	3	22,683	20,065	42,748	6,183	10,000	Argon	
115	251	200	550-1100	.0001	.0165	2.125	3	31,439	41,288	72,727	3,439	9,400	Air	
116	"	200	420-440	.0001	.0164	2.125	3	33,155	37,348	70,503	3,621	9,400	Air	
146	"	200	732	.0001	.0310	2.252	3	34,070	36,290	70,360	4,480	10,120	Air	
155	"	200	997	.001	.0321	2.261	3	31,931	35,047	66,978	4,320	9,810	Air	
162	"	200	900	.001	.0330	2.240	3	33,333	34,280	67,613	4,458	10,130	Air	
184	250	200	801	.001	.0330	2.19	3	33,963	35,113	69,076	4,388	10,000	Air	
213	"	200	1,663	.001	.0333	2.00	3	31,456	33,296	64,752	4,693	10,000	Air	
274	"	200	4,060	.001	.0344	1.0	3	27,000	42,400	69,400	4,300	10,000	Air	
S-214	"	200	2,599	.001	.0335	2.00	3	22,410	23,273	45,683	6,243	10,000	Air	
180	"	200	1,398	.001	.0324	2.193	3	36,310	36,310	71,920	4,200	10,000	Argon	
S-192	"	200	2,179	.001	.0332	2.165	3	23,775	21,718	44,500	6,920	10,000	Argon	
226	"	200	1,155	.001	.0336	1.995	3	30,797	36,670	67,467	4,470	10,000	Air	.005*

* 1st stroke tension

** 1st stroke compression

TABLE C-VII
(concl.)

Specimen No.	Melt	Test Temp. (°C)	N	Strain Rate (sec)	Area (in. ²)	Gage Length (in.)	Hold Time (min)	At Half Life			ϵ_p ($\times 10^{-6}$ in./in.)	ϵ_t ($\times 10^{-6}$ in./in.)	Atmos- phere	Prestrain (in./in.)
								σ_2	σ_1	σ_t				
								(psi)	(psi)	(psi)				
131	251	100	600-625	.0001	.0182	2.125	3	34,135	48,420	82,555	3,146	9,400	Air	
147	"	100	635	.0001	.0333	2.253	3	36,787	46,358	83,221	3,815	10,120	Air	
148	"	100	676	.0001	.0322	2.263	3	37,267	47,748	85,015	7,000	13,300	Air	
156	"	100	1,602	.001	.0332	2.249	3	35,956	44,051	80,007	4,139	10,200	Air	
187	250	100	1,784	.001	.0334	2.120	3	37,723	40,828	78,551	3,958	10,000	Air	
224	"	100	3,130	.001	.0329	2.007	3	36,500	40,000	76,500	4,210	10,000	Air	
266	"	100	12,076	.001	.0353	0.985	3	12,116	50,637	62,747	5,247	10,000	Air	
S-199	"	100	2,506	.001	.0333	2.00	3	26,652	29,580	56,232	5,740	10,000	Air	
179	"	100	1,733	.001	.0322	2.129	3	40,226	42,978	83,206	3,786	10,000	Argon	
S-191	"	100	3,018	.001	.0323	2.150	3	27,023	28,981	55,500	5,720	10,000	Argon	
231	"	100	1,130	.001	.0344	2.008	3	33,758	44,054	77,812	4,306	10,000	Air	.005*
201	250	300	100†	.001	.0335	2.000	3	26,940	38,321	65,261	4,173	10,000	Air	
202	"	300	300†	.001	.0326	2.000	3	26,610	37,883	64,493	4,242	10,000	Air	
203	"	300	488†	.001	.0335	2.000	3	28,358	37,388	65,746	4,137	10,000	Air	
219	250	500	3/4 life	.001	.0328	1.014	3	14,863	14,444	29,307	6,849	10,000	Air	
220	"	500	1/2 life	.001	.0337	1.013	3	14,955	14,614	29,599	6,818	10,000	Air	

* 1st stroke tension

† For tensile test