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STRESS-RUPTURE BEHAVIOR OF TYPES 304 AND 316 STAINLESS STEEL CLADDING IN HIGH-TEMPERATURE STATIC SODIUM

AEC Research and Development Report

Atomics International
North American Rockwell

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AND MATERIALS

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By

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ABSTRACT

Stress-rupture properties of the two austenitic stainless steels, Type 304 and Type 316, were studied in a high-purity static sodium environment. Thin-walled seamless tubing, fabricated from single heats of each alloy, were tested over the range of 900 to 1400°F. This tubing was supplied with 10 to 15% cold work, and the long-term performances of the cold-worked alloys were compared with annealed material from the same heats. In addition to cold-work effects, special tests were conducted to evaluate the influence of test environment (sodium vs helium) and stress mode (uniaxial, 2:1 biaxial, and 1:1 biaxial) on the stress-rupture behavior of the two alloys.

The strength benefits of cold work were found to be dependent on test temperature and degree of cold working. If the temperature was such that recovery processes occurred in the cold-worked alloy, the long-term strength was inferior to that of annealed material. Increasing the degree of cold work was found to enhance the rate of cold-work recovery. The strengthening benefits of cold work were retained longer for Type 316 alloy than for Type 304 at the same temperature. Apparently, the recovery processes are slower in Type 316 stainless steel. Cold work reduces the creep ductility of both alloys.

Sodium test environment was found to reduce the amount of tertiary creep strain in both alloys. This effect was most pronounced under uniaxial stress. With a 2:1 biaxial stress, rupture occurred at the onset of tertiary creep, and the sodium effect was not apparent.

Stress-rupture tests conducted on Type 304 stainless steel under three stress states (uniaxial, 2:1 biaxial, and 1:1 biaxial) have shown excellent correlation of rupture strength with von Mises' distortion theory. With Type 316 stainless steel, the von Mises correlation does not exist; instead, the rupture strength of this alloy correlates best with the maximum principal stress theory.

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I. INTRODUCTION

The properties and performance of austenitic stainless steels in a high-temperature sodium environment have been the subject of extensive studies, over the past several years. These alloys have been selected as prime candidates for fuel pin cladding and structural components in the first generation of test and demonstration fast breeder reactors. The high degree of reliability associated with these reactors makes it necessary to be able to predict component performance, with service life ranging from 1 to 30 years. Selected alloys must be thoroughly characterized, and their performance established in an environment involving the interactions of high-temperature sodium, severe thermal-mechanical stresses, and neutron irradiation.

The object of the present work was to investigate the long-term mechanical behavior of the two austenitic stainless steels — Type 304 and Type 316. While these studies were performed on thin-walled seamless tubing for fuel cladding applications, much of the information is applicable to design considerations of other reactor components. The scope of the work is limited to alloy performance in a non-nuclear environment. Design allowances for irradiation effects must be factored into the data from other programs.

Major emphasis was on the long-term performance of thin-walled tubing in high-purity static sodium under biaxial stress (2:1 stress ratio). In addition to providing baseline stress-rupture data on the two alloys, special studies were conducted to evaluate the variables of cold work, test environment, and stress mode.

The work was performed in support of the LMFBR Cladding and Structural Alloys Program. Initial work, which was primarily a scoping effort to define the rupture strengths over 100 to 1000 hr, was reported previously.[1] The present studies extend the data over wider temperature and time ranges, and evaluate the influence of various process and test variables on the long-term mechanical behavior of the two austenitic stainless steels.

TABLE 1

PROPERTIES OF TYPE 304 STAINLESS STEEL TUBING,
HEAT NO. 20013
(0.275 in. ID by 0.010 in. Wall)

Chemistry

	C	Mn	P	S	Si	Ni	Cr	N_2	Co	Cu	B	Fe
wt %	0.06	1.68	0.008	0.009	0.50	9.12	18.68	0.050	0.039	0.15	0.0008	Bal

Alloy Condition – 10 to 15% cold work

Grain Size – ASTM 7.5

Tensile Strength, Room Temperature – 111,000 psi

Yield Strength, Room Temperature – 87,000 psi

Elongation, Room Temperature – 32%

Hardness – R_c 23

TABLE 2

PROPERTIES OF TYPE 316 STAINLESS STEEL TUBING,
HEAT NO. 65808
(0.275 in. ID by 0.010 in. Wall)

Chemistry

	C	Mn	P	S	Si	Ni	Cr	N_2	Co	Cu	Mo	B	Fe
wt %	0.06	1.82	0.004	0.002	0.44	13.49	17.30	0.025	0.041	0.008	2.50	0.0007	Bal

Alloy Condition – 10 to 15% cold work

Grain Size – ASTM 7

Tensile Strength, Room Temperature – 106,900 psi

Yield Strength, Room Temperature – 87,300 psi

Elongation, Room Temperature – 35%

Hardness – R_c 23

II. EXPERIMENTAL PROCEDURES

A. TEST MATERIALS

The Type 304 and Type 316 stainless steel test specimens used in this study were taken from one highly characterized heat of each alloy. The material, in the form of thin-walled seamless tubing, 0.275 in. ID by 0.010 in. wall, was supplied with 10 to 15% cold work ("1/8 hard" condition). The range of cold work reflects the uncertainty in the absolute degree of cold work. While the final cold sink reduction was reported in the fabrication history, the allowable variations in dimensional tolerance, plus straightening operations, made it impossible to report an exact value for cold work. The tubing mill considered this "1/8 hard" temper to be the minimum amount of cold work which would yield consistent structure and properties among tubing lots.

Following detailed characterization studies on each heat,[2,3] the tubular material was judged to be of high quality. The microstructures contained very few non-metallic inclusions, with almost no stringer-type inclusions. Eddy-current and ultrasonic inspection were used to exclude defective tubing from the test program. The chemical composition and mechanical properties of the heats are given in Tables 1 and 2.

Small lots of the cold-worked tubing were solution annealed for 1/2 hr in dry hydrogen. For Type 304 stainless steel, the solution treatment was 1900°F, while the Type 316 stainless steel was treated at 1950°F. These heat treatments produced a fully annealed structure, with only a slight increase in grain size. This annealed tubing was used for subsequent comparative tests with the as-received cold-worked tubing.

The tubing was cut into 4-in. long test specimens. End plugs and pressurization probes, made of the same alloy, were electron beam welded to the ends of the tube lengths. The wall thickness of each specimen was measured to 0.0001 in. by an eddy current device (Vidigage). The variation in wall thickness on a given specimen was within ±0.0005 in. The outside diameter of each tubular specimen was measured to ±0.0001 in. with a special precision profilometer.

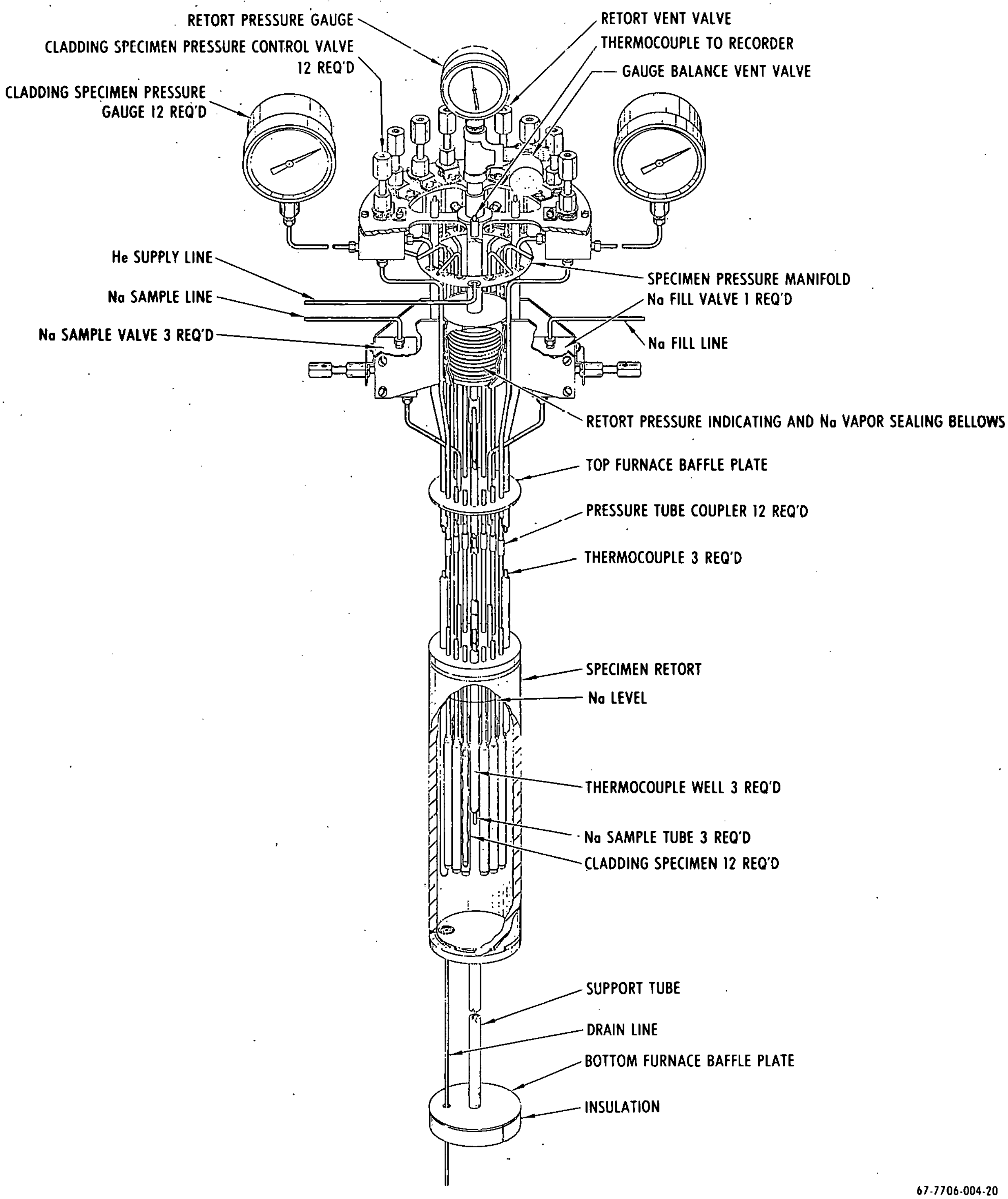

Figure 1. 12-Pin Biaxial Cladding Test Rctort for LMFBR

A limited number of Type 304 stainless steel specimens were fabricated from sheet stock. This material was obtained by slitting and rolling tube hollow material of the same heat used for the tubing. The sheet was rolled to a final dimension of 0.062 in., with final reductions to yield 38 and 11% cold work. Some of the sheet stock was also solution annealed (1900°F, 1/2 hr).

B. TEST RETORTS

The sodium retorts used in this program were of two basic designs. For stress-rupture tests where the specimen was stressed by internal gas pressure (2:1 biaxial stress ratio), a multiple-specimen testing concept was employed. As shown in Figure 1, 12 tubular specimens are suspended in the static sodium bath by means of small pressurization lines extending through the all-welded retort bulkhead. Particular care was taken to ensure that all retort components exposed to sodium were made of the same alloy as the test specimens. The specimen pressurization tubes extended to individual pressure valves and gauges which were used to adjust and monitor the specimen pressure during test. Sodium sample tubes and thermocouple wells extended through the retort bulkhead into the sodium, to enable characteriziation of the test environment during testing.

Single-specimen sodium retorts were used to impose uniaxial stress and 1:1 biaxial stress on tubular specimens. For uniaxial stress-rupture tests, extension rods were attached to end plugs welded to the tubing wall. Specially designed compression rings were applied over the plug welds, to reduce the stress in the weld region. Without these compression fittings, ruptures occurred prematurely in the heat-affected zone of the welds. Ball-and-socket joints were used on the extension rods, to provide a pure uniaxial component on loading. A stainless steel bellows provided a flexible coupling, to translate the applied tension load through the retort to the specimen. Metal-to-metal compression seals were used to provide air-tight closures at the retort ends. The retorts were installed in commercial creep machines (Arc Weld Model J-E). Because of the small cross-sectional area of the thin-walled tubing specimens, creep machines of low-load-magnification ratio (3:1 and 5:1) were used. Axial strain of the specimen during test was translated through the stainless steel bellows to a cross-head extensometer, and recorded on a strip chart recorder as a function of time.

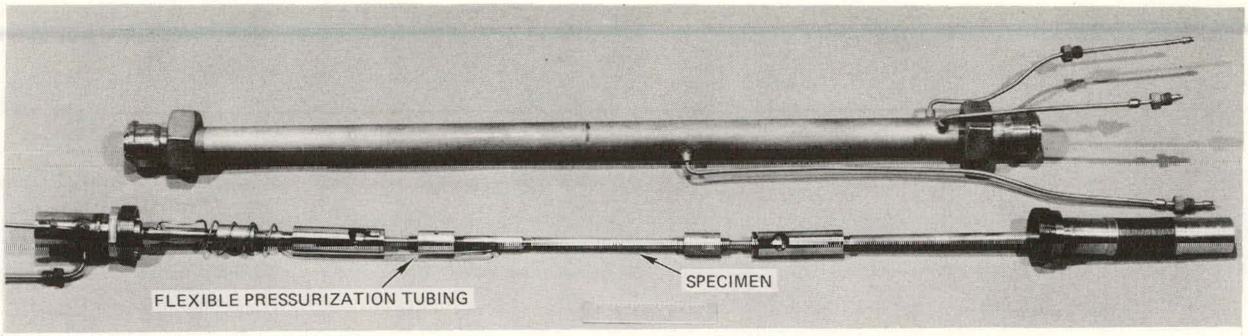

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Figure 2. Test Assembly for 1:1 Biaxial Stress-Rupture Tests

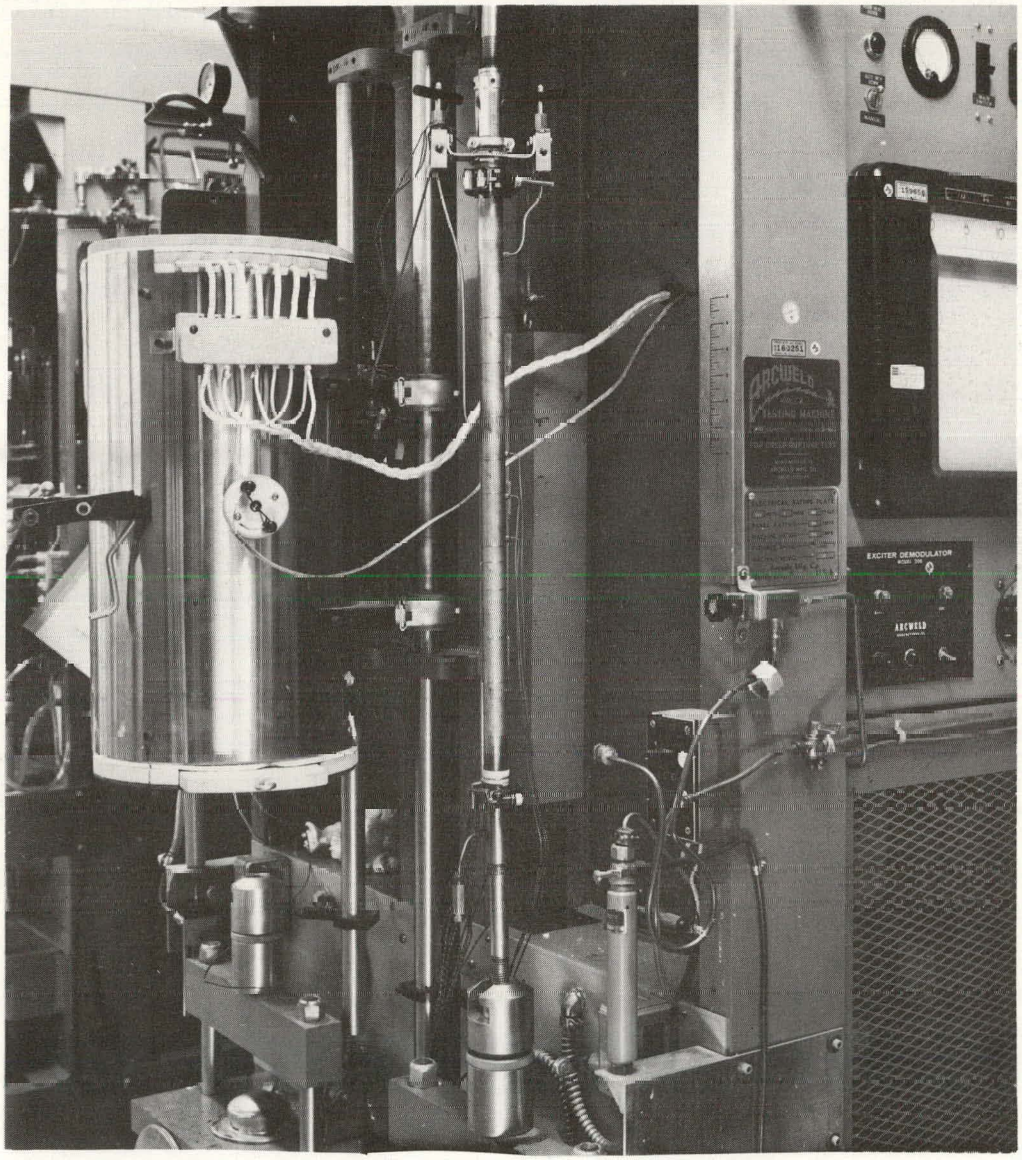

Figure 3. Assembled Single-Specimen Sodium Retort Installed in Creep Machine

Stress-rupture tests with equal axial and tangential stresses imposed on the tubing (1:1 biaxial) used the same basic sodium retort design with slight modifications. A small flexible pressurization tube was welded through the retort wall, to internally pressurize the tubular specimen with helium gas. The test assembly and sodium retort are shown in Figure 2. The assembled retort, installed in the creep machine, is pictured in Figure 3.

C. TEST ENVIRONMENTS

Sodium for the retort tests was supplied from a special loop, operated to provide a high-purity "system grade" sodium.[4] Oxygen and carbon impurities were controlled by cold trapping and hot trapping, respectively. Table 3 shows the chemistry specifications established as realistic values for reactor system sodium.[5] Plugging meter checks and weekly sampling for chemical analysis assured that the specification chemistry was maintained.

Transfer of sodium from the supply loop to the retorts was made by a special load-transfer device, described in detail in earlier reports.[6] About 450 cc of sodium was transferred to each 12-specimen test retort, with the single-specimen retorts requiring ~115 cc.

Helium was used as a test environment on a limited number of tests, to study the influence of the sodium on stress-rupture behavior. Helium was also used for internal pressurization of the specimens and as a cover gas above the sodium. All helium used in the program was of a special high-purity reactor grade. A certified analysis was obtained for each gas bottle. The nominal purity of the helium is given in Table 4.

D. SPECIMEN TEMPERATURE CONTROL AND MEASUREMENT

The specimens were heated by three-zone resistance-wound tube furnaces, 3-in. diameter bore by 24 in. long. An 8 in. isothermal zone was attained by adjustment of separate power transformers for each zone. Specimen temperatures were measured by three calibrated Chromel-Alumel thermocouples. In the 12-specimen retorts, these thermocouples were in thermocouple wells which extended into the sodium at three positions along the axial length of the specimen cluster. One thermocouple was at the axial midpoint of the specimens, while the other two were positioned 1/2 in. from each end. A second set of

TABLE 3

CHARACTERIZED SODIUM CHEMISTRY
(Typical Analysis)

Sodium Impurities		Sodium Impurities	
Element	Concentration (at 1200°F) (ppm)	Element	Concentration (at 1200°F) (ppm)
B	<1	Li	<5
C	<15	Mn	<5
Ca	<10	Ni	<25
Cd	<3	O	10 ± 5
Cl	<20	Pb	<10
Co	<3	Rb	<50
Cr	<20	Sn	<10
Fe	<50	H	<10
K	<200	N	<5

TABLE 4

HELIUM PURITY

Helium	99.99%
Oxygen	3 ppm
Hydrogen	0 ppm
Dew Point	-115°F (moisture ~0.67 ppm)

calibrated thermocouples was used as a secondary standard, to periodically check the drift of the test thermocouples. The temperature variation along the length of the specimens never exceeded ±2°F. Temperature variation from the indicated nominal test temperature was normally within ±3°F, although occasionally it fluctuated within ±5°F over the duration of the test.

E. STRESS-RUPTURE TESTING

1. 2:1 Biaxial Stress Rupture

These tests were conducted in 12-specimen static sodium retorts. Figure 4 shows a retort after sodium loading, ready for furnace installation. After heating to the desired test temperature, and isothermal conditions were established, the tubular specimens were individually pressurized with high-purity helium. The internal gas pressure required to produce the desired tangential (hoop) stress on the tubing wall was calculated from the equation for thin-wall tubing:[7]

$$P = \left(\frac{2t}{D}\right) \sigma_H$$

where:

P = internal gas pressure (psi)

σ_H = hoop stress (psi)

D = mean diameter of tubing (in.)

t = average minimum wall thickness (in.)

The gas pressures were applied slowly, to avoid shocking or overloading the specimens. Pressure was measured on a calibrated master gauge to ±0.5%. When the test pressure was attained, the specimens were individually valved from the pressurization system. The small pressure gauges provided for each specimen (see Figure 4) were for indication of internal pressure loss due to either specimen strain or rupture. Pressures were monitored visually on a semi-daily basis. Slight pressure loss, due to strain of the specimens, was often observed during primary and tertiary creep stages. The pressures were readjusted to the original value by using the master gauge. The stress-rupture tests were therefore constant-load tests. In the retorts with 12 specimens, it was routine to pressurize 3 specimens to the same stress level. For a given

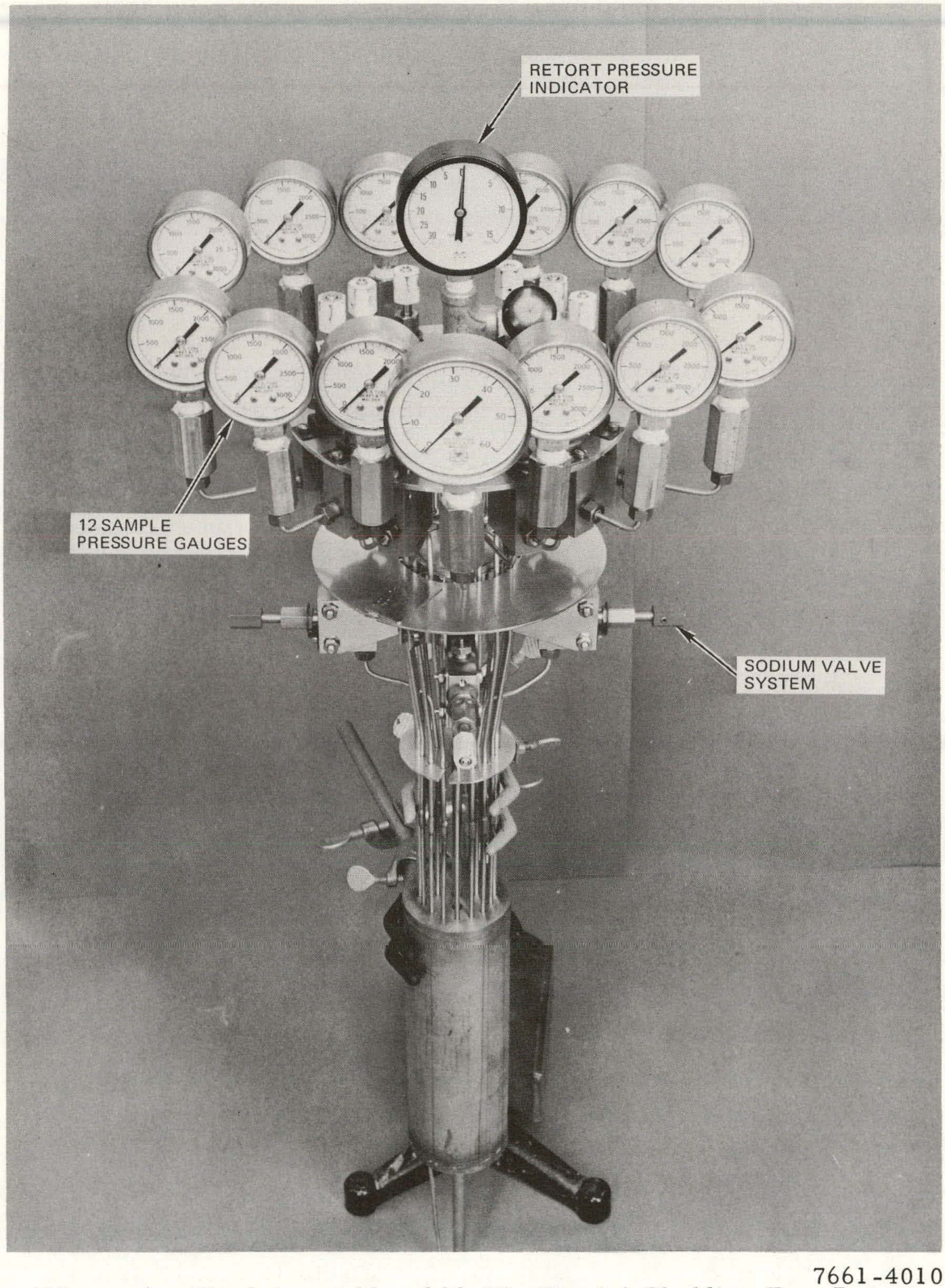

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Figure 4. Final Assembly of 12-Pin Biaxial Cladding Test Retort

retort, there were triplicate data points at four different stress levels. Specimen rupture was detected by the loss of internal pressure, concurrent with a rise in cover gas pressure above the sodium.

Three sodium samples were taken for chemical analysis on each sodium retort. The initial sample was obtained during sodium loading. The second sample was extracted from the retort midway through the test, and the final sample was obtained after all specimens had ruptured. All sodium samples were analyzed for oxygen and metal impurities. Carbon analysis was performed on ~1/3 of the samples. Figure 5 shows the oxygen levels as a function of time for the sodium retorts.

To study the effect of the sodium environment on the stress-rupture behavior of the cladding, some retorts were backfilled with helium, instead of sodium. Except for the 1 atm of helium surrounding the specimens, the tests were identical with the sodium tests.

2. 1:1 Biaxial Stress Rupture

The application of a hoop stress (internal gas pressure) and a simultaneous and equal axial stress produces a 1:1 biaxial stress ratio on the thin-walled cladding. Single-specimen sodium retorts, as described in Section II-B, were used for these tests. With the specimen under isothermal conditions at the test temperature, helium gas was introduced into the specimen to produce the desired hoop stress. At this stage, the stress in the axial direction is 1/2 the hoop stress (2:1 biaxiality). An additional axial stress was applied with a mechanical load (weights), so that the total axial stress (hydrostatic plus mechanical) was equal in magnitude to the hoop stress (1:1 biaxiality).

Specimen strain in the axial direction was monitored on a strip chart recorder throughout the tests. Diametral strain could only be measured after rupture, and removal of the specimens from the retort.

Specimen ruptures occurred as small longitudinal cracks in the tube wall. In theory, when such a failure occurred, all further specimen strain should cease. The internal gas is released, which reduces the hoop stress to zero and the axial stress to 1/2 the original value. However, it was found that, with sodium in the retort, the released gas increased the cover gas pressure above

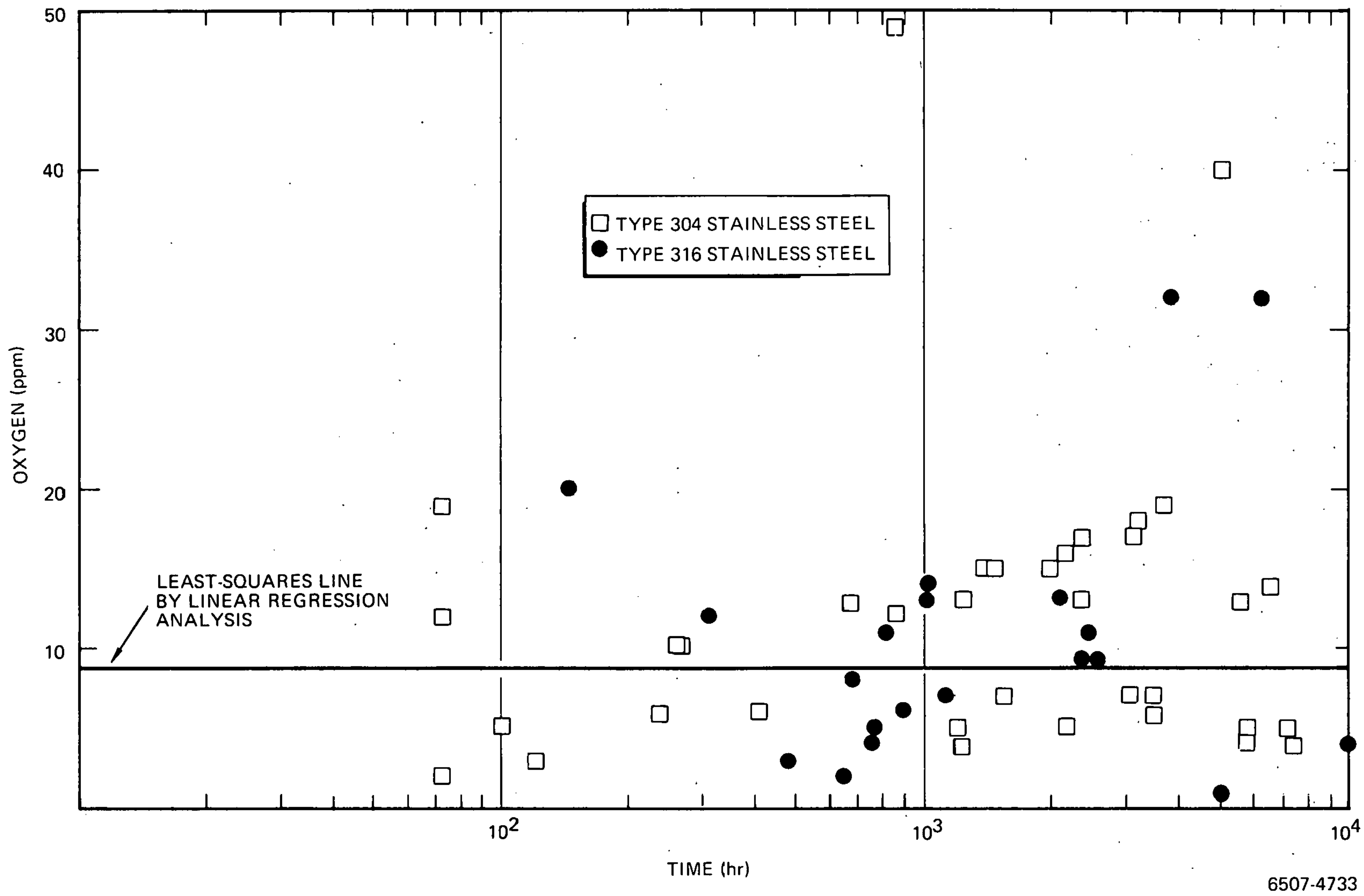


Figure 5. Static Sodium Retort Oxygen Level as Function of Test Time

the sodium. This high pressure in the cover gas region of the retort produced a significant axial load, and the specimens continued to strain in the axial direction. In tests conducted in helium, where a large gas volume existed, the gas released upon specimen rupture did not significantly increase the retort pressure, and specimen strain ceased when a rupture occurred in the tube wall.

3. Uniaxial Stress Rupture

These tests were conducted in the same sodium retorts as the 1:1 biaxial tests, except that the tubular specimens were backfilled with only 1 atm of internal helium gas. Tensile stress was applied in the axial direction on the thin-walled tubing. Some tests were also performed on Type 304 stainless steel sheet stock (0.062 in. thick) with different amounts of cold work. In some tests, helium was used in place of the sodium, to study the influence of the sodium on the various stages of creep.

F. POST-TEST EXAMINATIONS

At the completion of testing, and the procurement of the final sodium sample, the retorts were drained of sodium and disassembled. The specimens were immediately soaked in a bath of butyl alcohol, to remove sodium from the surfaces. The specimens were next rinsed in water, then absolute ethyl alcohol, and air-dried. The diameters of the specimens were measured with the same profilometer used in the before-test measurements. The specimens were examined to define the location and character of the ruptures. In most cases, the ruptures were very small — either pinholes or short longitudinal cracks. Explosive type ruptures were also encountered, especially below 1200°F, where high stresses were imposed on the tube wall. Metallographic examination was performed routinely, with x-ray diffraction and chemical analyses employed when needed.

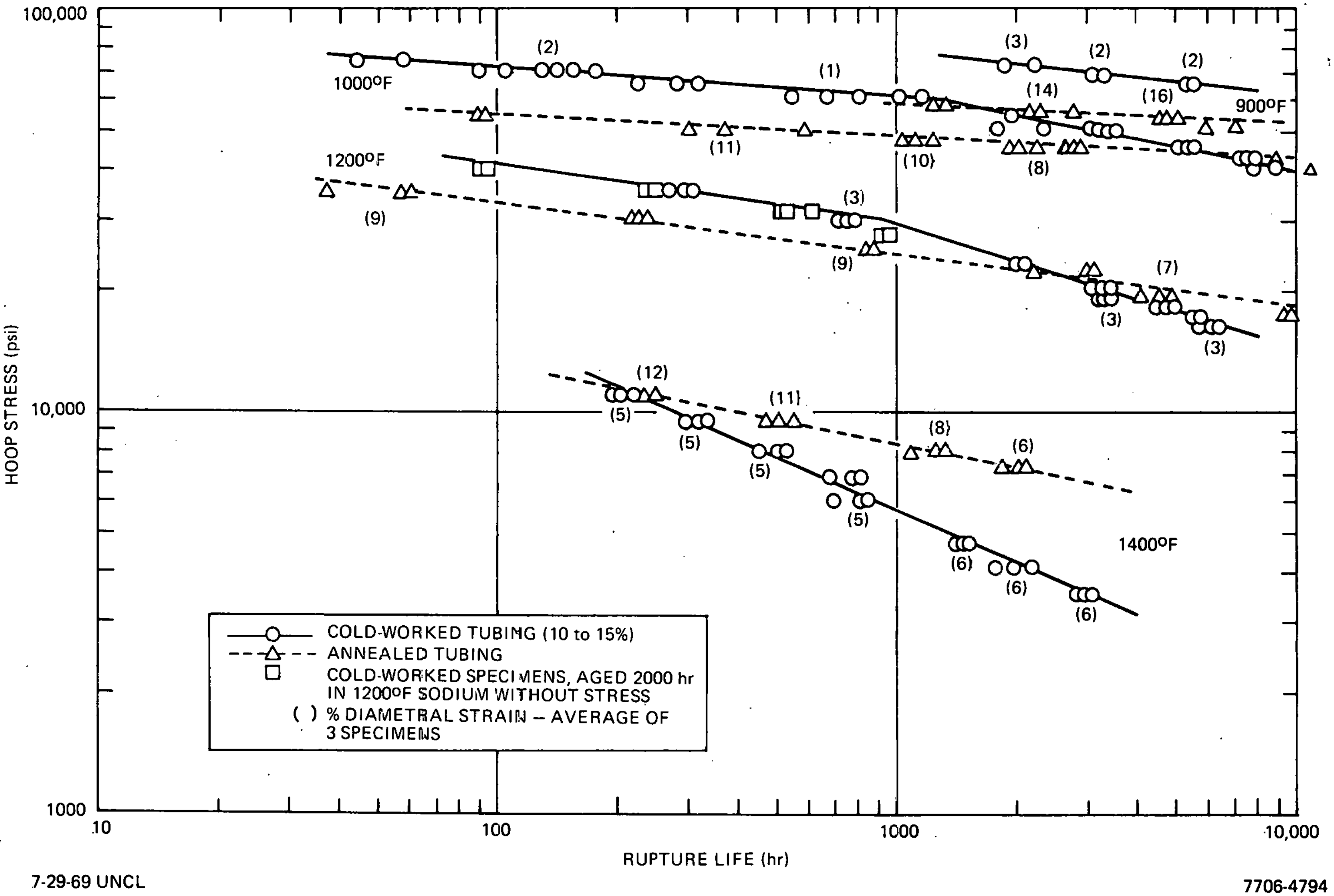


Figure 6. Biaxial Stress-Rupture Strength of Cold-Worked (10 to 15%) and Annealed Type 304 Stainless Steel in Static Sodium

III. RESULTS

A. TYPE 304 STAINLESS STEEL

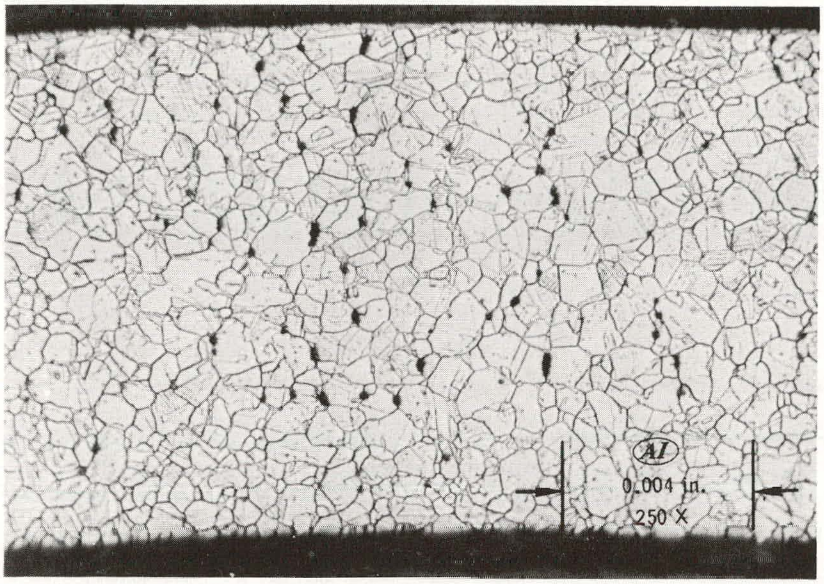
1. 2:1 Biaxial Stress

The biaxial stress-rupture results obtained on Type 304 stainless steel tubing in static sodium are plotted in Figure 6. Hoop stresses, produced by internal pressurization of the thin-walled tubing specimens (2:1 biaxiality), were selected to provide stress-rupture data over the range of 100 to 10,000 hr. Tests were conducted in 12-specimen static sodium retorts at temperatures of 900, 1000, 1200, and 1400°F. Both tubing containing 10 to 15% cold work and the annealed version of the same tubing were studied. Data on the individual test specimens are tabulated in the appendix, Tables A-1 and A-2.

The data presented in Figure 6 show that the cold-worked alloy is initially stronger than annealed material from the same lot. However, as the test time continues, the stress-rupture curves for the cold-worked alloy converge with those for the annealed material, which possesses superior long-term properties. The cold-work benefits are especially short lived at 1400°F. At lower temperatures, the strength benefits of the cold work are retained longer, with a rather strong dependence on temperature.

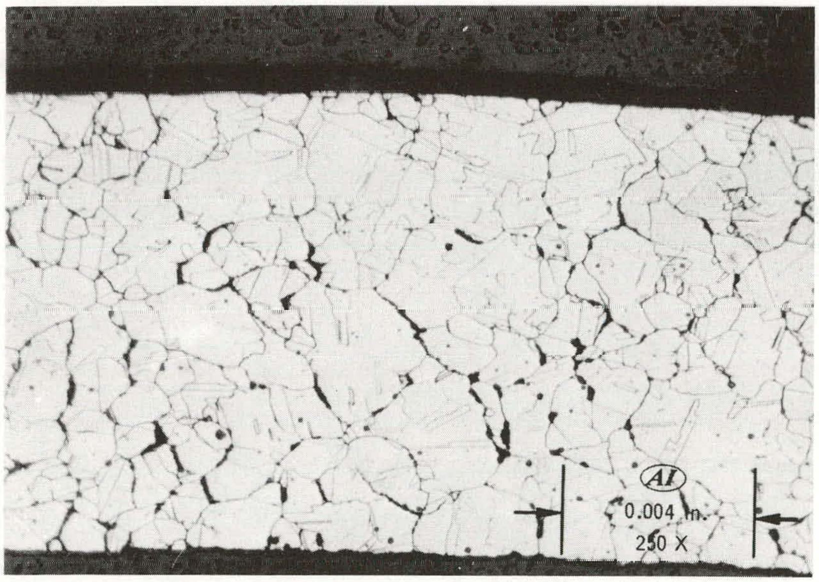
The temperature dependence suggests that the mechanism associated with the cold-work behavior involves a time-dependent, thermally activated process. To investigate this, series of tests were performed, whereby cold-worked specimens were thermally aged for 2000 hr in 1200°F sodium. The specimens were unstressed during aging. If recovery processes are operative, thermal treatment should produce changes in the stress-rupture behavior. However, subsequent biaxial stress-rupture testing revealed no change in stress-rupture properties as a result of the thermal soak (Figure 6). These observations suggest that, if recovery processes do occur, they must be activated by stress or by a combination of temperature, time, and stress parameters.

Evidence of stress-induced recrystallization and grain growth was found in the 10 to 15% cold-worked Type 304 stainless steel tubing. As an example, a specimen stressed at 17,000 psi hoop for 5600 hr at 1200°F showed no change in grain size, as compared to an unstressed control specimen in the same retort



Marble's Etch 8361-2-3

a. Hoop Stress = 17,000 psi, Rupture Time = 5600 hr



Marble's Etch 8361-1-4

b. Hoop Stress = 35,000 psi, Rupture Time = 370 hr

Figure 7. Influence of Stress on Recrystallization and Grain Growth of Type 304 Stainless Steel, Cold-Work Tested in 1200°F Helium

for the same time period. This specimen also had the same grain structure as the original starting material; however, a specimen in the same retort stressed at 35,000 psi hoop for 370 hr had a grain size 2 to 3 times larger than that of the specimen under 17,000 psi hoop stress. Figure 7 compares the grain structures of the two specimens, and illustrates the influence of stress level. It should be noted that both specimens had the same thermal exposure (5600 hr). It is apparent, from these observations, that recrystallization of cold-worked tubing is initiated at some threshold stress. The threshold stress level probably decreases as the amount of cold work increases. Grain growth was not apparent at test temperatures below 1200°F.

In annealed Type 304 stainless steel tubing, stress was found to promote grain growth at 1200°F and above, but the stress level was not found to be significant. In Figure 8, both specimens were exposed to 1200°F sodium for 5000 hr, but the specimen in Figure 8a was under stress for only 58 hr. Grain growth is apparently a function of time under stress, but is not stress-level dependent.

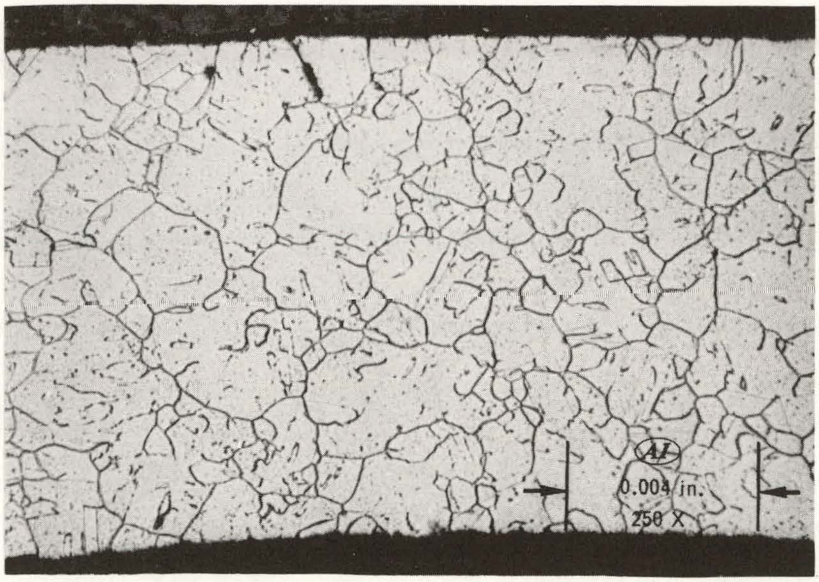
Cold working was also found to promote σ formation, as evidenced by microscopic examination. Distinct σ particles were found at grain boundaries and triple points, in all cold-worked specimens after test. While some σ particles were found in annealed tubing, the particles were sparse and smaller in size.

After stress-rupture testing, diametral strain measurements were taken on the tubular cladding with a precision profilometer, capable of measurements to ±0.00010 in. The difference between the diameter, before and after testing, represents the diametral rupture strain. These values, representing the average of triplicate tests, are shown in parentheses on the stress-rupture curves of Figure 6. It is of interest to note that the strain values of the cold-worked tubing are insensitive to stress level. The annealed alloy shows the expected behavior of decreasing strain with decreasing stress.

Diametral strain measurements were taken on over 150 biaxial (2:1) stress-rupture specimens of Type 304 stainless steel which had been tested in sodium at 900, 1000, 1200, and 1400°F. At temperatures of 900 and 1000°F, the specimen ruptures were generally of the explosive type, which produced large rupture openings and localized distortion of the tube wall. The dimensional measurements had to be taken on the tubing wall not affected by the rupture; therefore,

Marble's Etch 8373-5-3

a. Hoop Stress = 35,000 psi, Rupture Life = 58 hr, Total Sodium Exposure = 5,000 hr



Marble's Etch 8373-4-3

b. Hoop Stress = 19,000 psi, Rupture Life = 4,950 hr, Total Sodium Exposure = 5,000 hr

Figure 8. Grain Growth of Annealed Type 304 Stainless Steel During Stress-Rupture Testing in 1200°F Static Sodium

the strain values are slightly conservative. At 900°F, the rupture strain was about 50% greater than at 1000°F for annealed Type 304 stainless steel. This behavior is attributed to a change in strain mechanics, from one primarily consisting of grain boundary motion at the higher temperatures to one of transgranular slip, which is predominant at lower temperatures. Tubing containing 10 to 15% cold work also exhibited this type of strain-temperature behavior, but the magnitude of the strain was much lower than that for the annealed alloy. Figure 9 shows the strain vs temperature relationships for Type 304 stainless steel over the range of 900 to 1400°F for a 1000-hr rupture life. The increase in strain for the cold-worked alloy above 1200°F is attributed to recovery processes which become operative at the higher temperatures.

Strain rate values from pressurized tubular test specimens are obtained by dividing the strain at rupture by the time to rupture. This yields an average strain rate. Since it has been found that there is very little tertiary creep involved in the pressurized tube tests, the strain rate values obtained consist mostly of primary and secondary (steady-state) creep components. Figure 10 shows the strain rate behavior for annealed and cold-worked (10 to 15%) Type 304 stainless steel tubing in 900, 1000, and 1200°F sodium. The increased slope of the 1200°F cold-work curve is again a reflection of the recovery processes taking place in the alloy.

Metallographic studies on the stress-rupture specimens provide some important clues as to the mechanism leading to premature failure of the cold-worked alloy. As shown in Figure 11, the cold-worked alloy possesses extensive grain boundary voids and fissuring after stress-rupture test, as compared to a similar test on annealed material. This behavior is most pronounced at 1400°F, but was also prominent at the lower test temperatures. These observations suggest that cold working strengthens the grains of the alloy, by strain hardening and by promoting precipitation on slip bands and dislocation sites within the grains. Under stress, the grains resist deformation, and the applied stress is concentrated at the weaker grain boundaries. This leads to enhanced grain boundary sliding, grain rotation, and eventually to premature grain boundary cracking. This mechanism would also account for the insensitivity of stress to strain, observed on the cold-worked material. By contrast, the grains of the annealed alloy are ductile, and deform under stress. This accounts for the higher strain observed

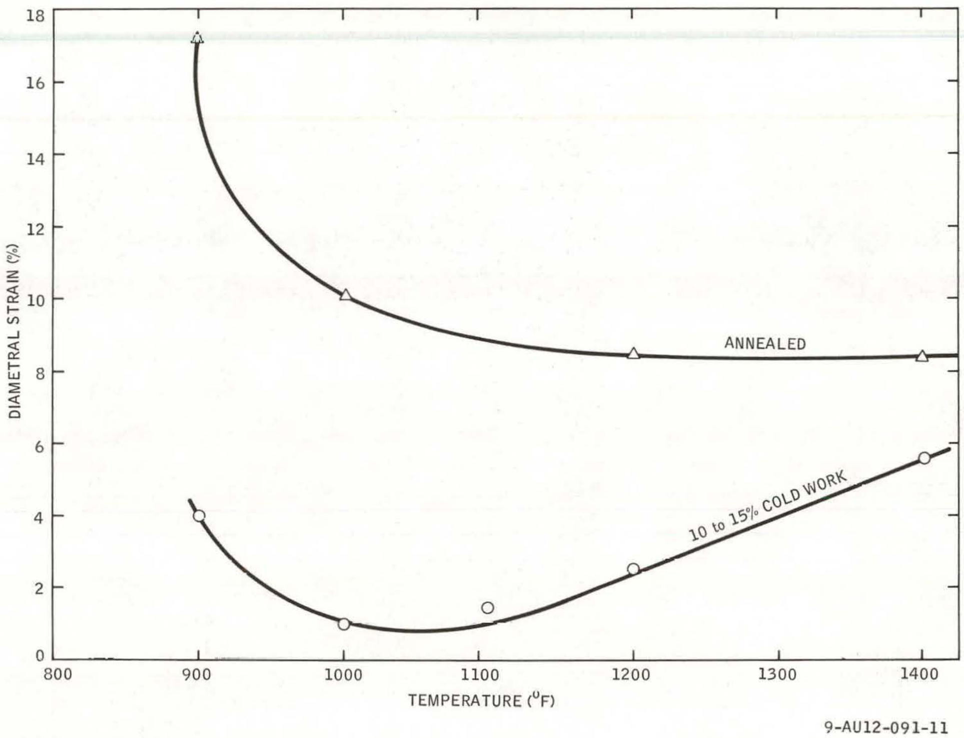


Figure 9. 1000-hr Rupture Strain as a Function of Temperature (Type 304 Stainless Steel)

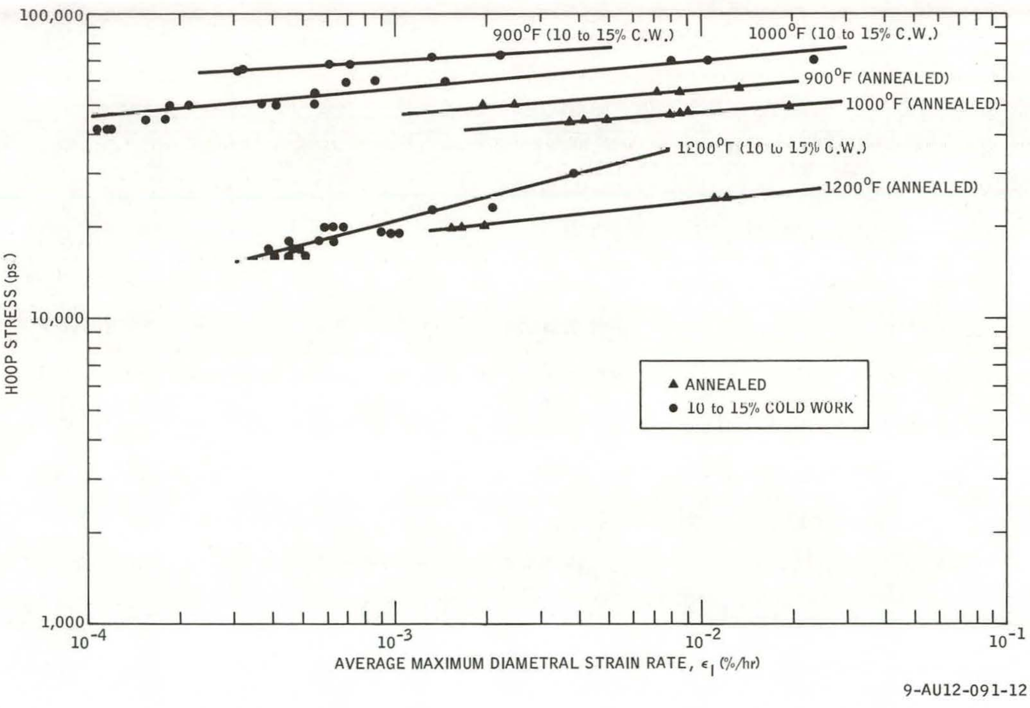
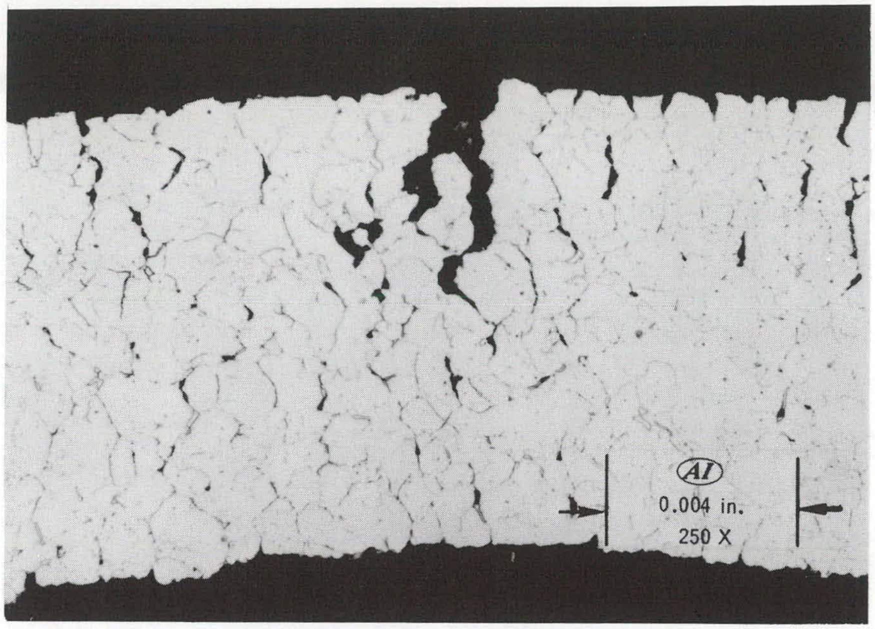
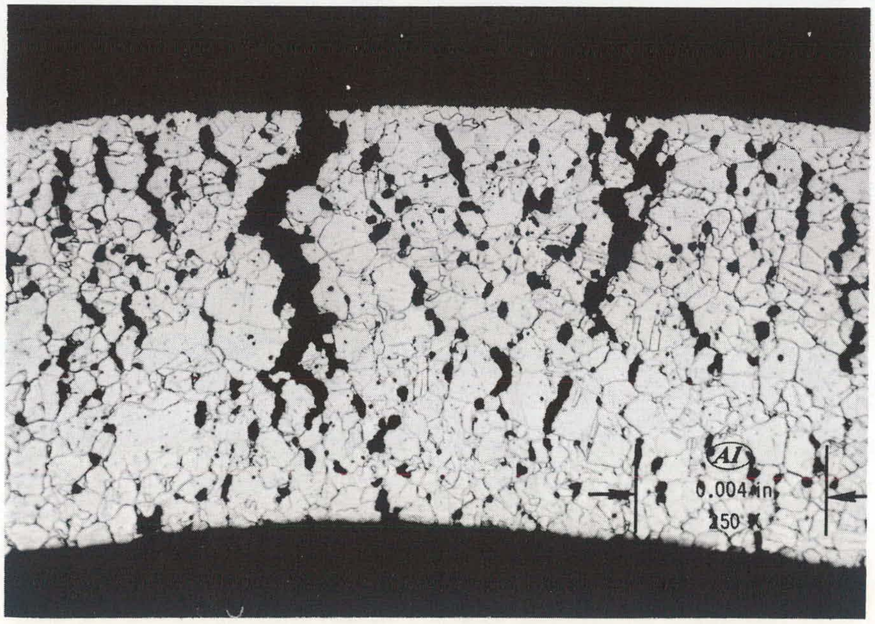


Figure 10. Effect of Stress on Average Strain Rate for Type 304 Stainless Steel in Static Sodium



Marble's Etch 8081-1-1

a. Annealed (σ = 7200 psi, Rupture Time = 2120 hr, ϵ = 6%)



Marble's Etch 8002-1-5

b. 10 to 15% Cold Work (σ = 6800 psi, Rupture Time = 813 hr, ϵ = 6%)

Figure 11. Effect of Cold Work on Microstructure and Void Density of Type 304 Stainless Steel in 1400°F Sodium

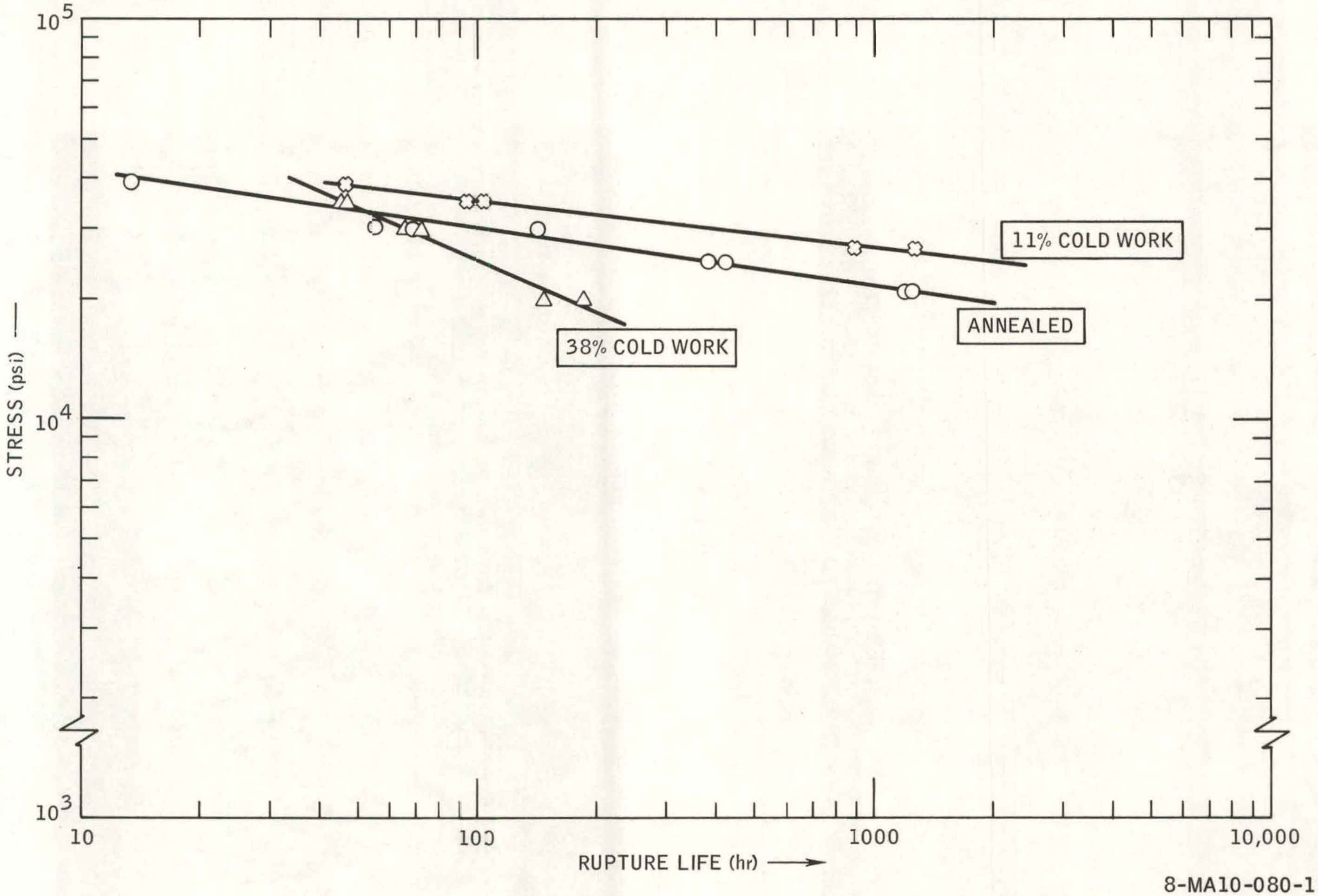


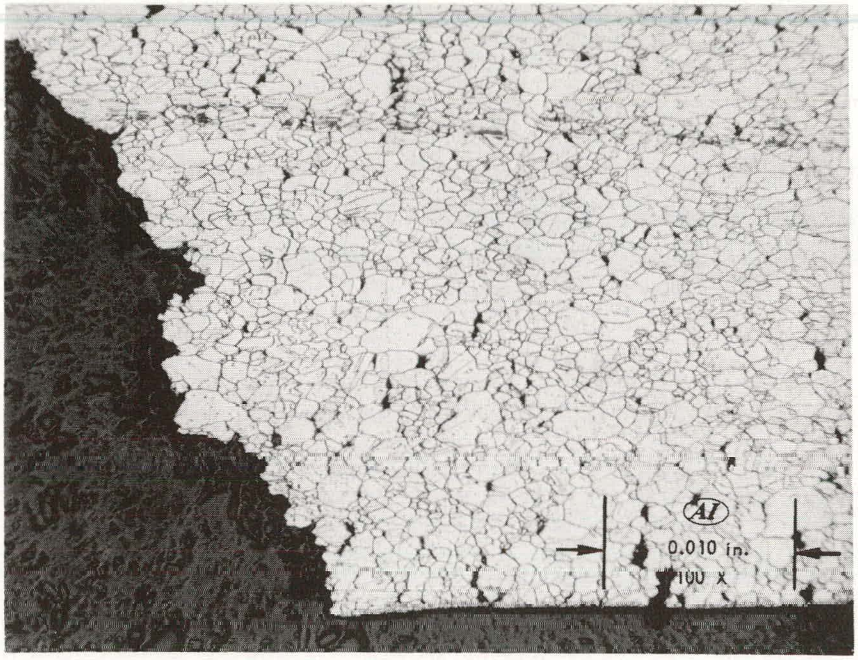
Figure 12. Uniaxial Stress-Rupture Behavior of Type 304 Stainless Steel in 1200°F Sodium (0.062 in. Sheet, Reference Heat No. 20013)

on annealed material. With the accommodation of strain within the grains, stresses at the grain boundaries are reduced, and grain boundary sliding is a less prominent factor.

Further information on cold work in Type 304 stainless steel was provided by a series of uniaxial stress-rupture tests in 1200°F sodium. These tests were performed on sheet stock from the same heat as that of the tubing. The results, shown in Figure 12, demonstrate the danger of introducing large amounts of cold work into the alloy. From this work and that on the 10 to 15% cold-worked tubing, it is apparent that, as the degree of cold work is increased, the more unstable the long-term mechanical behavior of the alloy. The microstructures of annealed and 38% cold-worked specimens after stress-rupture test are presented in Figure 13. The cold-worked material has undergone partial recrystallization and excessive grain growth. The optimum level of cold work for 1200°F service cannot be accurately defined from the scope of these studies. The few exploratory tests show that 38% cold work is definitely undesirable, but levels between 15 and 38% cold work were not investigated.

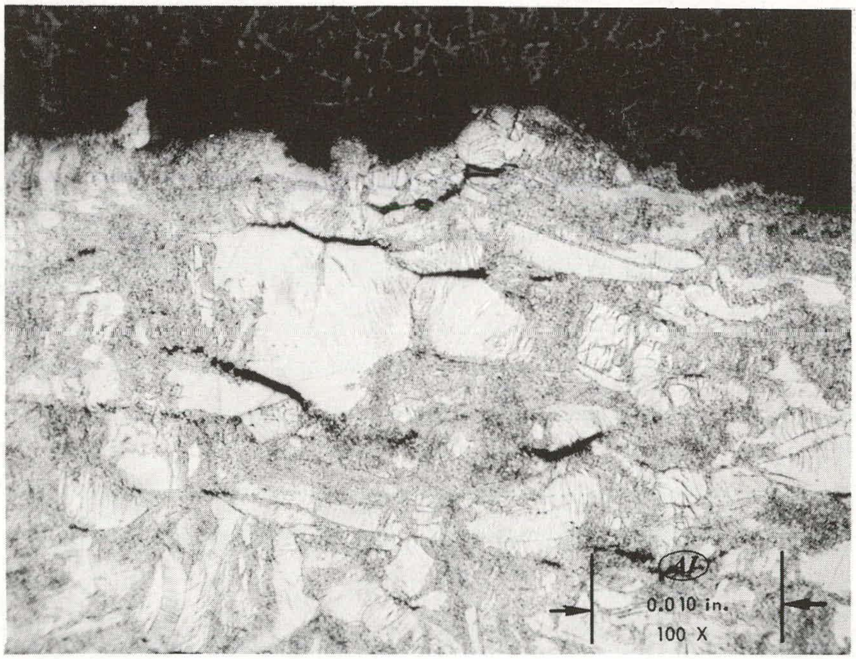
To study the influence of the static sodium environment on the stress-rupture properties of the Type 304 stainless steel cladding, tests were conducted, whereby high purity helium was used in place of sodium. Instead of the specimens being surrounded by sodium, the retorts were filled with 1 atm helium. Biaxial stress rupture tests were conducted at 1400, 1200, and 1000°F. The results of these tests are compared with sodium tests in Figure 14. The average diametral creep rate in sodium and helium at 1000°F are compared in Figure 15. From these results, it was concluded that the sodium environment does not influence the biaxial stress-rupture behavior of the alloy over the temperature range of 1000 to 1400°F.

Microstructural studies of 10 to 15% cold-worked Type 304 stainless steel tubing after long-term stress-rupture testing in 1200°F sodium revealed the presence of a semi-continuous grain boundary phase. It is suspected that this phase is either σ or ferrite, but positive identification could not be made by selective etching techniques. Figure 16a shows a specimen after 5900-hr sodium exposure. This is in contrast to only scattered σ particles observed after helium exposure for an approximately equivalent stress level and exposure time (Figure 16b). In annealed Type 304 stainless steel, σ phase was not found. Figure 8



Marble's Etch 8182-12-1

a. Annealed (σ = 21,000 psi, Rupture Time = 1253 hr, ϵ = 29%)



Marble's Etch 8182-10-1

b. 38% Cold Work (σ = 20,000 psi, Rupture Time = 180 hr, ϵ = 6.5%)

Figure 13. Microstructures of Uniaxial Stress-Rupture Specimens of Type 304 Stainless Steel Sheet After Testing in 1200°F Static Sodium

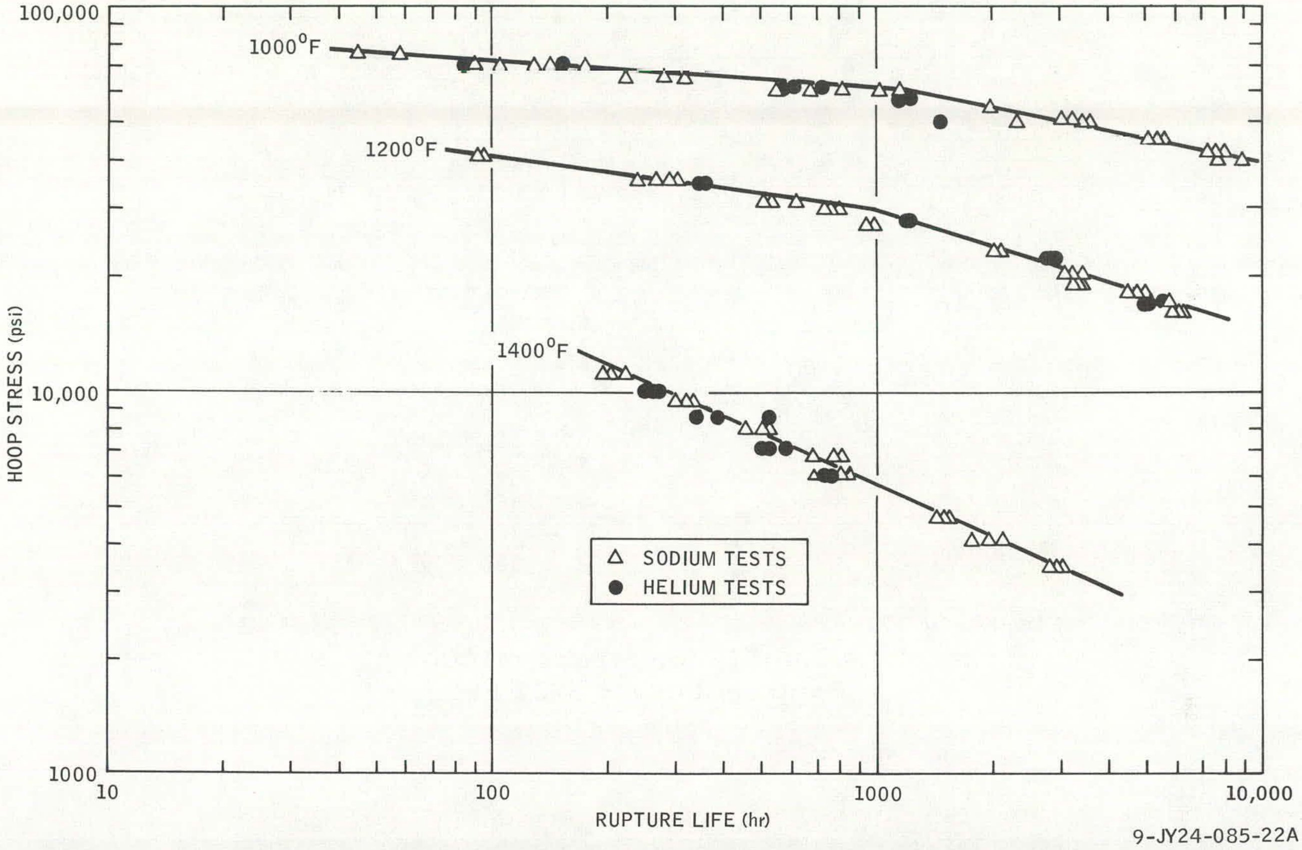


Figure 14. Comparison of Stress-Rupture Behavior of Type 304 Stainless Steel Cladding (10 to 15% Cold Work) in Static Sodium and Helium

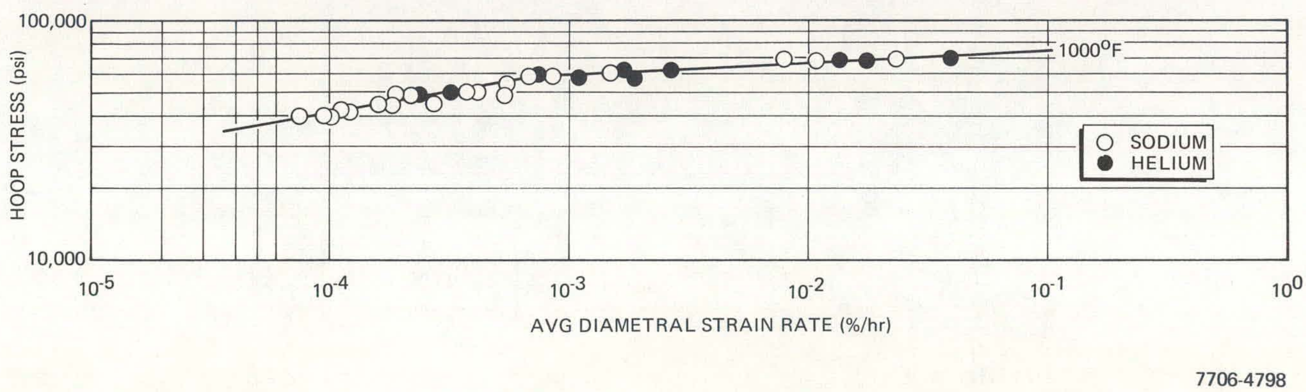
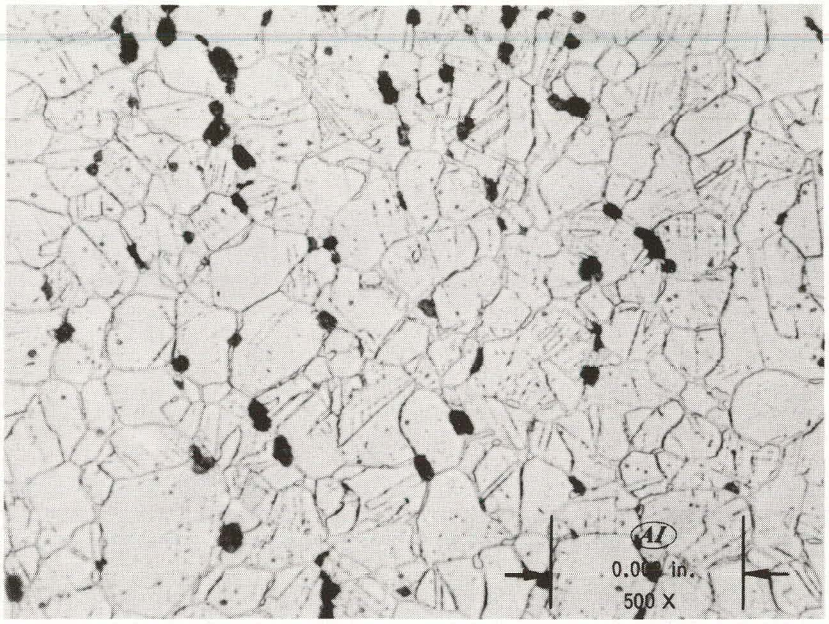
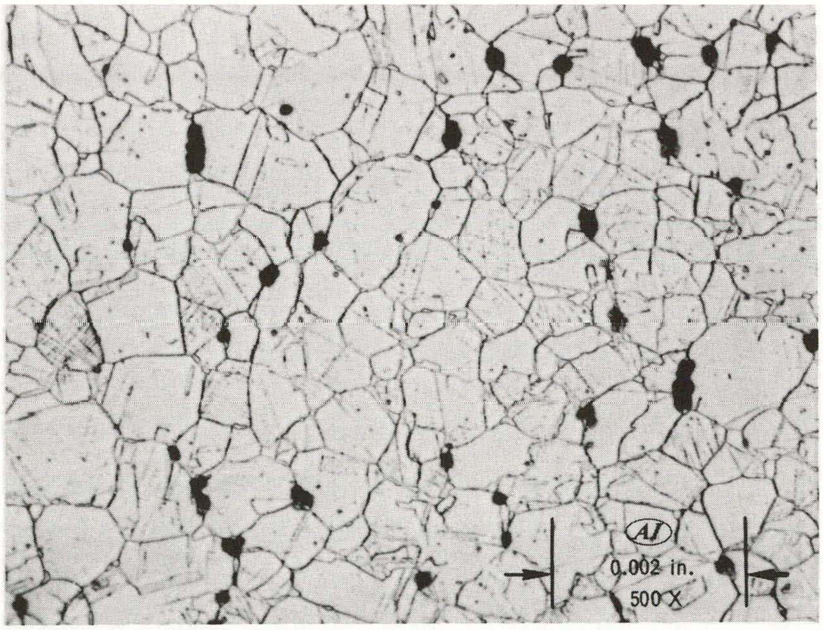


Figure 15. Strain-Rate Sensitivity of Type 304 Stainless Steel (10 to 15% Cold Work) to Stress in Sodium and Helium Environments



Marble's Etch 8373-1-2

a. In Sodium (Hoop Stress = 1600 psi, Rupture Time = 5927 hr)



Marble's Etch 8361-2-2

b. In Helium (Hoop Stress = 17,000 psi, Rupture Time = 5598 hr)

Figure 16. Type 304 Stainless Steel After Testing at 1200°F

shows an annealed structure after 5000 hr in 1200°F sodium. The structure shows grain growth (due to time, temperature and stress), but no evidence of σ formation.

2. Uniaxial Stress

Stress-rupture tests under a uniaxial stress were conducted on annealed 0.062-in. Type 304 stainless steel sheet stock. The stress-rupture strength is plotted in Figure 12. Table A-3 of the appendix presents additional data on each specimen. The sheet material was made from the same heat of alloy as the tubing used throughout this investigation. Four uniaxial stress-rupture tests were conducted at the same stress level and temperature (21,000 psi and 1200°F). Two of the tests were in a static sodium environment, and two were in helium. Creep curves on all four test are plotted in Figure 17. It is observed that the test environment does not affect the secondary (steady-state) creep rate of the alloy. However, an environmental effect becomes apparent in the tertiary stage of creep. The amount of tertiary strain before rupture is significantly greater in the helium environment. Under biaxial stress, this environmental effect was not observed. This can be explained by the fact that, under the 2:1 biaxial stress mode, there is very little tertiary creep prior to rupture. Therefore, the environmental influence of sodium would not be observed under biaxial test.

3. 1:1 Biaxial Stress

In fuel element operation, the cladding may be subjected to simultaneous hoop and axial stresses in the latter stages of life. To simulate this condition, tests were conducted with tubular specimens which were internally pressurized with gas while under axial tension. Conditions were chosen, such that the tension and hoop stresses were equal (1:1 biaxiality). Figure 18 presents the stress-rupture strength of annealed Type 304 stainless steel tubing under this biaxial stress mode. The data on each individual specimen is presented in Table A-4 of the appendix. As shown, the stress-rupture strength is similar to that obtained under uniaxial stress. The 1:1 biaxially stressed specimen, however, is weaker in stress rupture than under a 2:1 stress under the same conditions. The diametral strain after rupture was found to be more localized, but of about the same magnitude as the 2:1 stress ratio tests. The axial strain component under 1:1 stress was observed to be about equal to the diametral strain.

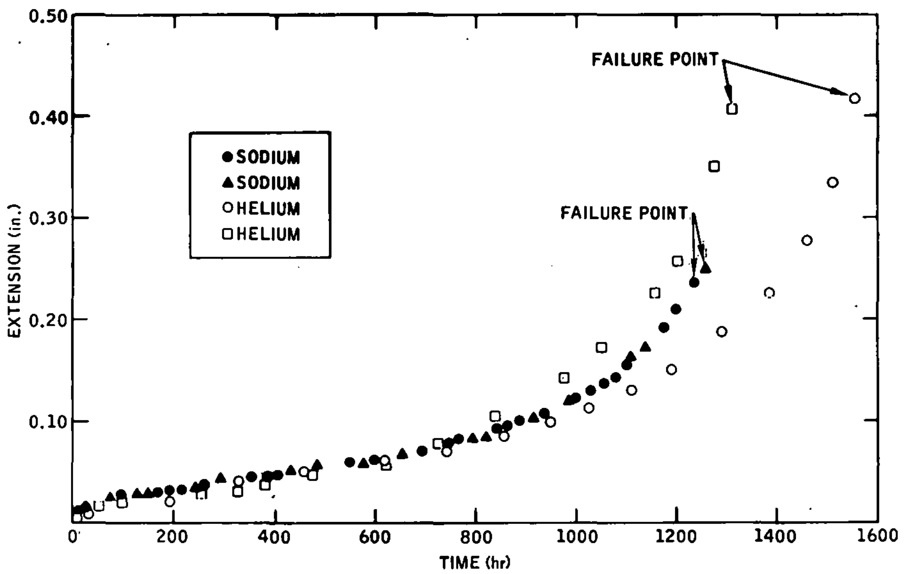


Figure 17. Uniaxial Creep of Annealed Type 304 Stainless Steel in 1200°F Sodium and Helium Environments (21,000 psi Stress)

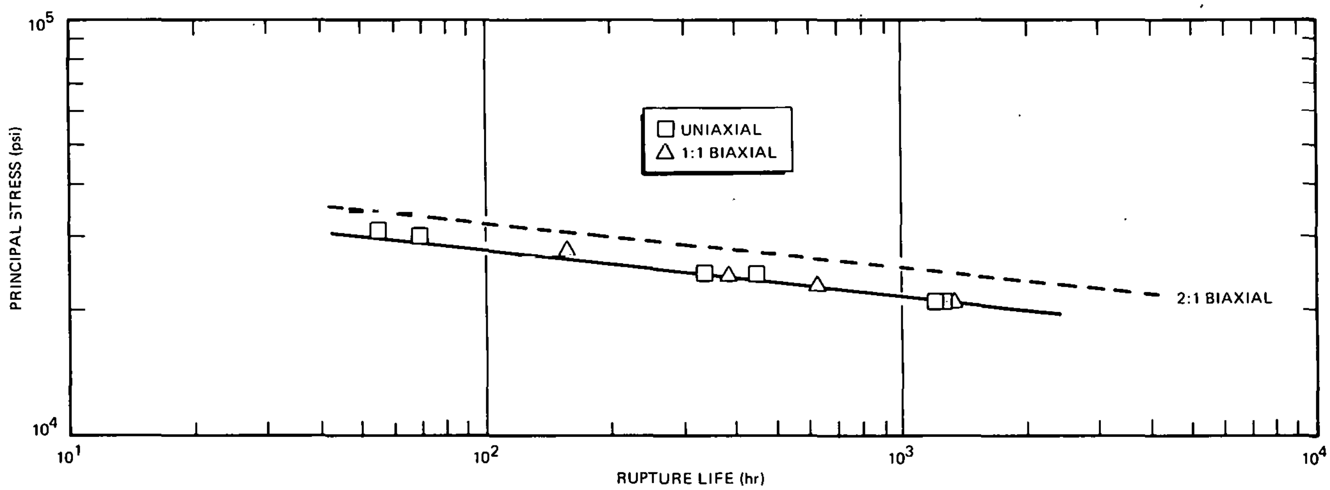


Figure 18. Uniaxial and 1:1 Biaxial Stress-Rupture Strength of Annealed Type 304 Stainless Steel in 1200°F Sodium

The total strain (axial plus diametral) under 1:1 biaxial stress is therefore approximately twice the strain observed on the 2:1 biaxial tests.

B. TYPE 316 STAINLESS STEEL

1. 2:1 Biaxial Stress

Tubing of Type 316 stainless steel was stress-rupture tested under 2:1 biaxial stress in high-purity static sodium. The results of tests conducted at 1400, 1200, and 1000°F are plotted in Figure 19, and tabulated in Tables A-5 and -6 of the appendix. The tubing containing 10 to 15% cold work was found to have significantly stronger short-term properties at 1200 and 1400°F. However, at 1400°F, alloy instability develops which degrades the strength of the cold-worked material. This behavior, also observed on cold-worked Type 304 stainless steel, seems to be related to recovery and recrystallization processes in the alloy. At 1200 and 1000°F, the stress-rupture strength of the cold-worked alloy remains stable to beyond 10,000 hr.

The stress-rupture strength of annealed Type 316 stainless steel at 1000°F exhibits unexpected behavior. Instead of being parallel with the cold-worked curve, as is the case at 1200°F, the curve possesses a steeper slope. It seems that the cold-worked and annealed tubing have identical strength, up to about a 200-hr rupture life. Beyond this, the annealed tubing becomes progressively weaker as the rupture stress is lowered. This behavior seems to be real, since two retorts, involving a total of 24 specimens, gave reproducible results. Metallographic examination of the ruptured specimens failed to provide any insight into the cause for this anomalous behavior.

The influence of thermal aging on the stress-rupture behavior of Type 316 stainless steel cladding (10 to 15% cold work) in high-purity static sodium was investigated. Twelve specimens were aged for 2000 hr in 1200°F sodium. The specimens were unstressed during this aging step. On subsequent biaxial stress-rupture tests, it was found that the rupture strength was essentially unchanged. The data points are shown in Figure 19. Apparently, the carbide precipitation, σ formation, and probable cold-work recovery effects which take place in this time-temperature range are not of sufficient magnitude to alter the stress-rupture properties of the alloy. A similar test, at 1000°F, also showed no effect of aging. In this test, the unstressed specimens were aged in 1000°F sodium for 3000 hr.

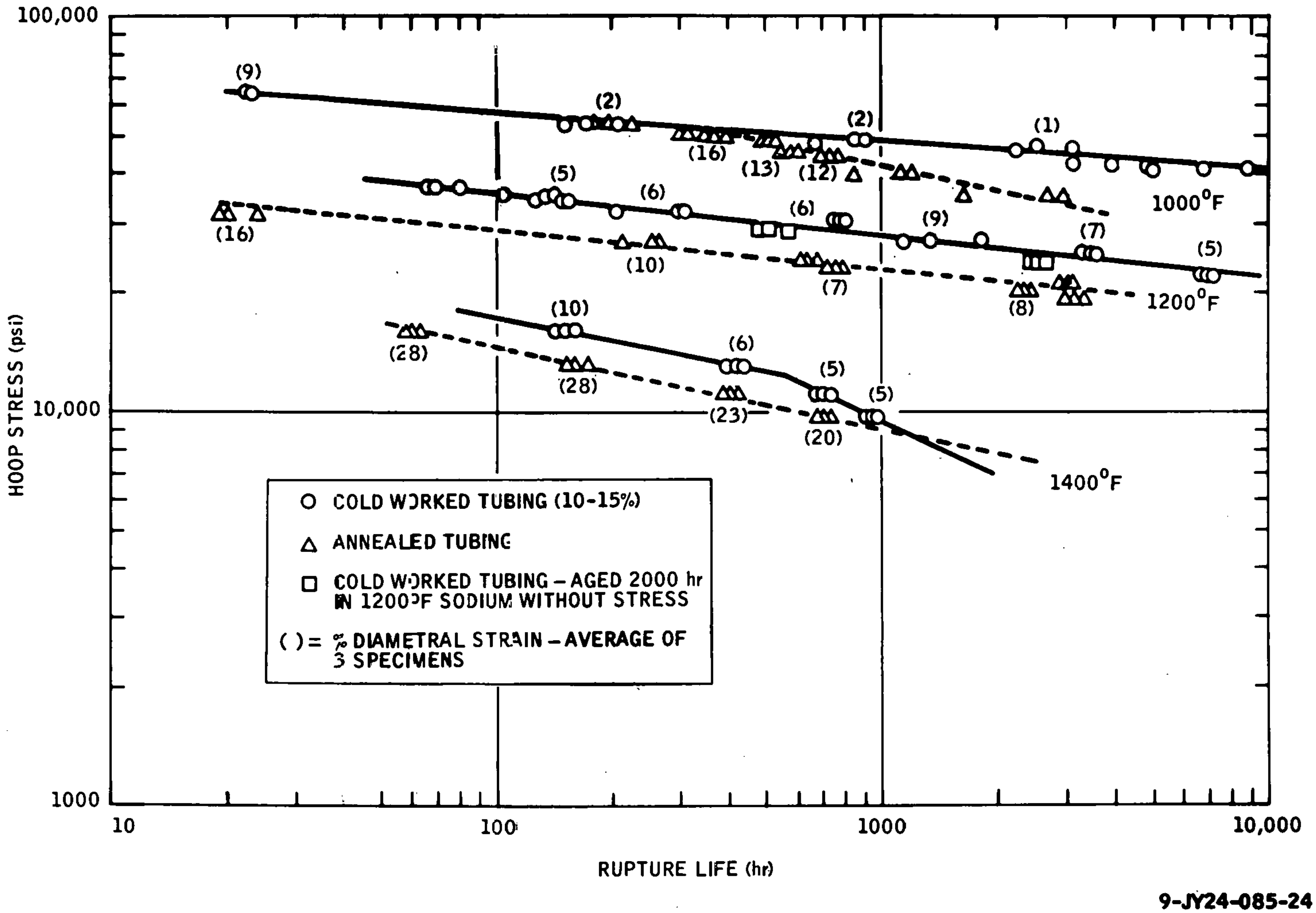


Figure 19. Biaxial Stress-Rupture Strength of Cold-Worked (10 to 15%) and Annealed Type 316 Stainless Steel in Static Sodium

From diameter measurements taken on the specimens before and after test, diametral strain values were obtained. These values are shown in parentheses on the stress-rupture curves of Figure 19. Average strain-rate data was also calculated, and the results yielded the stress sensitivity to strain-rate relationships shown in Figure 20. It is of interest to note that the anomaly in stress-rupture strength observed on the annealed alloy at 1000°F (Figure 19) is not apparent in the strain-rate plot of Figure 20.

An apparent effect of sodium environment on the stress-rupture properties of Type 316 stainless steel containing 10 to 15% cold work has been observed on tests at 1000°F. While no effect of environment (sodium vs helium) was observed for Type 316 stainless steel at 1400°F, tests of Type 316 stainless steel in 1000°F helium exhibited a significant difference in stress-rupture behavior, when compared to similar tests in sodium. This behavior is illustrated in Figure 21. At stress levels which produce rupture in <1500 hr, the rupture strength of the alloy is reduced in a sodium environment; for example, at a stress level of 50,000 psi hoop, the rupture time was 400 hr in sodium, compared to 1300 hr in helium. The strain at rupture was found to be lower in the helium environment. Two separate 12-specimen retorts have been tested with the same results. The sodium and helium curves do not cross each other, but merge after they meet. The reason for this environmental behavior is not understood, at this time. Annealed Type 316 stainless steel tubing did not show this effect of test environment. Figure 22 shows excellent agreement in stress-rupture strength with sodium and helium environments.

Further indication of an environmental effect in cold-worked Type 316 stainless steel tubing is the appearance of the ruptures in the tubing wall of the 1000°F tests. In 1000°F sodium, the ruptures were of the explosive type, with large holes and associated localized tube wall distortion. In helium, only very small pinhole type fractures were observed. The experimental evidence indicates that the test environment causes alteration of fracture behavior, hence influencing the long-term mechanical properties of the alloy.

2. Uniaxial Stress

Uniaxial stress-rupture tests were performed on both annealed and cold-worked (10 to 15%) tubing. All tests were performed in 1200°F static sodium. The results are tabulated in Table A-7 of the appendix.

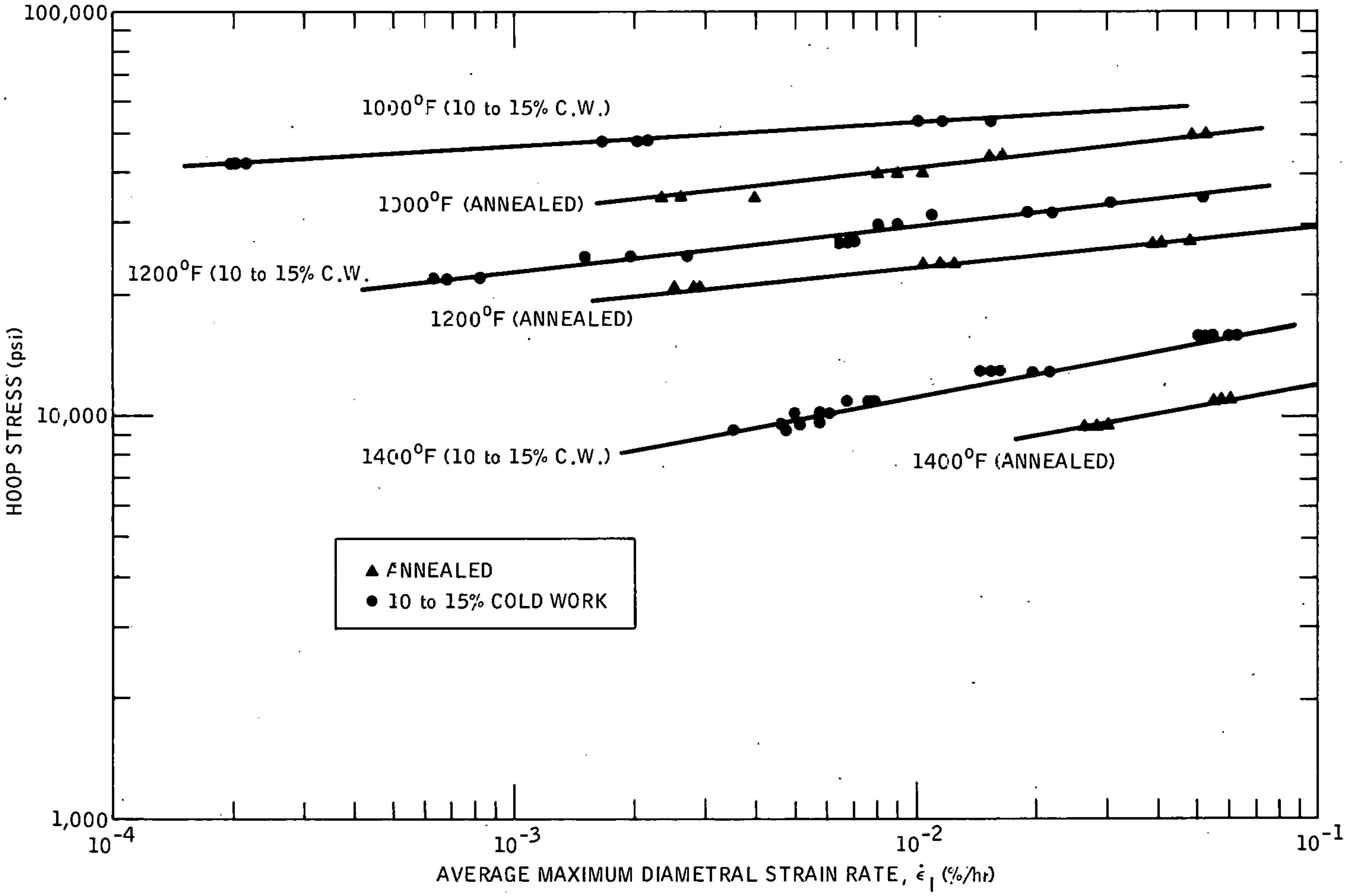


Figure 20. Effect of Stress on Average Strain Rate for Type 316 Stainless Steel in Static Sodium

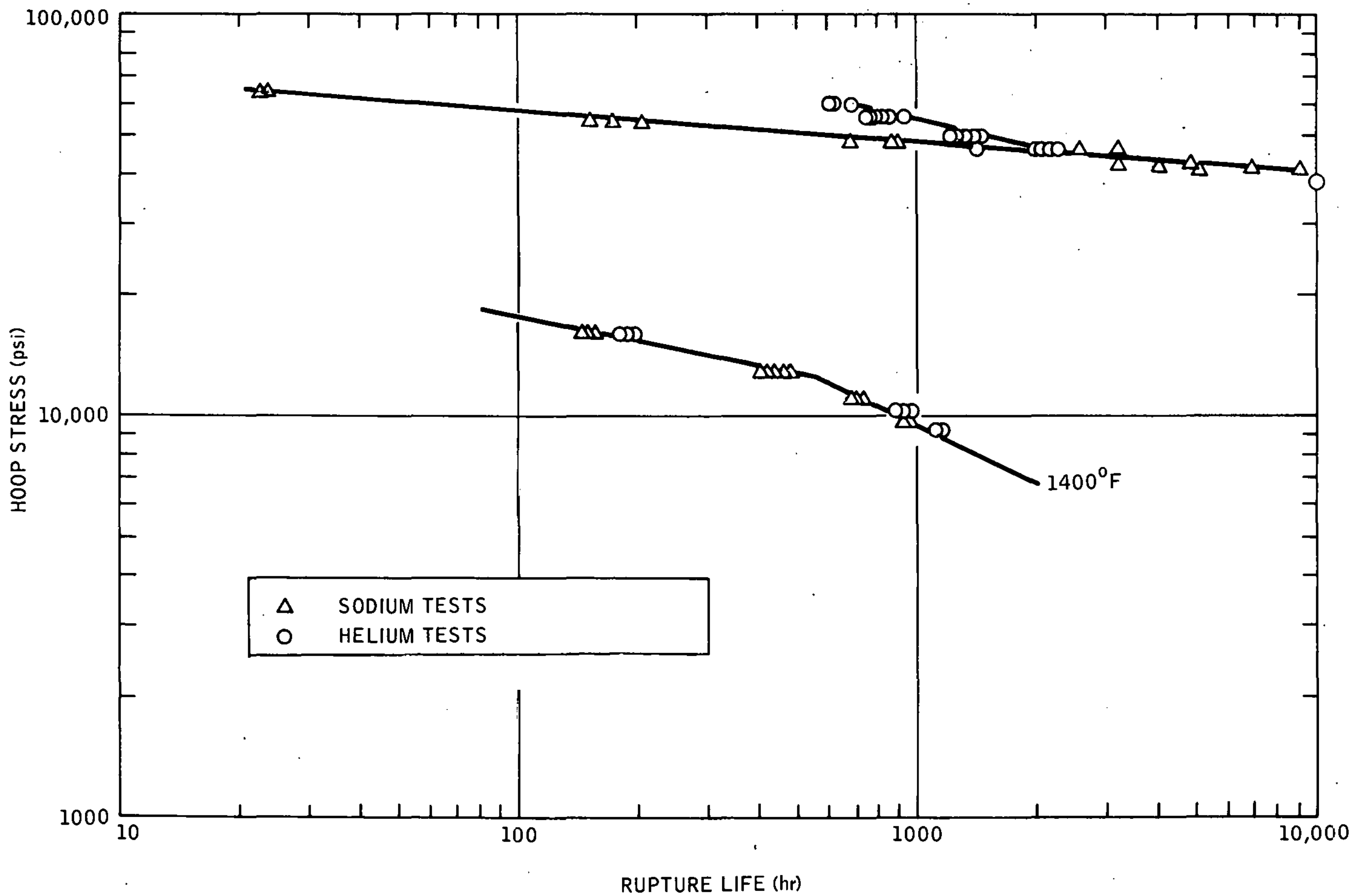


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Figure 21. Comparison of Stress-Rupture Behavior of Type 316 Stainless Steel Cladding (10 to 15% Cold Work) in Static Sodium and Helium

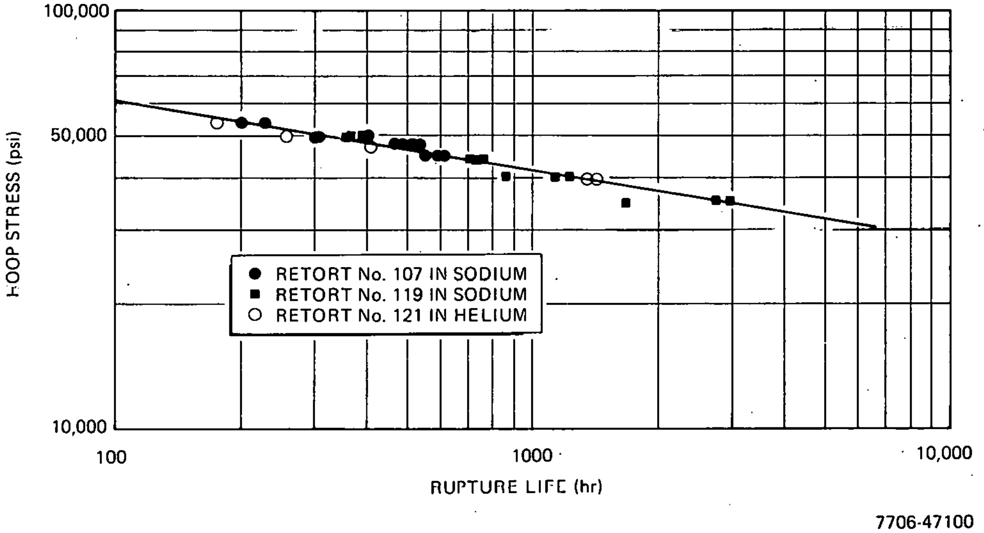

Figure 22. 1000°F Biaxial Stress-Rupture Behavior of Annealed Type 316 Stainless Steel

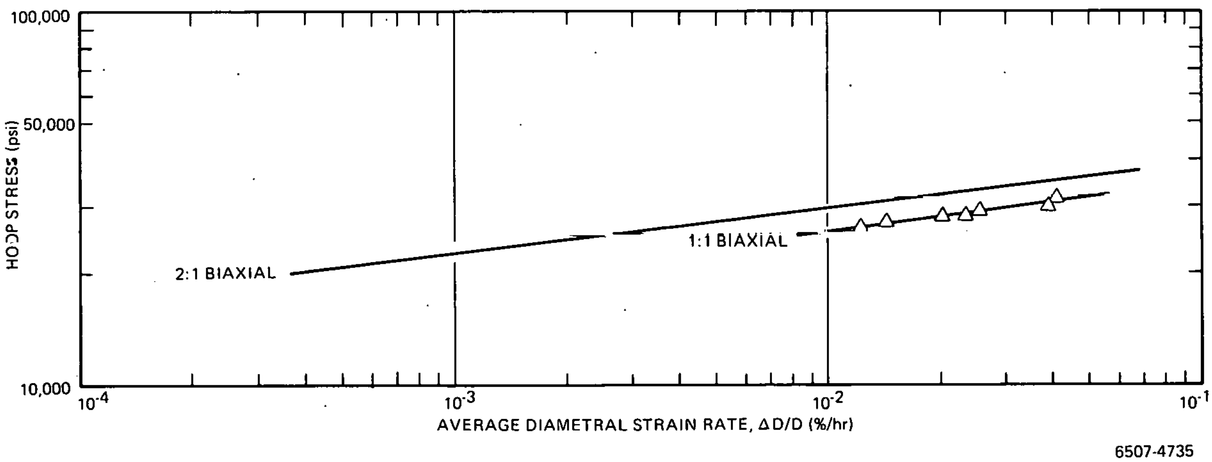

Figure 23. Stress vs Average Diametral Strain Rate for 10 to 15% Cold-Worked Type 316 Stainless Steel in 1200°F Sodium

3. 1:1 Biaxial Stress

Biaxial stress-rupture tests with an equal hoop and axial stress were conducted on annealed and cold-worked tubing in 1200°F sodium. Table A-8 in the appendix lists the stress-rupture properties. Under this stress state, the specimen is strained in both axial and tangential directions. It was found that the tangential strain is about equal to the axial strain. The tangential strain was also about 1/2 the strain observed under uniaxial stress, for an equivalent stress level. A comparison of the stress sensitivity to average diametral strain rate for the 1:1 and 2:1 biaxial stress states is presented in Figure 23. For a given stress, the strain rate in the hoop direction was found to be greater for 1:1 biaxiality. This same behavior was observed for the Type 304 stainless steel tubing.

IV. DISCUSSION OF RESULTS

The multiple-specimen biaxial stress-rupture testing concept produced accurate, consistent data, with a high statistical confidence. The static sodium was sampled several times during each test, and the ability to maintain a high-purity sodium environment for the test specimens was demonstrated. With the multiple-specimen testing capability, a large amount of data can be generated in the shortest possible time. The static sodium provides excellent environmental control, which is necessary to define process and metallurgical effects. The rigid control on test conditions, and the large amount of data which must be generated on such studies, makes the static sodium retort concept both technically and economically attractive. It is recognized that the static sodium tests do not provide for the system effects of flowing sodium and the associated corrosion and mass transfer. Flowing sodium tests, currently in progress on another task, have demonstrated the complementary relationship between the static and dynamic sodium tests. The accurate baseline data provided by the static sodium tests permit direct evaluation of flowing system effects and greatly reduce the number of the more expensive loop tests.

In this study, the influence of such parameters as cold work, test environment, and stress mode were evaluated with respect to long-term mechanical properties. A comparison of the two stainless steel alloys, in relation to these parameters, follows.

A. COLD WORK EFFECTS

In studies on the mechanical behavior of austenitic stainless steels in high-temperature sodium, thin-wall seamless tubing from two highly characterized heats of Types 304 and 316 stainless steel were used. The tubing was purchased with 10 to 15% cold work, introduced by cold reduction in the final draw. The reported range of cold work reflects an uncertainty in the exact amount of cold work, due to dimensional tolerance variations inherent in the tubing, just prior to the final drawing operation. In spite of this potential cold-work variation, the creep and stress-rupture data have exhibited excellent reproducibility, within the individual alloy heats. Whether this reproducibility is due to a consistent amount of cold work, or to the insensitivity to small variations of cold work, is not known at this time.

The experimental studies show that, under certain conditions of temperature and stress, cold work in the 10 to 15% range can impact undesirable properties to the cladding. This is illustrated in Figures 6 and 19, which show that the strengthening effects of cold work are temporary, with the duration decreased with increasing test temperature. The observed behavior is more pronounced for Type 304 stainless steel than for Type 316 stainless steel; the strengthening benefits of cold work are retained longer for Type 316 stainless steel than for Type 304 stainless steel at the same temperature. These observations suggest that the recovery processes are slower, at the same temperature and stress, in Type 316 stainless steel than in Type 304 stainless steel. Other investigators[8,9] have found improved alloy stability and increased recrystallization temperatures in austenitic stainless steels containing refractory metal additions (e.g., molybdenum in Type 316 stainless steel).

As expected, a reduction in rupture strain by the presence of cold work has been observed for both stainless steels. Figure 9 shows the 1000-hr biaxial rupture strain of Type 304 stainless steel is greatly reduced at all temperatures (900 to 1400°F) for the 10 to 15% cold-worked tubing. The Type 316 stainless steel tubing exhibits similar cold-worked behavior, although the magnitudes of strain in the cold-worked material are greater for Type 316 stainless steel. Under uniaxial stress, a similar strain behavior has been observed with cold work. The amount of cold work governs strain during each stage of creep, as can be seen in Figure 24. For each stage of creep, the strain decreases as the cold work increases, with the greatest influence of cold work showing up in third-stage creep. While there appears to be a saturation effect on the rupture strain at higher cold-work levels, the rupture strength and strain rate have been found to be strongly influenced by high degrees of cold work. In Figure 12, the stress-rupture strength of the 38% cold-worked alloy is much less than that of the annealed material. Unfortunately, insufficient data are available to define the level of cold work which can be tolerated for given alloy, stress, temperature, and time parameters.

In the solution-annealed condition, both alloys exhibit about the same stress-rupture characteristics. As shown in Figure 25, the data could be considered to lie within the scatter band expected for heat-to-heat variation for a given alloy.[10] The similarity in strain rates of the two annealed alloys is presented in Figure 26.

In contrast, the stress-rupture behavior of Type 304 stainless steel and Type 316 stainless steel in the 10 to 15% cold worked condition is presented in Figure 27. While the annealed behavior is almost identical, the behavior of the

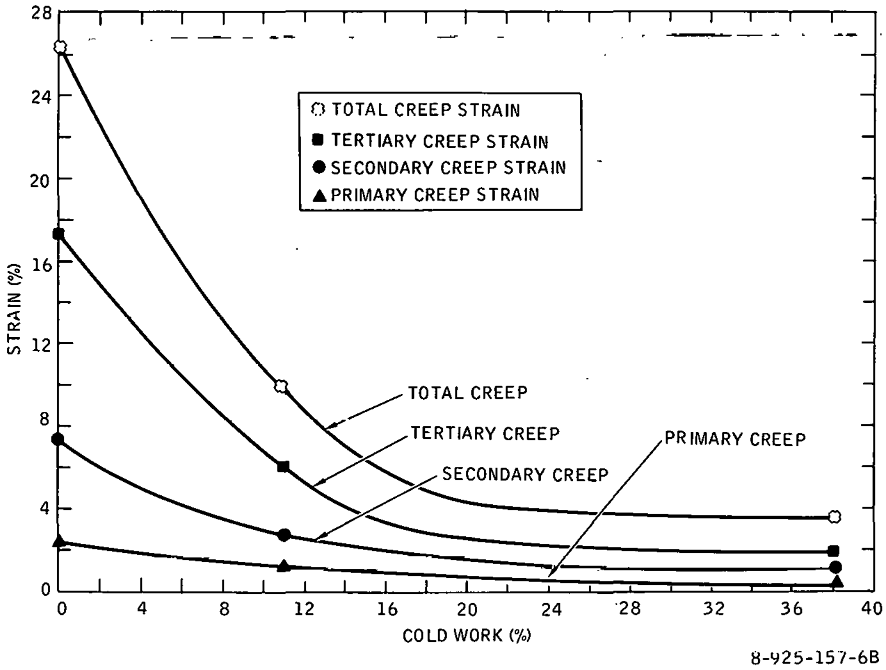

Figure 24. Effect of Cold Work on the Strain, in Three Stages of Uniaxial Creep in Sodium at 1200 °F, for Type 304 Stainless Steel

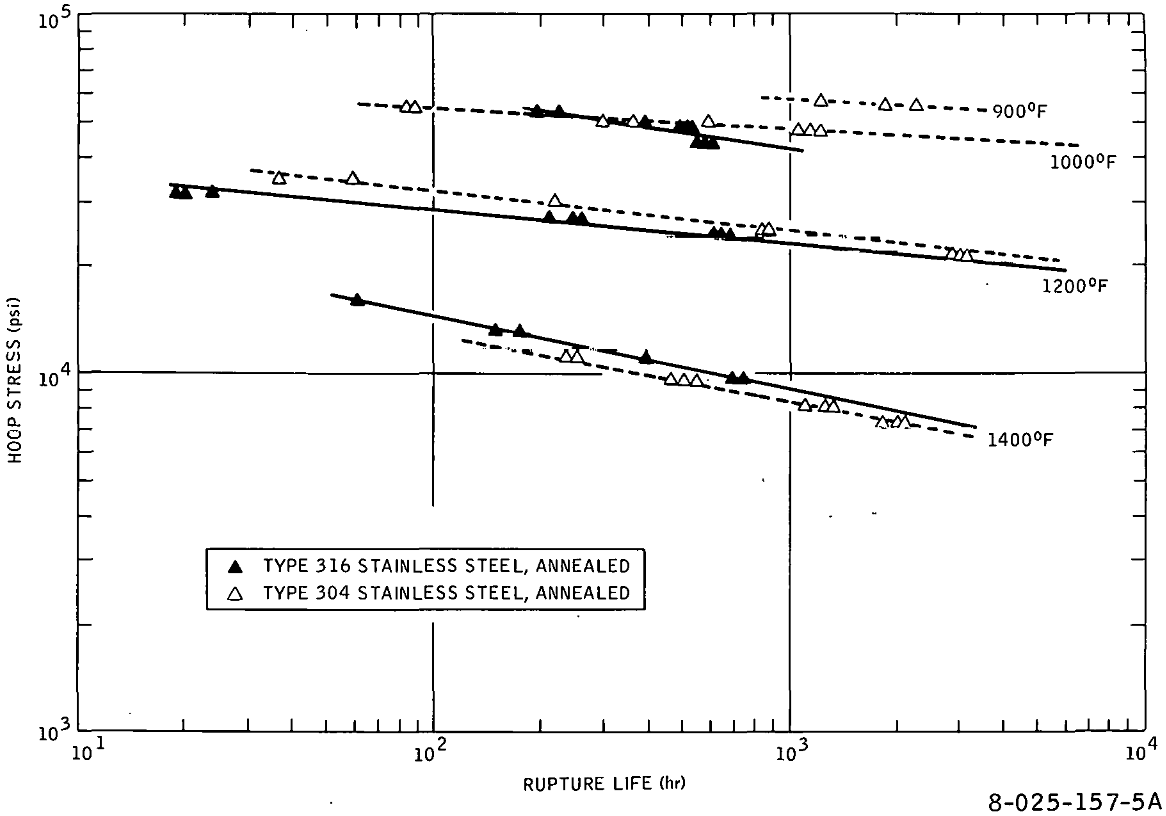

Figure 25. Biaxial Stress-Rupture Behavior of Annealed Types 304 and 316 Stainless Steel in Static Sodium

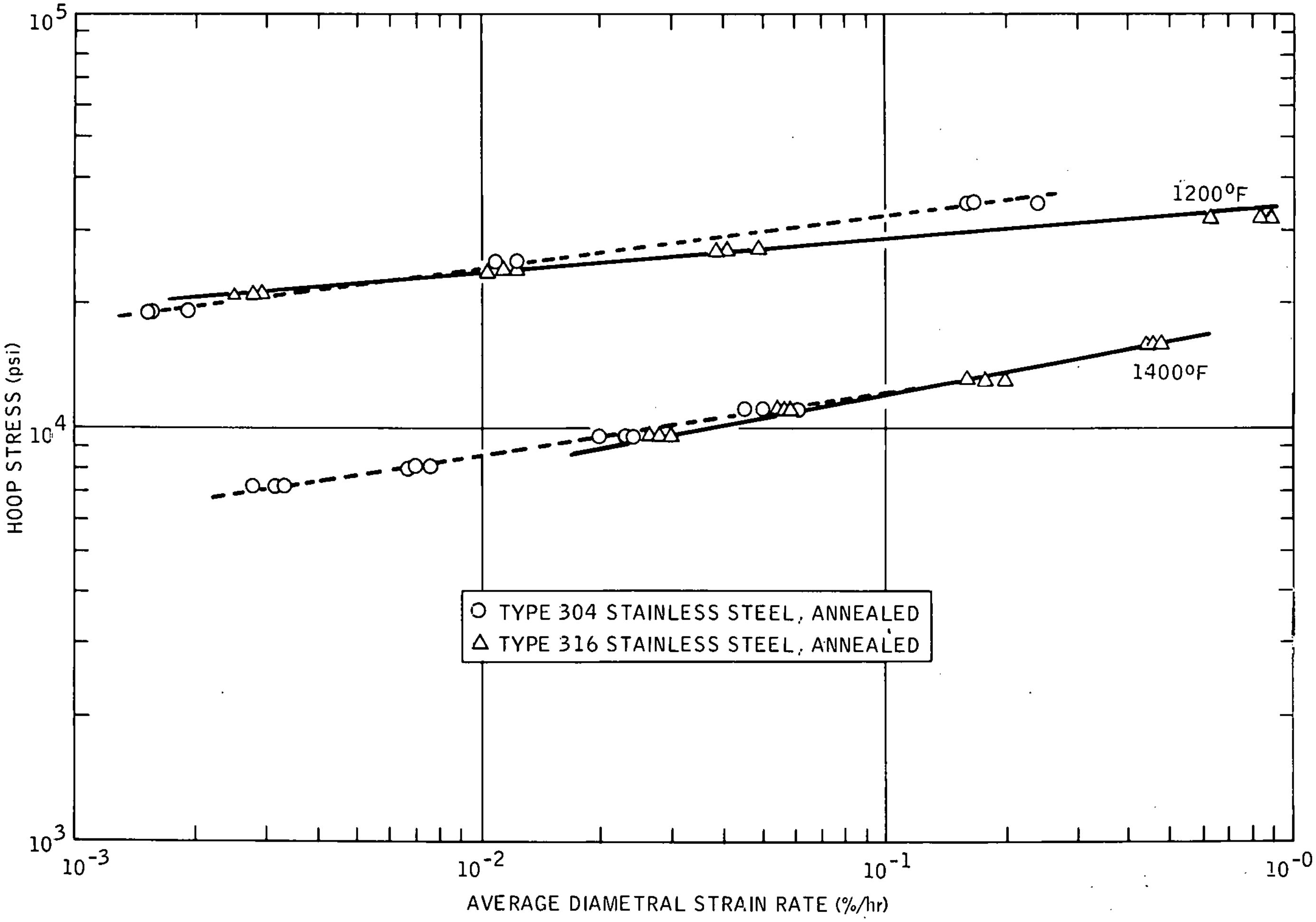

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Figure 26. Strain-Rate Sensitivity to Biaxial Stresses for Annealed Types 304 and 316 Stainless Steel in Static Sodium

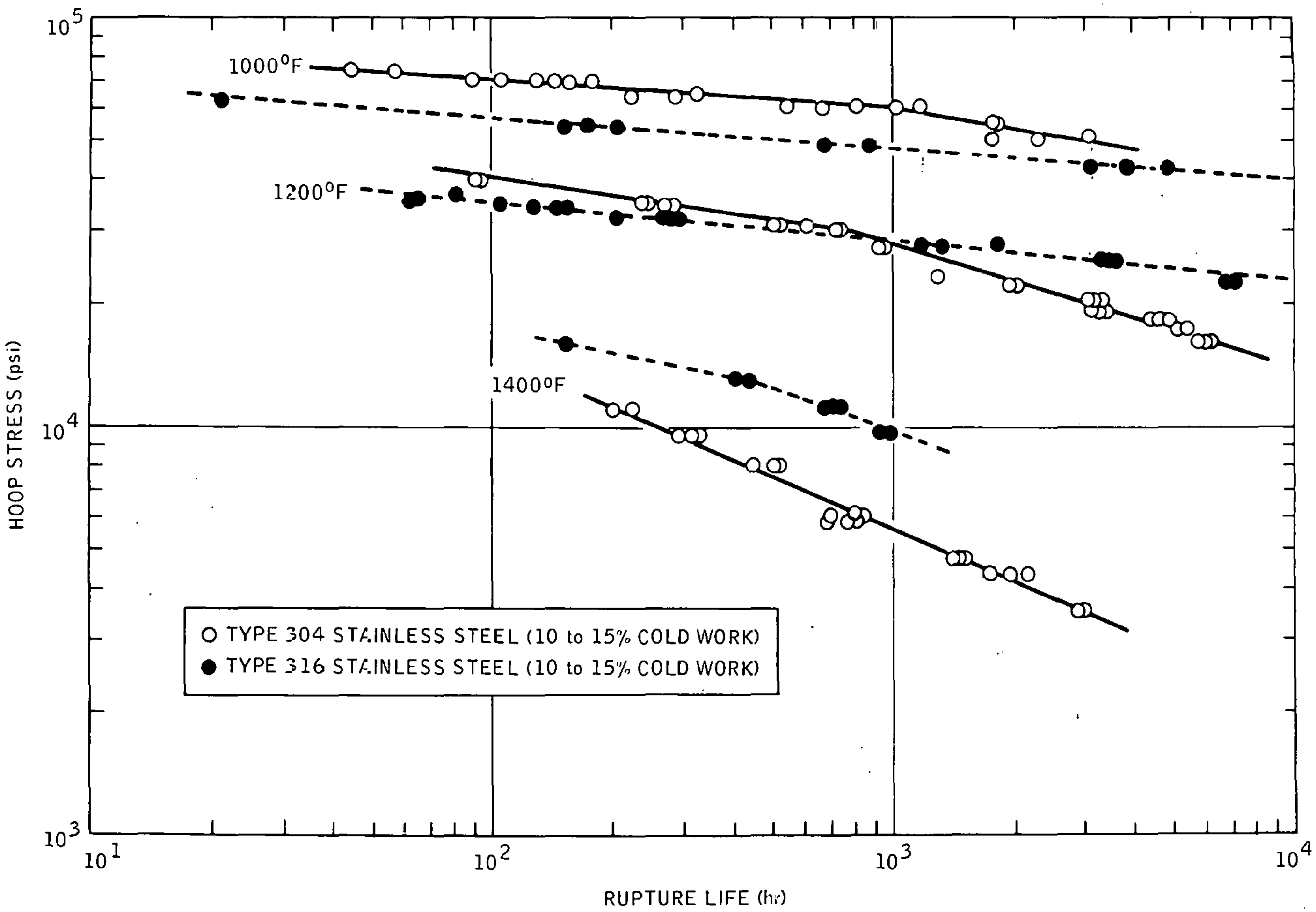

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Figure 27. Biaxial Stress-Rupture Behavior of Cold-Worked Types 304 and 316 Stainless Steel in Static Sodium

cold-worked tubes is not. The cold-worked Type 316 stainless steel alloy is stronger in the high temperature range (~1400°F) and weaker in the low temperature range (~1000°F) than the Type 304 stainless steel alloy. However, the Type 304 stainless steel exhibits an instability which makes the Type 316 stainless steel alloy more attractive for long-term, low-stress applications.

Microstructural examination of cold-worked and annealed specimens revealed that σ phase is enhanced by cold work. Cold working promotes the transformation of austenite to ferrite which, in turn, can more readily form σ. In Type 304 stainless steel, σ formation was found to be enhanced by stress. Luba et al.[8] observed that recrystallization of other cold-worked alloys accelerates σ formation. In Type 304 stainless steel, σ formation was found concentrated at grain boundaries; but, in Type 316 stainless steel, much of the σ was found as a fine precipitate within grains and on slip bands. In both alloys, σ particles were observed to be more prominent at 1400 and 1200°F than at 1000 and 900°F.

While σ-phase formation is generally regarded as undesirable, there was no evidence that it contributed to the degradation of the mechanical properties of the cold-worked alloys. It is believed that recovery and recrystallization effects contribute to the major loss in properties, and σ phase plays, at most, a secondary role.

B. FRACTURE MODE

Metallographic examination of the stress-rupture specimens tested, in both sodium and helium, revealed that all fractures were intergranular, with fissuring along grain boundaries in regions away from the rupture. When explosive-type ruptures occurred, the fracture mechanism was initially intergranular, but became partially transgranular as the crack propagated across the tube wall.

Under a biaxial stress mode, the ruptures are generally small longitudinal cracks in the tubing wall. Below 1200°F, and occasionally at 1200°F, failure sometimes occurred by an explosive-type rupture. The cause of this type of rupture has not been identified. The rupture is characterized by a large longitudinal crack, accompanied by localized distortion similar to that experienced on short-term burst tests. The sudden release of high-pressure gas apparently creates a shock wave which is transmitted through the sodium. This high-energy

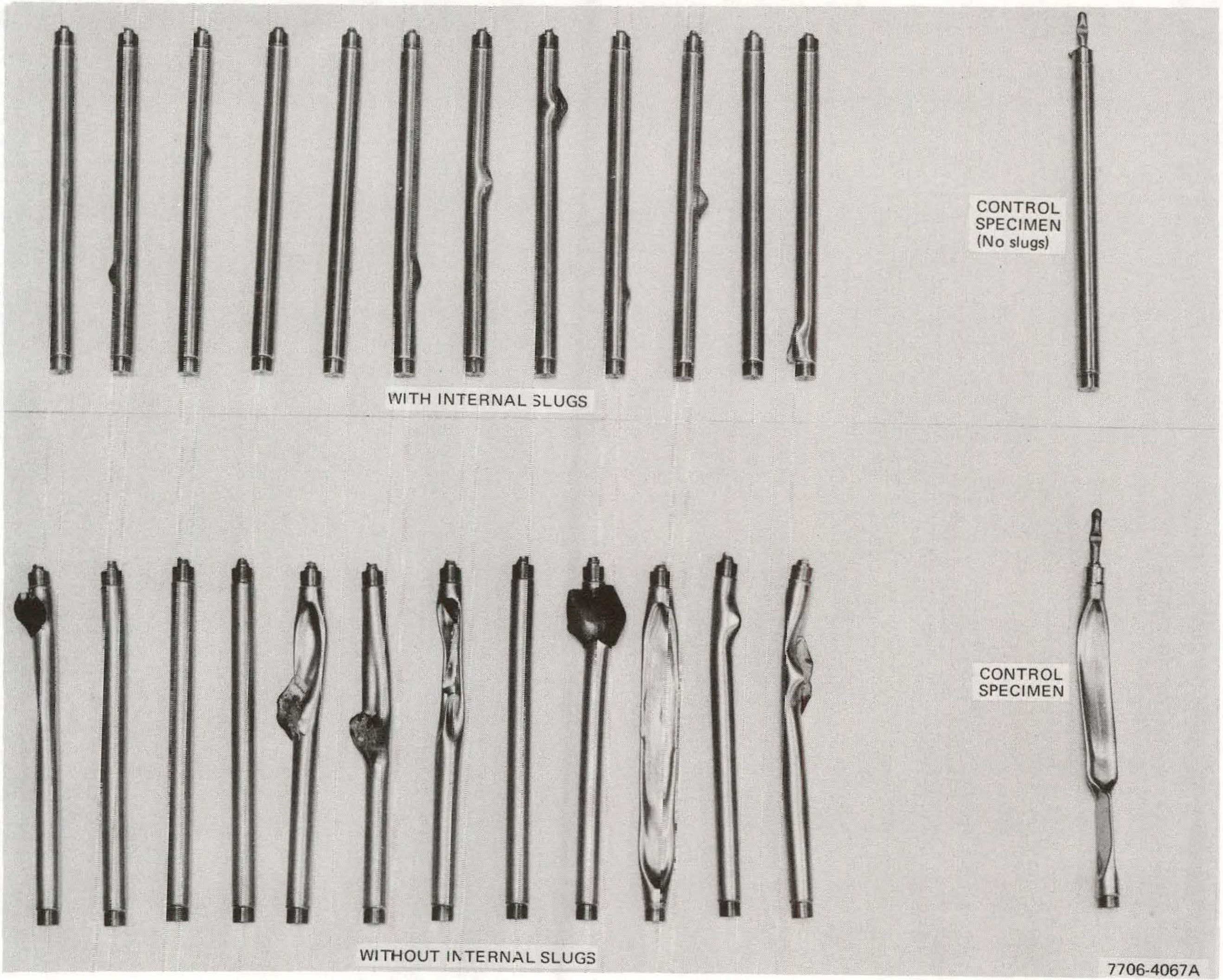

Figure 28. Influence of Internal Slugs in Specimens Tested in 1000°F Sodium

wave results in bending and twisting of the pressure tubes connected to the specimens, and a flattening of previously ruptured specimens which are no longer internally pressurized. To alleviate this problem, solid stainless steel slugs were placed inside the specimens to reduce the gas volume. This procedure was found to greatly reduce the extent of damage. While explosive-type ruptures still occurred, damage to neighboring specimens was eliminated. The unstressed control specimen (containing no internal slug or gas pressure) was also undamaged. Figure 28 compares the specimens from two retort tests, one with internal specimen slugs and the other without slugs. It is clear that the insertion of the solid slugs was effective in reducing damage to the specimens by the explosive force accompanying specimen rupture.

C. SODIUM EFFECTS

In any mechanical testing study, one must be concerned about the test environment and its potential influence on the test results. Considering the numerous reports of liquid metals causing a loss in mechanical properties of materials,[11-14] it was necessary to evaluate the effect of the static sodium in the present study. Therefore, the sodium tests were compared with similar tests in high-purity helium under identical test conditions.

Under biaxial stress at 1200°F and above, the static sodium environment had no effect on the stress-rupture behavior of the two stainless steels (Figures 14, 15, 21, and 22). However, under uniaxial stress, sodium was found to decrease the amount of tertiary creep (Figure 17). A similar observation was reported by Böhm[15] with tubing filled internally with sodium. While comparative tests on Type 316 stainless steel tubing under uniaxial stress are limited, they do show the same environmental effect on tertiary creep as for Type 304 stainless steel.

At a test temperature of 1000°F, a sodium effect was noted on biaxial stress-rupture of cold-worked Type 316 stainless steel. The behavior is depicted in Figure 21. The apparent stress dependence, fracture behavior, and strain relationship, as a result of environment, seems to be related only to the cold-worked tubing. The mechanisms causing the observed sodium effect are apparently different from those at higher temperatures, but more studies are needed to define the effect.

Based on microstructural comparisons of specimens tested in both sodium and helium, it seems that the presence of sodium promotes the formation of a grain boundary phase. This phase is believed to be either σ or ferrite. This would suggest that sodium is removing austenite stabilizers from the metal grain boundaries.

D. STRESS MODE

During reactor operation, structural materials may be subjected to a variety of complex stress conditions resulting from thermal bowing, thermal gradients, fission gas generation, fuel swelling, and mechanical interactions with housing and spacers. While the interrelationship and magnitude of these stresses cannot be accurately defined, valuable insight into the influence of stress mode on stress-rupture behavior can be gained by experimental studies.

In the present studies, the stress-rupture properties of the two austenitic stainless steels were explored under three different stress modes. One of the objectives of this work was to attempt to correlate the properties and stress mode, so that the properties could be expressed independent of the state of stress. For the Type 304 stainless steel alloy, under uniaxial, 2:1 biaxial, and 1:1 biaxial stresses, the stress-rupture curves can be brought into good agreement by applying the von Mises distortion energy yield theory to the stress. This can be expressed mathematically by[16]

$$\sigma_o^2 = 1/2(\sigma_1 - \sigma_2) + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \quad , \qquad \ldots (1)$$

where:

σ_o = effective stress

σ_1 = axial stress

σ_2 = tangential stress

σ_3 = radial stress.

For thin-walled tubes subjected to an axial load and internal hydrostatic pressure, radial stresses are insignificant, and Equation 1 reduces to

$$\sigma_o^2 = \sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 \quad . \qquad \ldots (2)$$

For the three stress states (uniaxial, 2:1 biaxial, and 1:1 biaxial), the effective stresses are $\sigma_o = \sigma_1$, $\sigma_o = 0.866\sigma_2$, and $\sigma_o = \sigma_1 = \sigma_2$, respectively.

Using the effective stress, the uniaxial and biaxial stress-rupture results obtained in 1200°F sodium on annealed Type 304 stainless steel were compared. Figure 29 shows the very good correlation obtained, using von Mises' yield criterion. Good agreement was also found at 1400°F, where 2:1 biaxial tests in sodium were compared with Kramer's work[17] on the same heat of alloy in vacuum.

For Type 316 stainless steel, the von Mises criterion did not hold — rather, the stress-rupture strength was found to best correlate with the maximum principal stress theory. The stress-rupture strength of cold-worked Type 316 stainless steel tubing, tested under three stress modes in 1200 and 1000°F sodium, are plotted in Figure 30, using the principal stress. Norton[18] studied Type 316 stainless steel under the same three stress states used in this investigation. He also concluded that the maximum principal stress seems to be the best criterion for rupture life of Type 316 stainless steel.

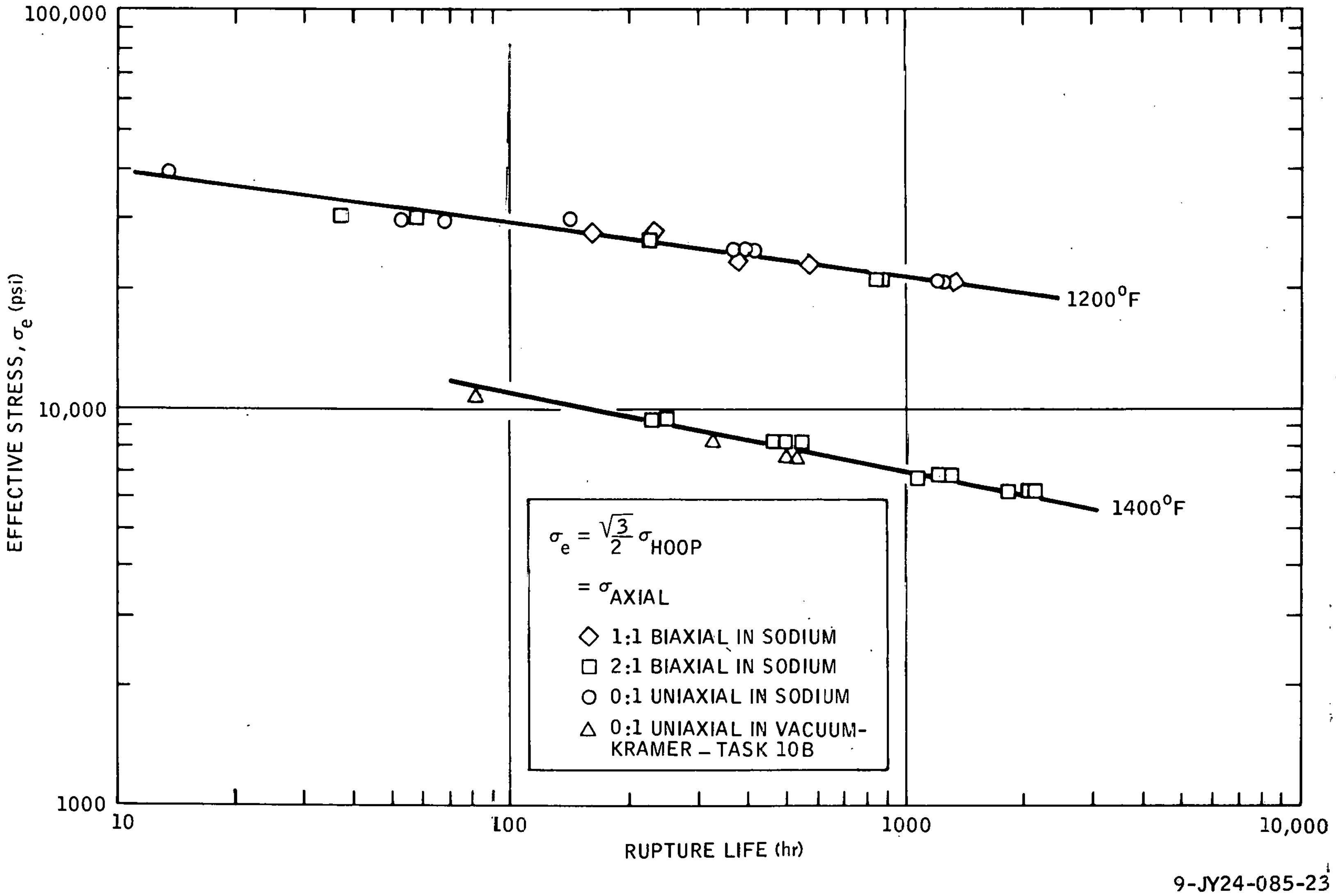

Figure 29. Correlation of Stress State With Rupture Life, Using von Mises' Yield Theory — Annealed Type 304 Stainless Steel

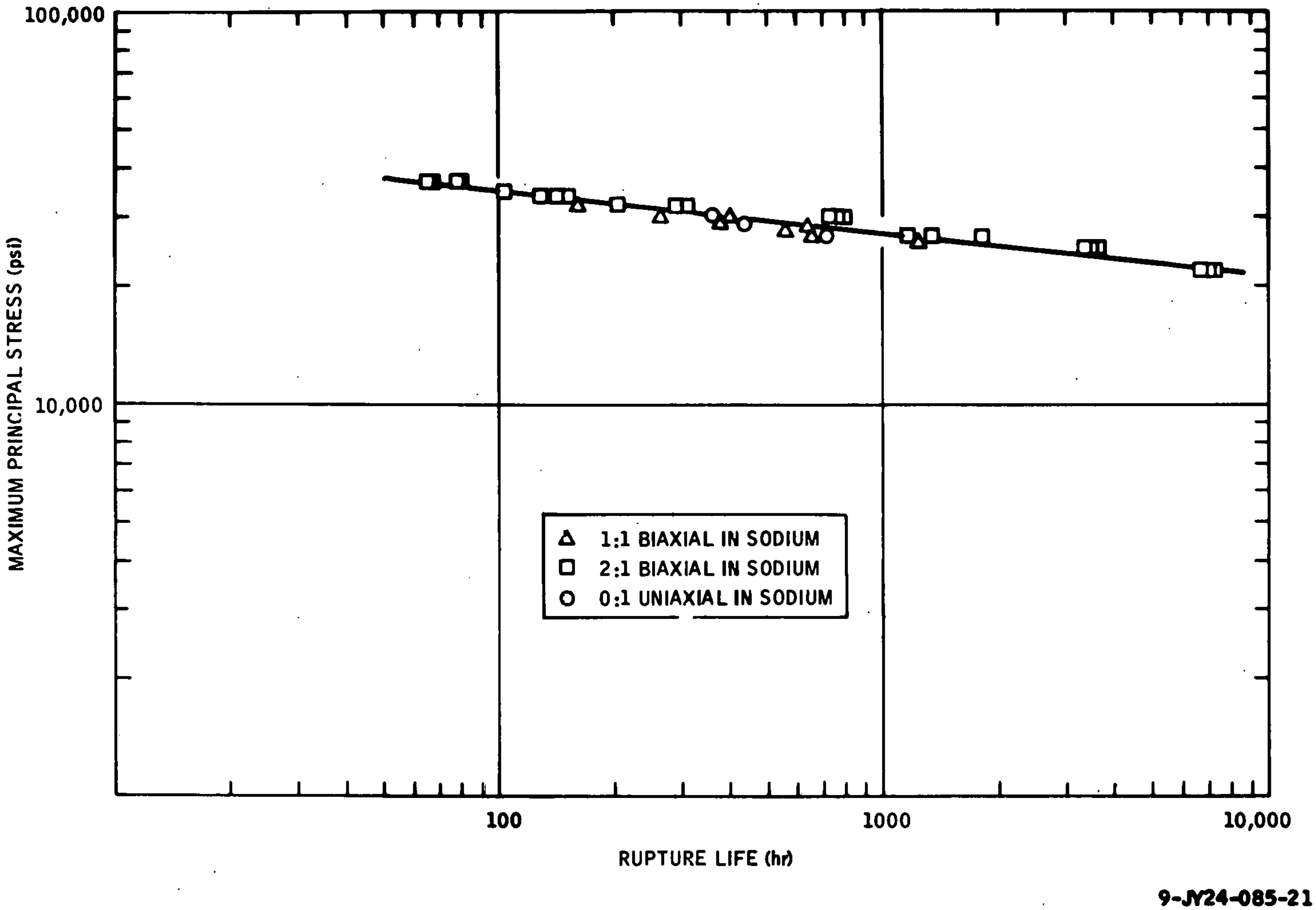

Figure 30. Effect of Stress Mode on Cold-Worked (10 to 15%) Type 316 Stainless Steel in 1200°F Sodium

V. CONCLUSIONS

The experimental studies have provided a better understanding of the relative stability of Type 304 and Type 316 stainless steel to long-term high-temperature sodium service. Some of the important observations are:

1) In the solution-annealed condition, both alloys have about the same stress-rupture characteristics. The data could be considered to lie within the scatter band expected for heat-to-heat variation for a given alloy.

2) With cladding containing 10 to 15% cold work, important differences between the two alloys were observed. The strengthening benefits of cold work are retained longer for Type 316 alloy than for Type 304 stainless steel at the same temperature. Apparently, the recovery processes are slower, at the same temperature and stress, for Type 316 stainless steel.

3) Cold work reduces the creep ductility of both alloys, but the percentage reduction is significantly greater for Type 304 stainless steel. This effect is particularly pronounced at higher strain rates.

4) The formation of σ phase is much more pronounced in stainless steel containing 10 to 15% cold work than it is in the annealed version of the alloy. Cold work promotes the transformation of austenite to ferrite which, in turn, can more easily form σ phase. The σ formation in cold-worked Type 304 is also enhanced by stress on the thin-wall cladding. Under low-stress, long-term conditions, a semi-continuous grain boundary phase develops. This phase has the appearance of either σ or ferrite. The change in slope observed on the stress-rupture curves seems to be related to the formation of this grain boundary phase. A continuous grain boundary phase was not observed in Type 316 stainless steel containing 10 to 15% cold work. Much of the σ formed in this alloy is found as a fine precipitate within the grains and on slip bands.

5) The sodium test environment was found to reduce the amount of tertiary creep strain in both alloys. This effect was most pronounced under uniaxial stress. With a 2:1 biaxial stress, rupture occurs at the onset of tertiary creep, and the sodium effect was not apparent. However, biaxial stress-rupture tests on cold-worked Type 316 stainless steel tubing exhibited different properties in sodium and helium at 1000°F. Additional studies are required to clarify the observed behavior.

6) Stress-rupture tests, conducted on Type 304 stainless steel under three stress states (uniaxial, 2:1 biaxial, and 1:1 biaxial), have shown an excellent correlation of rupture strength with von Mises' distortion theory. With Type 316 stainless steel, the von Mises correlation does not exist. Although testing is not complete on Type 316 stainless steel, it appears that stress state on this alloy correlates best with the maximum principal stress theory.

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APPENDIX

DATA TABLES

TABLE A-1

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR ANNEALED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013)
(Sheet 1 of 2)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 20 — 900°F Sodium				
A4-29	57,000	1228	16.30*	1.33×10^{-2}
A4-27	55,000	2326	16.58*	7.13×10^{-3}
A4-28	55,000	1893	16.17*	8.54×10^{-3}
A4-25	50,000	7100	13.89*	1.96×10^{-3}
A4-26	50,000	5910	14.63	2.47×10^{-3}
Retort No. 25 — 900°F Sodium				
A4-70	56,000	2238	NA	NA
A4-69	56,000	2819	NA	NA
A4-67	54,000	4842	NA	NA
A4-66	54,000	4817	NA	NA
A4-65	54,000	5173	NA	NA
A4-64	52,000	6622	NA	NA
A4-63	52,000	6922	NA	NA
A4-62	52,000	8350	NA	NA
Retort No. 21 — 1000°F Sodium				
A4-42	55,000	89	†	-
A4-41	55,000	89	†	-
A4-40	55,000	85	†	-
A4-39	50,000	300	†	-
A4-38	50,000	598	11.81*	1.97×10^{-2}
A4-37	50,000	370	†	-
A4-36	47,000	1105	9.39*	8.50×10^{-3}
A4-35	47,000	1236	9.85	7.97×10^{-3}
A4-34	47,000	1089	9.85	9.04×10^{-3}
A4-33	45,000	2024	8.27*	4.09×10^{-3}
A4-32	45,000	2280	8.37*	3.67×10^{-3}
A4-31	45,000	2000	9.82	4.91×10^{-3}
Retort No. 22 — 1000°F Sodium				
A4-60	45,000	2709	NA	NA
A4-59	45,000	2922	NA	NA
A4-58	45,000	2895	NA	NA
A4-57	42,000	7066	NA	NA
A4-56	42,000	8856	NA	NA
A4-53	42,000	5944	NA	NA
A4-51	40,000	7179	NA	NA
A4-49	40,000	7360	NA	NA
A4-48	40,000	4620	NA	NA
A4-45	37,000	10,462	NA	NA

TABLE A-1

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR ANNEALED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013)
(Sheet 2 of 2)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 17 — 1200°F Sodium				
A4-12	22,000	2984	NA	NA
A4-11	22,000	2234	NA	NA
A4-10	22,000	3106	NA	NA
A4-9	17,000	9768	NA	NA
A4-8	17,000	11,460	NA	NA
A4-7	17,000	9728	NA	NA
A4-6	15,000	14,296	NA	NA
Retort No. 18 — 1200°F Sodium				
A4-24	35,000	58	9.48	1.63×10^{-1}
A4-23	35,000	58	9.28	1.60×10^{-1}
A4-22	35,000	37	8.77	2.37×10^{-1}
A4-21	30,000	228	†	-
A4-20	30,000	228	†	-
A4-19	30,000	228	†	-
A4-17	25,000	850	9.34	1.10×10^{-2}
A4-16	25,000	875	10.72	1.22×10^{-2}
A4-15	19,000	4949	7.56	1.53×10^{-3}
A4-14	19,000	4561	8.61	1.89×10^{-3}
A4-13	19,000	4097	6.42	1.57×10^{-3}
Retort No. 8 — 1400°F Sodium				
A4-139	11,000	230	13.8	6.00×10^{-2}
A4-138	11,000	230	10.5	4.56×10^{-2}
A4-137	11,000	250	12.5	5.00×10^{-2}
A4-136	9,500	552	11.1	2.01×10^{-2}
A4-135	9,500	468	11.3	2.41×10^{-2}
A4-134	9,500	502	12.0	2.39×10^{-2}
A4-133	8,000	1260	8.7	6.90×10^{-3}
A4-132	8,000	1306	7.4	6.69×10^{-3}
A4-131	8,000	1044	8.2	7.52×10^{-3}
A4-130	7,200	2120	5.8	2.74×10^{-3}
A4-129	7,200	1834	5.8	3.17×10^{-3}
A4-128	7,200	2073	6.7	3.24×10^{-3}

* Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-2

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013) (Sheet 1 of 5)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 26 – 900°F Sodium				
4-235	70,000	4916	NA**	NA**
4-233	70,000	4740	NA**	NA**
Retort No. 16 – 1000°F Sodium				
4-195	70,000	130	1.38*	1.06×10^{-2}
4-194	70,000	143	1.14*	7.97×10^{-3}
4-193	70,000	90	2.12*	2.35×10^{-2}
4-192	60,000	815	0.57*	6.99×10^{-4}
4-191	60,000	1185	1.01*	8.52×10^{-4}
4-190	60,000	1017	1.51*	1.48×10^{-3}
4-189	55,000	1869	1.01*	5.40×10^{-4}
4-188	55,000	1858	0.67*	3.60×10^{-4}
4-186	50,000	3106	1.14	3.67×10^{-4}
4-185	50,000	1800	0.97	5.39×10^{-4}
4-184	50,000	2328	0.94*	4.04×10^{-4}
Retort No. 19 – 1000°F Sodium				
4-205	50,000	3212	†	-
4-204	50,000	3518	0.67*	1.87×10^{-4}
4-203	50,000	3446	0.74*	2.15×10^{-4}
4-202	45,000	5409	1.44*	2.66×10^{-4}
4-183	45,000	5217	0.94*	1.80×10^{-4}
4-182	45,000	5551	0.87	1.57×10^{-4}
4-181	42,000	7953	0.92	1.15×10^{-4}
4-180	42,000	7478	0.91*	1.22×10^{-4}
4-179	42,000	7690	0.84	1.09×10^{-4}
4-178	40,000	7706	0.57	7.39×10^{-5}
4-177	40,000	9718	0.96	9.88×10^{-5}
4-176	40,000	8902	0.84*	9.44×10^{-5}
Retort No. 19 – 1000°F Sodium				
4-205	50,000	3212	†	-
4-204	50,000	3518	0.67*	1.87×10^{-4}
4-203	50,000	3446	0.74*	2.15×10^{-4}
4-202	45,000	5409	1.44*	2.66×10^{-4}
4-183	45,000	5217	0.94*	1.80×10^{-4}
4-182	45,000	5551	0.87	1.57×10^{-4}
4-181	42,000	7953	0.92	1.15×10^{-4}
4-180	42,000	7478	0.91*	1.22×10^{-4}
4-179	42,000	7690	0.84	1.09×10^{-4}
4-178	40,000	7706	0.57	7.39×10^{-5}
4-177	40,000	9718	0.96	9.88×10^{-5}
4-176	40,000	8902	0.84*	9.44×10^{-5}

Notes: * Explosive ruptures – strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available – test still in progress

TABLE A-2

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013) (Sheet 2 of 5)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 27 — 1000°F Helium				
4-249	70,000	86	3.43*	3.99×10^{-2}
4-248	70,000	152	2.69*	1.77×10^{-2}
4-247	70,000	138	1.85	1.34×10^{-2}
4-246	62,000	615	0.79	1.28×10^{-3}
4-245	62,000	729	1.21*	1.66×10^{-3}
4-244	62,000	591	1.58*	2.67×10^{-3}
4-243	58,000	670	1.26	1.88×10^{-3}
4-242	58,000	1209	0.77*	6.37×10^{-4}
4-241	58,000	1137	1.24*	1.09×10^{-3}
4-240	50,000	1473	0.50*	3.39×10^{-4}
4-239	50,000	2802	0.67*	2.39×10^{-4}
4-236	50,000	1193	0.27*	2.26×10^{-4}
Retort No. 9 — 1000°F Sodium				
4-88	75,000	58	†	-
4-87	75,000	45	†	-
4-86	75,000	58	†	-
4-85	70,000	105	†	-
4-84	70,000	155	†	-
4-83	70,000	179	†	-
4-82	65,000	285	†	-
4-81	65,000	321	†	-
4-80	65,000	225	†	-
4-79	60,000	660	†	-
4-78	60,000	321	†	-
4-77	60,000	680	†	-
Retort No. 7 — 1100°F Sodium				
4-76	43,000	737	1.85	2.50×10^{-3}
4-75	43,000	675	†	-
4-74	43,000	494	†	-
4-73	40,000	1328	†	-
4-72	40,000	1174	†	-
4-71	40,000	1125	†	-
4-70	38,000	1477	1.50	1.02×10^{-3}
4-69	38,000	1560	†	-
4-68	38,000	1762	1.51	8.60×10^{-4}
4-67	35,000	3300	1.85	5.61×10^{-4}
4-66	35,000	3373	1.68	4.98×10^{-4}
4-65	35,000	3206	1.55	4.83×10^{-4}

Notes: * Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-2

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013) (Sheet 3 of 5)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 11 – 1200°F Sodium				
4-112	35,000	273	†	-
4-111	35,000	297	†	-
4-110	35,000	297	†	-
4-109	30,000	765	3.00	3.9×10^{-3}
4-108	30,000	743	†	-
4-107	30,000	729	2.80	3.8×10^{-3}
4-106	23,000	1305	2.70	2.1×10^{-3}
4-105	23,000	2030	2.60	1.3×10^{-3}
4-104	23,000	2030	2.70	1.3×10^{-3}
4-103	19,000	3400	3.30	9.7×10^{-4}
4-102	19,000	3273	3.30	10.1×10^{-4}
4-101	19,000	3360	3.00	8.9×10^{-4}
Retort No. 13 – 1200°F Helium				
4-148	35,000	372	†	-
4-147	35,000	372	2.18	5.86×10^{-3}
4-151	28,000	1257	2.80	2.23×10^{-3}
4-150	28,000	1233	2.18	1.77×10^{-3}
4-145	22,000	2751	2.45	0.89×10^{-3}
4-144	22,000	2783	2.79	1.00×10^{-3}
4-143	22,000	2937	3.12	1.06×10^{-3}
4-142	17,000	5598	3.52	6.29×10^{-4}
4-141	17,000	5012	3.09	6.16×10^{-4}
4-140	17,000	4964	2.90	5.84×10^{-4}
Retort No. 15 – 1200°F Sodium				
4-175	20,000	3121	1.95	6.25×10^{-4}
4-174	20,000	3296	2.25	6.83×10^{-4}
4-173	20,000	3397	1.98	5.83×10^{-4}
4-172	18,000	4560	2.52	5.53×10^{-4}
4-171	18,000	4953	3.13	6.32×10^{-4}
4-170	18,000	4431	1.98	4.47×10^{-4}
4-169	17,000	5487	2.66	4.85×10^{-4}
4-168	17,000	5271	2.59	4.91×10^{-4}
4-167	17,000	5473	2.12	3.87×10^{-4}
4-166	16,000	6102	2.75	4.51×10^{-4}
4-165	16,000	5927	3.03	5.11×10^{-4}
4-164	16,000	6208	2.49	4.01×10^{-4}
Retort No. 14 (Sodium Aged for 2000 hr at 1200°F) – 1200°F Sodium				
4-163	40,000	94	6.05*	6.44×10^{-2}
4-162	40,000	92	†	-
4-161	40,000	94	†	-

Notes: * Explosive ruptures – strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available – test still in progress

TABLE A-2

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013) (Sheet 4 of 5)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 14 (Sodium Aged for 2000 hr at 1200°F) – 1200°F Sodium (Continued)				
4-160	35,000	240	3.16	1.32×10^{-2}
4-159	35,000	249	†	-
4-158	35,000	273	†	-
4-157	31,000	609	4.07*	6.68×10^{-3}
4-156	31,000	513	†	-
4-155	31,000	577	5.18*	8.98×10^{-3}
4-154	27,000	970	2.99*	3.08×10^{-3}
4-153	27,000	956	3.36	3.51×10^{-3}
4-152	27,000	680	1.91	2.81×10^{-3}
Retort No. 6 – 1400°F Sodium				
4-64	11,000	201	5.61	2.79×10^{-2}
4-63	11,000	201	4.94	2.46×10^{-2}
4-62	11,000	222	4.74	2.14×10^{-2}
4-61	9,500	320	5.21	1.63×10^{-2}
4-60	9,500	332	4.94	1.49×10^{-2}
4-59	9,500	296	3.80	1.28×10^{-2}
4-58	8,000	512	5.04	0.98×10^{-2}
4-57	8,000	512	5.48	1.07×10^{-2}
4-56	8,000	455	3.53	7.80×10^{-3}
4-55	6,800	813	6.08	7.50×10^{-3}
4-54	6,800	682	3.22	4.70×10^{-3}
4-53	6,800	775	5.27	6.80×10^{-3}
Retort No. 10 – 1400°F Sodium				
4-100	6,000	825	5.69	6.9×10^{-3}
4-99	6,000	696	3.80	5.5×10^{-3}
4-98	6,000	849	5.38	6.4×10^{-3}
4-97	4,700	1402	5.35	3.8×10^{-3}
4-96	4,700	1449	5.99	4.1×10^{-3}
4-95	4,700	1488	5.92	4.0×10^{-3}
4-94	4,100	1785	4.20	2.3×10^{-3}
4-93	4,100	1990	6.66	3.3×10^{-3}
4-92	4,100	2192	6.40	2.9×10^{-3}
4-91	3,500	3032	7.33	2.4×10^{-3}
4-90	3,500	2864	5.65	2.0×10^{-3}
4-89	3,500	2915	5.82	2.0×10^{-3}

Notes: * Explosive ruptures – strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available – test still in progress

TABLE A-2

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 304 STAINLESS STEEL TUBING (Heat No. 20013) (Sheet 5 of 5)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 3 — 1400°F Helium				
4-36	9,950	263	5.98	2.10×10^{-2}
4-35	9,950	267	5.07	1.71×10^{-2}
4-34	9,950	262	5.11	1.72×10^{-2}
4-33	8,570	344	6.05	1.44×10^{-2}
4-32	8,570	344	3.36	8.80×10^{-3}
4-31	8,570	380	4.77	1.11×10^{-2}
4-30	7,200	531	3.97	6.34×10^{-3}
4-29	7,200	503	4.67	7.28×10^{-3}
4-28	7,200	584	5.72	8.08×10^{-3}
4-27	6,140	734	5.81	6.57×10^{-3}
4-26	6,140	710	5.14	6.53×10^{-3}
4-25	6,140	789	7.15	7.38×10^{-3}

Notes: * Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-3

UNIAXIAL STRESS RUPTURE OF TYPE 304 STAINLESS STEEL SHEET
(0.062 in. Thick, Heat No. 20013)

Specimen No.	Temper	Test Media	Temperature (°F)	Stress (psi)	Rupture Life (hr)	Strain — Axial Direction				Steady-State Strain Rate (%/hr)
						Primary (%)	Secondary (%)	Tertiary (%)	Total (%)	
404-U	A*	Sodium	1200	21,000	1253	3.2	3.0	11.2	17.4	6.3×10^{-3}
403-U	A	Sodium	1200	21,000	1233	2.0	4.7	17.8	24.5	7.6×10^{-3}
431-U	A	Helium	1200	21,000	1310	1.8	4.2	38.5	44.5	6.8×10^{-3}
429-U	A	Helium	1200	21,000	1569	0.0	8.5	36.5	45.0	7.2×10^{-3}
402-U	A	Sodium	1200	25,000	388	2.0	7.0	22.5	31.5	2.8×10^{-2}
401-U	A	Sodium	1200	25,000	421	2.5	4.0	35.5	42.0	2.4×10^{-2}
421-U	A	Sodium	1200	30,000	69	3.2	5.4	8.0	16.6	1.2×10^{-1}
406-U	A	Sodium	1200	30,000	55	2.8	4.3	5.1	12.2	1.3×10^{-1}
405-U	A	Sodium	1200	30,000	143	4.0	8.5	29.5	42.0	1.2×10^{-1}
422-U	11% CW	Sodium	1200	27,000	897	0.5	1.3	9.7	11.5	2.4×10^{-3}
418-U	11% CW	Sodium	1200	27,000	1290	0.5	1.1	5.7	7.3	2.0×10^{-3}
419-U	11% CW	Sodium	1200	35,000	93	0.5	2.1	10.6	13.2	3.8×10^{-2}
417-U	11% CW	Sodium	1200	35,000	105	0.6	1.3	6.8	8.7	2.0×10^{-2}
415-U	11% CW	Sodium	1200	39,000	47	1.9	2.1	11.3	15.3	8.6×10^{-2}
414-U	38% CW	Sodium	1200	20,000	147	0.2	0.4	5.6	6.2	1.1×10^{-1}
413-U	38% CW	Sodium	1200	20,000	187	0.4	0.7	6.1	7.2	9.8×10^{-1}
412-U	38% CW	Sodium	1200	30,000	72	0.3	0.7	1.80	2.9	1.9×10^{-2}
411-U	38% CW	Sodium	1200	30,000	66	0.2	1.1	1.7	3.0	2.4×10^{-2}
408-U	38% CW	Sodium	1200	35,000	47	0.6	0.5	1.5	2.6	1.9×10^{-2}
407-U	38% CW	Sodium	1200	35,000	46	0.5	0.6	1.7	2.8	2.9×10^{-2}

*A = Annealed
CW = Cold worked

TABLE A-4

1:1 BIAXIAL STRESS RUPTURE OF TYPE 304 STAINLESS STEEL TUBING (0.275 in. ID by 0.010 in. Wall, Heat No. 20013)

Specimen No.	Temper	Test Media	Temperature (°F)	Stress (psi)	Rupture Life (hr)	Strain — Axial Direction				Steady-State Strain Rate (%/hr)	Total Hoop Strain (%)	Average Hoop Strain Rate (%/hr)
						Primary (%)	Secondary (%)	Tertiary (%)	Total (%)			
426-B	A*	Sodium	1200	28,000	158	0.8	1.3	6.2	8.3	1.69×10^{-2}	8.7	5.25×10^{-2}
424-B	A	Helium	1200	28,000	221	0.8	1.4	7.8	10.0	1.54×10^{-2}	12.9	4.52×10^{-2}
427-B	A	Sodium	1200	24,000	372	0.6	1.0	4.7	6.3	6.25×10^{-3}	7.9	1.69×10^{-2}
433-B	A	Sodium	1200	23,000	632	0.5	0.4	5.8	6.7	1.90×10^{-3}	11.4	1.12×10^{-2}
430-B	A	Sodium	1200	21,000	1334	0.7	0.6	5.7	7.0	1.02×10^{-3}	8.2	5.25×10^{-3}
428-B	CW	Sodium	1200	30,000	413	0.4	0.7	2.6	3.7	3.61×10^{-3}	1.2	8.91×10^{-3}
425-B	CW	Helium	1200	30,000	460	0.2	0.9	4.5	5.6	3.50×10^{-3}	8.7	1.21×10^{-2}

*A = Annealed
CW = Cold Worked

TABLE A-5

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 316 STAINLESS STEEL TUBING (Heat No. 65808) (Sheet 1 of 3)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 103 — 1000°F Sodium				
6-36	64,000	22	10.02*	4.36×10^{-1}
6-34	64,000	23	7.88*	3.43×10^{-1}
6-33	54,000	206	2.45*	1.19×10^{-2}
6-32	54,000	152	2.35*	1.55×10^{-2}
6-31	54,000	176	1.84*	1.04×10^{-2}
6-30	48,000	674	1.41*	2.09×10^{-3}
6-29	48,000	875	1.44*	1.65×10^{-3}
6-28	48,000	898	1.98	2.20×10^{-3}
6-27	42,000	3970	0.80	2.01×10^{-4}
6-26	42,000	4884	1.07	2.19×10^{-4}
6-25	42,000	3170	0.64	2.02×10^{-4}
Retort No. 110 — 1000°F Sodium				
6-68	46,000	3177	NA	-
6-67	46,000	2270	NA	-
6-66	46,000	2585	NA	-
6-65	41,000	5049	NA	-
6-64	41,000	9022	NA	-
6-63	41,000	6285	NA	-
6-85	40,000	10,745	NA	-
Retort No. 116 (Sodium Aged for 3000 hr at 1000°F) — 1000°F Sodium				
6-138	48,000	2578	NA	-
6-137	48,000	2476	NA	-
6-136	48,000	1930	NA	-
6-135	44,000	3297	NA	-
6-134	44,000	3876	NA	-
6-133	44,000	3908	NA	-
6-132	42,000	3970	NA	-
6-131	42,000	4340	NA	-
6-130	42,000	4786	NA	-
6-128	40,000	7005	NA	-
Retort No. 108 — 1000°F Helium				
6-62	60,000	610	1.14	1.87×10^{-3}
6-61	60,000	694	1.64	2.36×10^{-3}
6-60	60,000	610	1.07	1.75×10^{-3}
6-59	56,000	791	0.90	1.14×10^{-3}
6-58	56,000	862	1.24	1.44×10^{-3}
6-57	56,000	937	1.07	1.14×10^{-3}
6-56	50,000	1330	0.33	2.48×10^{-4}
6-55	50,000	1234	0.43	3.48×10^{-4}
6-54	50,000	1270	0.43	3.38×10^{-4}
6-53	46,000	2228	0.43	1.93×10^{-4}
6-52	46,000	1418	0.30	2.11×10^{-4}
6-51	46,000	2098	0.40	1.91×10^{-4}

Notes: * Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-5

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 316 STAINLESS STEEL TUBING (Heat No. 65808) (Sheet 2 of 3)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 115 — 1000°F Helium				
6-126	56,000	811	NA	-
6-125	56,000	825	NA	-
6-124	56,000	767	NA	-
6-123	50,000	777	NA	-
6-122	50,000	1485	NA	-
6-121	50,000	1425	NA	-
6-120	46,000	2517	NA	-
6-119	46,000	2052	NA	-
Retort No. 102 — 1200°F Sodium				
6-24	35,000	105	5.50	5.24×10^{-2}
6-23	35,000	129	†	-
6-22	35,000	129	†	-
6-21	30,000	764	†	-
6-20	30,000	790	6.34	8.03×10^{-3}
6-19	30,000	752	6.94	9.23×10^{-3}
6-18	25,000	3396	5.10	1.50×10^{-3}
6-17	25,000	3623	9.82	2.71×10^{-3}
6-16	25,000	3412	6.67	1.96×10^{-3}
6-15	22,000	7046	4.76	6.76×10^{-4}
6-14	22,000	7152	5.77	8.07×10^{-4}
6-13	22,000	6770	4.26	6.29×10^{-4}
Retort No. 109 — 1200°F Sodium				
6-79	37,000	81	†	-
6-78	37,000	67	†	-
6-77	37,000	68	†	-
6-76	34,000	129	3.95*	3.06×10^{-2}
6-75	34,000	143	†	-
6-74	34,000	153	†	-
6-73	32,000	206	2.48	1.20×10^{-2}
6-72	32,000	310	6.44	2.20×10^{-2}
6-71	32,000	296	5.30	1.92×10^{-2}
6-70	27,000	1822	12.17	6.68×10^{-3}
6-50	27,000	1354	8.68	6.41×10^{-3}
6-49	27,000	1189	8.28	6.96×10^{-3}

Notes: * Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-5

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR 10 TO 15% COLD-WORKED TYPE 316 STAINLESS STEEL TUBING (Heat No. 65808) (Sheet 3 of 3)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 114 (Sodium Aged for 2000 hr at 1200°F) — 1200°F Sodium				
6-114	31,000	315	†	-
6-113	31,000	336	15.09*	4.49×10^{-2}
6-112	31,000	301	†	-
6-111	29,000	517	12.41*	2.40×10^{-2}
6-110	29,000	483	†	-
6-109	29,000	581	15.22*	2.62×10^{-2}
6-108	24,000	2580	9.66	3.74×10^{-3}
6-107	24,000	2472	11.50	4.65×10^{-3}
6-106	24,000	2607	13.43	5.15×10^{-3}
6-105	23,000	3402	8.78	2.58×10^{-3}
6-104	23,000	3259	7.98	2.45×10^{-3}
6-103	23,000	3194	8.65	2.71×10^{-3}
Retort No. 101 — 1400°F Helium				
6-12	16,000	152	9.12	6.00×10^{-2}
6-11	16,000	152	10.79	7.10×10^{-2}
6-10	16,000	152	10.96	7.21×10^{-2}
6-9	13,000	405	6.37	1.57×10^{-2}
6-8	13,000	440	6.94	1.58×10^{-2}
6-7	13,000	405	5.93	1.46×10^{-2}
6-6	11,000	689	5.26	7.63×10^{-3}
6-5	11,000	727	4.86	6.69×10^{-3}
6-4	11,000	705	5.56	7.89×10^{-3}
6-3	9,600	968	4.93	5.10×10^{-3}
6-2	9,600	944	5.36	5.68×10^{-3}
6-1	9,600	944	4.36	4.62×10^{-3}
Retort No. 104 — 1400°F Helium				
6-48	16,000	182	11.63	6.39×10^{-2}
6-47	16,000	182	11.50	6.32×10^{-2}
6-46	16,000	182	12.64	6.94×10^{-2}
6-45	13,000	433	8.45	1.95×10^{-2}
6-44	13,000	454	7.27	1.60×10^{-2}
6-43	13,000	469	10.02	2.14×10^{-2}
6-42	10,332	925	5.26	5.69×10^{-3}
6-41	10,332	925	4.62	4.99×10^{-3}
6-40	10,332	963	5.83	6.05×10^{-3}
6-39	9,332	1123	8.68	7.73×10^{-3}
6-38	9,332	1142	5.43	4.75×10^{-3}
6-37	9,332	1549	5.43	3.51×10^{-3}

Notes: * Explosive ruptures — strain measured adjacent to rupture
† Specimens collapsed due to explosive ruptures
NA Data not available — test still in progress

TABLE A-6

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR ANNEALED TYPE 316 STAINLESS STEEL TUBING (Heat No. 65808) (Sheet 1 of 2)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
		Retort No. 107 — 1000°F Sodium		
A6-42	54,000	228	21.19*	9.29×10^{-2}
A6-41	54,000	176	†	-
A6-40	54,000	200	16.08*	8.04×10^{-2}
A6-39	50,000	304	13.75	4.52×10^{-2}
A6-38	50,000	398	21.14	5.31×10^{-2}
A6-37	50,000	300	14.74	4.91×10^{-2}
A6-36	48,000	489	12.35*	2.52×10^{-2}
A6-35	48,000	513	13.08	2.55×10^{-2}
A6-34	48,000	529	13.63	2.58×10^{-2}
A6-33	45,000	587	10.89*	1.85×10^{-2}
A6-32	45,000	544	13.23	2.43×10^{-2}
A6-31	45,000	610	11.62	1.90×10^{-2}
		Retort No. 119 — 1000°F Sodium		
A6-113	50,000	370	19.21*	5.19×10^{-2}
A6-112	50,000	357	†	-
A6-111	50,000	398	19.21	4.82×10^{-2}
A6-110	44,000	733	11.28	1.54×10^{-2}
A6-108	44,000	705	11.30*	1.60×10^{-2}
A6-107	44,000	757	12.01	1.58×10^{-2}
A6-106	40,000	1209	9.83	8.13×10^{-3}
A6-105	40,000	1127	10.16	9.01×10^{-3}
A6-104	40,000	861	8.99*	1.04×10^{-2}
A6-103	35,000	1661	6.64*	3.99×10^{-3}
A6-102	35,000	2725	7.23	2.65×10^{-3}
A6-101	35,000	2974	6.91	2.32×10^{-3}
		Retort No. 121 — 1000°F Helium		
A6-138	50,000	255	18.21*	7.14×10^{-2}
A6-137	50,000	255	18.21*	7.14×10^{-2}
A6-135	48,000	464	15.79*	3.40×10^{-2}
A6-134	48,000	403	15.86*	3.93×10^{-2}
A6-133	48,000	447	16.70	3.74×10^{-2}
A6-132	40,000	1623	9.02	5.56×10^{-3}
A6-130	40,000	1358	9.12	6.71×10^{-3}
A6-129	40,000	1396	8.58	6.15×10^{-3}
A6-128	35,000	3846	6.57	9.28×10^{-4}
A6-127	35,000	4384	6.77	1.54×10^{-3}
A6-126	35,000	1101	6.91	6.27×10^{-3}

Notes: *Explosive ruptures — strain measured adjacent to rupture
†Specimens collapsed due to explosive ruptures

TABLE A-6

BIAXIAL (2:1) STRESS-RUPTURE DATA FOR ANNEALED TYPE 316 STAINLESS STEEL TUBING (Heat No. 65808) (Sheet 2 of 2)

Specimen No.	Hoop Stress (psi)	Rupture Life (hr)	Maximum Diametral Strain (%)	Average Diametral Strain Rate (%/hr)
Retort No. 106 — 1200°F Sodium				
A6-13	32,000	24	15.91	6.63×10^{-1}
A6-14	32,000	20	17.75	8.87×10^{-1}
A6-15	32,000	19	16.58	8.73×10^{-1}
A6-16	27,000	214	10.38	4.85×10^{-2}
A6-17	27,000	264	10.62	4.02×10^{-2}
A6-18	27,000	259	10.05	3.88×10^{-2}
A6-19	24,000	645	7.44	1.15×10^{-2}
A6-20	24,000	621	7.60	1.22×10^{-2}
A6-21	24,000	631	7.24	1.06×10^{-2}
A6-22	21,000	3054	7.60	2.49×10^{-3}
A6-23	21,000	2958	8.48	2.87×10^{-3}
A6-24	21,000	3006	8.51	2.83×10^{-3}
Retort No. 117 — 1200°F Sodium				
A6-88	23,000	763	11.30	1.48×10^{-2}
A6-87	23,000	744	9.53	1.28×10^{-2}
A6-86	23,000	763	10.23	1.34×10^{-2}
A6-85	20,000	2371	17.03	7.18×10^{-3}
A6-84	20,000	2467	19.55	7.92×10^{-3}
A6-83	20,000	2321	15.79	6.80×10^{-3}
A6-82	19,000	3356	17.74	5.29×10^{-3}
A6-81	19,000	3043	18.17	5.97×10^{-3}
A6-80	19,000	3278	19.05	5.81×10^{-3}
A6-79	18,000	5657	22.11	3.91×10^{-3}
A6-78	18,000	5744	23.74	4.13×10^{-3}
A6-77	18,000	4883	19.38	3.97×10^{-3}
Retort No. 105 — 1400°F Sodium				
A6-12	16,000	61	26.5	4.35×10^{-1}
A6-11	16,000	61	27.7	4.54×10^{-1}
A6-10	16,000	61	29.4	4.82×10^{-1}
A6-9	13,000	176	28.4	1.61×10^{-1}
A6-8	13,000	152	27.2	1.79×10^{-1}
A6-7	13,000	152	29.9	1.97×10^{-1}
A6-6	11,000	397	22.9	5.77×10^{-2}
A6-5	11,000	397	23.7	5.97×10^{-2}
A6-4	11,000	397	22.0	5.54×10^{-2}
A6-3	9,600	731	19.5	2.67×10^{-2}
A6-2	9,600	681	20.5	3.01×10^{-2}
A6-1	9,600	681	19.1	2.80×10^{-2}

Notes: *Explosive ruptures — strain measured adjacent to rupture
†Specimens collapsed due to explosive ruptures

TABLE A-7

UNIAXIAL STRESS RUPTURE OF TYPE 316 STAINLESS STEEL TUBING (0.275 in. ID by 0.010 in. Wall, Heat No. 65808)

Specimen No.	Temper	Test Media	Temperature (°F)	Stress (psi)	Rupture Life (hr)	Strain — Axial Direction				Steady-State Strain Rate (%/hr)
						Primary (%)	Secondary (%)	Tertiary (%)	Total (%)	
615-U	A*	Sodium	1200	21,000	870.6	1.1	2.4	28.4	31.9	1.4×10^{-2}
618-U	A	Sodium	1200	22,000	895.7	0.8	1.3	17.4	19.5	7.4×10^{-3}
603-U	A	Sodium	1200	22,000	1026.9	0.9	2.6	22.4	25.9	8.1×10^{-3}
614-U	A	Sodium	1200	24,000	285	1.1	3.7	13.0	17.8	3.4×10^{-2}
621-U	CW	Sodium	1200	27,000	705.4	0.0	2.0	20.7	22.7	8.3×10^{-3}
625-U	CW	Helium	1200	27,000	737.5	0.0	2.0	26.3	28.3	9.1×10^{-3}
623-U	CW	Sodium	1200	29,000	442.6	0.0	2.0	14.6	16.6	1.1×10^{-2}
622-U	CW	Sodium	1200	30,000	360.8	0.0	0.9	19.1	20.0	9.6×10^{-3}
634-U	A	Sodium	1000	42,000	1221	0.1	1.2	0.3	1.6	1.1×10^{-3}
632-U	A	Sodium	1000	48,000	567.3	0.7	0.3	0.8	1.8	1.2×10^{-3}
627-U	CW	Sodium	1000	48,000	748.1	0.0	0.2	0.0	0.2	2.9×10^{-4}
626-U	CW	Sodium	1000	50,000	1162.1	0.1	0.2	1.0	1.3	5.5×10^{-4}
635-U	A	Sodium	1000	54,000	412	0.0	0.2	1.1	1.3	3.7×10^{-4}
633-U	CW	Sodium	1000	54,000	663.9	0.0	0.1	1.3	1.4	2.2×10^{-4}

*A = Annealed
CW - Cold worked

TABLE A-8

1:1 BIAXIAL STRESS RUPTURE OF TYPE 316 STAINLESS STEEL TUBING
(0.275 in. ID by 0.010 in. Wall, Heat No. 65808)

Specimen No.	Temper	Test Media	Temperature (°F)	Stress (psi)	Rupture Life (hr)	Strain – Axial Direction				Steady-State Strain Rate (%/hr)	Total Hoop Strain (%)	Average Hoop Strain Rate (%/hr)
						Primary (%)	Secondary (%)	Tertiary (%)	Total (%)			
602-B	A*	Sodium	1200	22,000	436	0.5	1.0	4.5	6.0	6.1×10^{-3}	6.1	1.40×10^{-2}
601-B	A	Sodium	1200	22,000	286	0.8	0.9	2.9	4.6	6.5×10^{-3}	8.8	3.08×10^{-2}
607-B	A	Sodium	1200	22,000	693.7	0.4	0.7	7.3	8.4	4.2×10^{-3}	13.2	1.90×10^{-2}
616-B	A	Sodium	1200	23,000	322	0.5	1.6	3.8	5.9	1.0×10^{-2}	7.8	2.42×10^{-2}
605-B	A	Sodium	1200	24,000	428	0.4	1.4	3.2	5.0	6.3×10^{-3}	8.6	2.01×10^{-2}
604-B	A	Sodium	1200	24,000	457	0.6	1.1	5.7	7.4	6.6×10^{-3}	13.0	2.84×10^{-2}
617-B	A	Sodium	1200	26,000	96.2	0.6	1.8	1.1	3.5	3.0×10^{-2}	7.5	7.81×10^{-2}
606-B	A	Sodium	1200	27,000	124.2	0.6	1.1	5.3	7.0	3.1×10^{-2}	10.8	8.71×10^{-2}
619-B	A	Sodium	1200	27,000	76	0.4	2.41	1.4	4.2	4.5×10^{-2}	5.4	7.10×10^{-2}
611-B	CW	Sodium	1200	26,000	1220	0.1	0.3	4.6	5.0	7.0×10^{-4}	14.8	1.21×10^{-2}
620-B	CW	Sodium	1200	27,000	657	0.0	0.7	4.2	4.9	2.3×10^{-3}	9.4	1.43×10^{-2}
610-B	CW	Sodium	1200	28,000	640	0.0	0.5	4.5	5.0	1.6×10^{-3}	14.7	2.30×10^{-2}
612-B	CW	Sodium	1200	28,000	558	0.2	0.4	4.0	4.6	2.0×10^{-3}	11.3	2.02×10^{-2}
613-B	CW	Sodium	1200	29,000	380	0.0	1.1	3.5	4.6	4.0×10^{-3}	9.6	2.53×10^{-2}
609-B	CW	Sodium	1200	30,000	269	0.1	0.7	4.8	5.6	6.2×10^{-3}	10.5	3.90×10^{-2}
608-B	CW	Sodium	1200	32,000	161.3	0.0	0.6	4.4	5.0	7.7×10^{-3}	6.5	4.04×10^{-2}
631-B	A	Sodium	1000	48,000	376.6	7.0	1.5	0.0	8.5	4.1×10^{-3}	2.7	7.16×10^{-3}
628-B	CW	Sodium	1000	48,000	1367.4	0.0	0.6	0.8	1.4	4.35×10^{-4}	0.4	2.93×10^{-4}
630-B	CW	Sodium	1000	50,000	685	0.1	0.4	1.0	1.5	6.0×10^{-4}	1.2	1.75×10^{-3}
629-B	CW	Sodium	1000	52,000	661	0.0	0.4	0.5	0.9	5.9×10^{-4}	1.2	1.81×10^{-3}

*A = Annealed
CW = Cold Worked