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# CREEP-RUPTURE TESTS OF INTERNALLY PRESSURIZED HASTELLOY-X TUBES

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16. Abstract

Fifty-two seamless Hastelloy-X tubes with 0.935-cm (0.375-in.) outside diameter and 0.064-cm (0.025-in.) wall thickness were tested to failure at temperatures from 1033 to 1172 K ($1400^o$ to $1650^o$ F) and internal helium pressures from $5.5\times10^6$ to $12.4\times10^6$ $N/m^2$ (800 to 1800 psi). Lifetimes ranged from 58 to 3600 hr. The creep-rupture strength of the tubes was from 20 to 40 percent lower than that of sheet specimens. Larson-Miller correlations and photomicrographs of some specimens are presented.

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# CREEP-RUPTURE TESTS OF INTERNALLY PRESSURIZED HASTELLOY-X TUBES

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## SUMMARY

In order to obtain creep-rupture data for designing a helium-to-air heat exchanger, 52 seamless Hastelloy-X tubes were tested to failure at constant temperature and pressure. The tubes were pressurized internally with helium but were tested in an air atmosphere.

Tubes with 0.935-centimeter (0.375-in.) outside diameter and 0.064-centimeter (0.025-in.) wall thickness were purchased. Hastelloy-X is a nickel-base superalloy and was selected for its high strength at high temperatures, its fabricability, and its resistance to oxidation and corrosion.

The test temperatures and pressures were chosen to simulate the proposed service conditions. The test temperatures ranged from 1033 to 1172 K ($1400^{\circ}$ to $1650^{\circ}$ F), with helium pressures from $5.5 \times 10^{6}$ to $12.4 \times 10^{6}$ newtons per square meter (800 to 1800 psi) corresponding to equivalent stresses from $32.31 \times 10^{6}$ to $74.81 \times 10^{6}$ newtons per square meter (4.70 to 10.81 ksi). The lifetimes for the tubes ranged from 58 to 3600 hours.

The test pressures were converted to equivalent stresses, which were correlated with the lifetimes and test temperatures by the Larson-Miller parameter. Comparison of the creep-rupture data for the tube specimens with the data for sheet specimens showed that the rupture strength of the tubes was from 20 to 40 percent lower than that of the sheet specimens.

To demonstrate the application of the test results, the lifetime of a tube with a 0.635-centimeter (0.250-in.) outside diameter and a 0.076-centimeter (0.030-in.) wall thickness was calculated. This tube had an internal pressure of $10.3 \times 10^{6}$ newtons per square meter (1500 psi) and a temperature of 1089 K ($1500^{\circ}$ F). For these conditions, the predicted lifetime is 2820 hours, and with a safety factor of 1.5 on the stress, the predicted lifetime is 610 hours.

## INTRODUCTION

In order to provide data for a helium-to-air heat exchanger design for a mobile nuclear reactor, tests were conducted on candidate heat-exchanger materials. Internally pressurized tubes were tested in furnaces at conditions selected to simulate the proposed heat-exchanger environment. The helium-to-air heat exchanger will be designed to operate for 10 000 hours at temperatures up to 1144 K ($1600^{\circ}$ F) and pressures up to $12.41 \times 10^6$ newtons per square meter (1800 psi).

One of the materials selected as a candidate was Hastelloy-X. This is a nickel-base superalloy, and is available commercially in seamless tube form. This alloy was chosen because it is one of the strongest of the wrought, nickel-base superalloys at the engine operating conditions. This rank is based on a comparison of uniaxial tensile-test data for the nickel-base superalloys. Besides having high strength, the alloy is oxidation resistant and can be welded and fabricated. Hastelloy-X is the fourth alloy in a series of superalloy tubes to be tested for heat exchanger design data (refs. 1 to 3).

The test results were correlated by the method used in references 1 and 2. This method assumes that the von Mises criterion holds for creep strain, that the secondary creep rate is a power function of stress, and that for long lifetimes, primary and tertiary creep may be neglected. The test results are presented in tabular form and by means of stress-parameter plots.

All measurements were made in U.S. customary units.

## SYMBOLS

| | |
|---|---|
| B | material constant |
| C | Larson-Miller parameter constant |
| n | stress exponent |
| P | Larson-Miller parameter, $1.8T(\log t + C)\times 10^3$ for T in K; $(T + 460)(\log t + C)\times 10^3$ for T in $^{\circ}$F |
| p | pressure, N/m$^2$ (psi) |
| T | temperature, K ($^{\circ}$F) |
| t | time, hr |
| $\dot{\epsilon}$ | strain rate, hr$^{-1}$ |
| $\dot{\epsilon}_{\theta a}$ | diametral strain rate at bore of tube, hr$^{-1}$ |

| | |
|---|---|
| $\dot{\epsilon}_{\theta b}$ | diametral strain rate at outside diameter of tube, $hr^{-1}$ |
| $\dot{\bar{\epsilon}}_a$ | equivalent strain rate at bore of tube, $hr^{-1}$ |
| $\rho$ | ratio of outside diameter to inside diameter of tube |
| $\bar{\sigma}$ | equivalent stress, $N/m^2$ (ksi) |

# PROCEDURES

## Material

Fifty-two seamless tubes of Hastelloy-X (refs. 4 and 5) were tested. This alloy is a nickel-base superalloy. Because it is oxidation resistant and has high strength at high temperatures, this alloy is used for furnace and jet engine parts exposed to high temperatures. Hastelloy-X keeps its good oxidation resistance up to about 1370 K ($2000^{\circ}$ F). The alloy is ductile and can be cold worked and forged. It can be welded by several methods. The Hastelloy-X tubes used in the test were solution-treated at 1450 K ($2150^{\circ}$ F) and then rapidly cooled in air.

Table I lists the chemical analyses of several samples as well as the Aeronautical Material Specification for Hastelloy-X. An independent laboratory performed the analysis of the as-received tube specimens used in this investigation. The identification code for the sheet tensile test specimens indicates the test data source and the thickness of the test specimens in thousandths of an inch (ref. 6).

## Test Specimens

The Hastelloy-X tube specimens were from 35.6 to 40.6 centimeters (14 to 16 in.) long and had a nominal outside diameter of 0.935 centimeter (0.375 in.) and a wall thickness of 0.064 centimeter (0.025 in.). Table II shows the measured outside diameter and wall thickness of each tube. The tube length was chosen so that the welded ends of the tube specimens remained outside the 30.5-centimeter- (12-in.-) long test section of the furnaces. The ratio of tube diameter to wall thickness was about 15, which classifies these specimens as thick tubes.

Each tube-specimen test assembly (fig. 1) was fabricated with gas tungsten-arc welds. The materials were first ultrasonically cleaned and degreased. The end plug and inlet fitting, made from Inconel, and the hanger wire and the inlet tube with sleeve and sleeve nut, made from 304 stainless steel, were welded in place. Finally, the completed tube test specimens were tested with a mass spectrometer to ensure that the welds were helium tight.

## Tests

Figure 2 is a schematic of the tube test rig. Four tubes were tested at a time in one of the electric resistance furnaces in an air atmosphere. The tubes were tested at constant temperatures and static internal helium pressures until failure. Three Chromel-Alumel thermocouples located at the middle and ends of the 5-centimeter- (2-in.-) long constant-temperature zone ($\pm$1.7 K, $\pm 3^{\circ}$ F) measured the test temperatures, which were recorded on a 24-channel strip-chart recorder. The thermocouples were suspended from the top of the furnace and were not attached to the specimens. The test pressures were monitored by a pressure transducer in the pressure circuit of each specimen and were recorded continuously on a second 24-channel strip-chart recorder.

Before the test, the tubes were pressurized with helium to about $8.3\times10^{6}$ newtons per square meter (1200 psi), and then the pressure was reduced to atmospheric. Several cycles of this procedure purged the tubes of air. The furnaces were then brought up to the test temperatures. When the temperatures had stabilized, each tube was pressurized with helium to its test pressure and then was sealed off by means of a valve. The pressures were monitored daily to check for minor leaks and tube failures. If small leaks in the system other than in the test specimen caused loss of pressure, helium was added as required to maintain the test pressure. A pressure drop to one-third of the test pressure in less than 48 hours constituted failure.

The helium test pressures ranged from $5.5\times10^{6}$ to $12.4\times10^{6}$ newtons per square meter (800 to 1800 psi), the temperatures ranged from 1033 to 1172 K ($1400^{\circ}$ to $1650^{\circ}$ F), and the test times varied from 58 to 3600 hours. The effective stresses at the tube bore were from $32.31\times10^{6}$ to $74.81\times10^{6}$ newtons per square meter (4.70 to 10.81 ksi). The tests were run in furnace air so that the effects of oxidation on life could be observed.

## Metallography

Sections of the tubes were taken both before and after testing, in both the longitudinal and transverse directions. For the post-test specimens, the sections were taken near the point of failure. The surfaces of the sections were polished and etched electrolytically with 10 percent chromic acid.

## Accuracy

The uncertainty in the specimen temperature was about $\pm 2.8$ K ($\pm 5^{\circ}$ F). The furnace controller sensitivity of $\pm 2$ microvolts and thermocouple variations contributed to the temperature uncertainty. The accuracy of the specimen pressures was estimated at $\pm 0.07 \times 10^{6}$ newtons per square meter ($\pm 10$ psi). This accuracy was affected by small leaks in the system, by daily variations in the room temperature, and by expansion of the tubes due to creep. The variation of the tube wall thickness was $\pm 1.2$ percent.

## Analysis

The analysis of the tube test data is described in detail in reference 1, and it is based on the following assumptions:

(1) The tube material is isotropic.

(2) The von Mises criterion for yielding is applicable to creep in the pressure tube wall.

(3) The principal strain rates are proportional to the reduced, or deviatoric, principal stresses (ref. 7).

(4) The axial strain rate is zero.

(5) The principal axes of stress and creep strain coincide.

(6) Norton and Bailey's exponential stress law, presented in reference 8, applies :

$$\dot{\epsilon} = B\bar{\sigma}^{n} \tag{1}$$

(7) The strain rate remains uniform over the life of the specimen; that is, primary and tertiary creep are negligible compared to secondary creep. Therefore, the diametral strain rate $\dot{\epsilon}_{\theta b}$ is equal to the strain measured at the outside diameter at rupture divided by the lifetime of the specimen.

On the basis of these assumptions, the following equations are used in the analysis. The equivalent stress at the bore of the tube is

$$\sigma = \frac{\frac{\sqrt{3}}{n}\rho^{2/n}}{\rho^{2/n} - 1} p \tag{2}$$

The diametral strain rate at the tube bore is related to the strain rate at the outside diameter by

$$\dot{\epsilon}_{\theta a} = \rho^2 \dot{\epsilon}_{\theta b} \tag{3}$$

The equivalent strain rate at the tube bore is

$$\dot{\bar{\epsilon}}_a = \frac{2}{\sqrt{3}} \rho^2 \dot{\epsilon}_{\theta b} \tag{4}$$

### Strain Measurement

The difference of the diameters of the failed and as-received tubes divided by the diameter of the as-received tube measured the circumferential strain at fracture. The outside diameters were measured, both before and after the test, with a micrometer at four points spaced $45^{\circ}$ apart on each tube circumference. The measurements before the test were made at the middle of the tube. Following the tests, the tubes were measured at the point of fracture. Each set of four measurements was averaged to obtain the as-received and the strained diameters.

The diameters were also measured at a point 2.5 centimeters (1 in.) from the inlet end of the tube. Since this point was outside the furnace, no change in diameter was expected. Comparisons of measurements before and after the test show that there was no change. This check was necessary because the tube wall thickness could not be measured before the test. Therefore, the tube was cut apart following the test, and the wall thickness was measured with a caliper type micrometer 2.5 centimeters (1 in.) from the inlet and at four places spaced $45^{\circ}$ apart. The four measurements were averaged to obtain the wall thickness.

## RESULTS AND DISCUSSION

Fifty-two creep-rupture test specimens were fabricated from commercially purchased, seamless Hastelloy-X tubing. The specimens were pressurized internally with helium and tested in an electric resistance furnace at constant temperature in air at atmospheric pressure. The internal helium pressures ranged from $5.5\times10^{6}$ to $12.4\times10^{6}$ newtons per square meter (800 to 1800 psi), while the test temperatures ranged from 1033 to 1172 K ($1400^{\circ}$ to $1650^{\circ}$ F). The effective stresses at the tube bore varied from $32.31\times10^{6}$ to $74.81\times10^{6}$ newtons per square meter (4.70 to

10.81 ksi), and the lifetimes ranged from 58 to 3600 hours. The test results are listed in tables II and III.

## Correlation

The equivalent stresses and the Larson-Miller parameter values are shown in table III and figures 3 and 4 for the tubes, and in table IV and figures 4 and 5 for the unwelded sheet creep-rupture data. The equivalent stresses were calculated by using equation (2), which gives the equivalent stress at the tube bore by the distortion energy theory.

The values of the stress exponent $n$ used in equation (2) are a function of temperature and are listed in table II. The values used in this report ranged from 9.10 at 1033 K ($1400^{\circ}$ F) to 3.70 at 1172 K ($1650^{\circ}$ F). The method used to calculated $n$ was described in reference 3.

The Hastelloy-X sheet data from reference 6 covered sheet thicknesses from 0.015 to 0.637 centimeter (0.006 to 0.250 in.). The sheets with thicknesses of 0.015 to 0.025 centimeter (0.006 to 0.010 in.) are referred to as thin sheets in this report. The remainder of the sheets, with thicknesses of 0.277 to 0.637 centimeter (0.109 to 0.250 in.), are referred to as thick sheets.

The test results for the tubes and the sheet materials were used as input for the computer program of Mendelson, Roberts, and Manson (ref. 9). This program correlated the stress, lifetime, and temperature data by means of the Larson-Miller parameter. The program selected a parameter constant of 16.652 for the tubes and 18.186 for the combined thick and thin sheet specimens. The results are plotted in figures 3 and 5, which show the fitted parameter curves with $\pm 1$ standard deviation.

Since the parameter constants for the tubes and sheet were different, a direct comparison would not be meaningful. In order to make a comparison, the test results and the uniaxial sheet test data were correlated by means of the Larson-Miller parameter with a constant of 20.0. This is a commonly used value and therefore permits comparison with other published data that also use this constant. The results of the computer calculations are listed in tables III and IV and are shown in figure 4. This figure shows that the rupture strength of the tubes for a given value of $P$ is about 20 to 40 percent lower than that of the sheet creep-rupture specimens (ref. 6). The difference increases with higher values of the Larson-Miller parameter.

A sample calculation to predict the lifetime of a tube under given temperature and pressure conditions based on the test results is shown in the appendix. In this sample calculation, the lifetime of a Hastelloy-X tube with a 0.635-centimeter (0.250-in.) outside diameter and a 0.076-centimeter (0.030-in.) wall thickness is calculated. The internal pressure is $10.3 \times 10^6$ newtons per square meter (1500 psi), and the temperature is 1089 K ($1500^\circ$ F). For these conditions, the lifetime is predicted to be 2820 hours, and with a safety factor of 1.5 on the stress, the service life is predicted to be 610 hours.

### Creep-Strain Rate

The creep-strain rate was obtained by measuring the diametral strain at rupture, calculating the equivalent bore strain, and dividing the bore strain by the lifetime of the tube. The equivalent bore strain rates obtained by this method are listed in table III. It should be noted that this method assumes that the creep-strain rates are uniform over the lifetime of the specimens and that the primary and tertiary creep are negligible compared to secondary creep, so that the resultant creep-strain rates are average values. Table IV lists the creep-strain rates for the sheet test specimens calculated from the test results reported in reference 6.

### Fracture

The fractures occurred on radial planes parallel to the tube axis. The failure areas were not large enough to be identified by the unaided eye. A bubble leak test was performed, therefore, in order to identify the leak location. The failures are similar to those reported in reference 1 for seamless Haynes Alloy No. 25 tubes. The pressure drop following failure was less rapid than the drop observed for the Haynes Alloy No. 25 tubes. The time to drop to one-third of the test pressure following the fracture ranged from 2 to more than 48 hours.

### Metallography

Figures 6 to 8 are photomicrographs of typical tube specimens both before and after the test showing both longitudinal and transverse sections. The original photomicrographs were magnified 100 times. The outside surface is at the top in all photographs.

Figure 6 shows a tube in the as-received condition. Figure 6(a) shows a transverse section, while figure 6(b) shows a longitudinal section. These photographs show carbides as stringers in the direction of work during the tube forming process.

Figure 7 shows tube specimen 2 after 3600 hours at 1033 K ($1400^{\circ}$ F) and an internal pressure of $9.65 \times 10^{6}$ newtons per square meter (1400 psi). Oxidation appears as a thin layer on both the inside and outside surfaces of the tube, while changes in grain size are not apparent. Carbide precipitate particles are evident within the grains, and voids due to depletion appear as dark round spots.

Figure 8 shows tube specimen 45 after 396 hours at 1139 K ($1590^{\circ}$ F) and $5.52 \times 10^{6}$ newtons per square meter (800 psi). Both photographs show a large number of cracks perpendicular to the tube wall, and some of the cracks have oxidation on their surfaces. The fractures appear to have started at the outside surface and propagated radially inward along the grain boundaries. Oxidation is faintly visible at the outside surface only. Again, the grain size did not change. Carbide precipitate particles appeared within the grains, and voids due to depletion appear at the grain boundaries.

## SUMMARY OF RESULTS

Fifty-two seamless Hastelloy-X tubes, pressurized internally with helium, were tested in an electric resistance furnace until failure. The tests in an air atmosphere ranged from 58 to 3600 hours. The test temperatures ranged from 1033 to 1172 K ($1400^{\circ}$ to $1650^{\circ}$ F), and the pressures ranged from $5.5 \times 10^{6}$ to $12.4 \times 10^{6}$ newtons per square meter (800 to 1800 psi). The pressures resulted in equivalent stresses at the tube bore of $32.37 \times 10^{6}$ to $74.81 \times 10^{6}$ newtons per square meter (4.70 to 10.81 ksi). The pressures were converted to equivalent stresses and correlated with the test temperatures and lifetimes by the Larson-Miller parameter. The parameter constants for the tubes and the sheet creep-rupture test specimens were selected by a computer program. A graph is shown for the sheet and tube correlations. Both sets of data were also correlated by the Larson-Miller parameter with a constant of 20.0, which permits both sets to be presented on one graph for comparison.

Analysis of the test data and the photomicrographs produced the following results and conclusions:

1. Tests of the seamless Hastelloy-X tubes showed that the creep-rupture strength was about 20 to 40 percent lower than that of the sheet specimens.

2. Reliable predictions of the creep-rupture lifetimes for seamless Hastelloy-X tubes under given temperature and stress conditions can not be made on the basis of sheet creep-rupture data.

3. Failures of the seamless Hastelloy-X tubes started at the outside surface and propagated radially inward.

4. Fractures were too small to be visible to the naked eye. Leaks due to the fractures required from 2 to more than 48 hours to lower the pressure in the test specimens to one-third of the test pressure.

5. The test results indicate that a 0.635-centimeter- (0.250-in.-) diameter tube with a 0.076-centimeter (0.030-in.) wall at a temperature of 1089 K ($1500^{\circ}$ F) and an internal helium pressure of $10.3 \times 10^{6}$ newtons per square meter (1500 psi) would have a predicted lifetime of 2820 hours. With a safety factor of 1.5, the predicted service life would be 610 hours.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, November 17, 1972,

501-24.

## APPENDIX - APPLICATION OF DATA

One example of the application of the creep-rupture data is the calculation of the service lifetime for tubes in a heat exchanger at a constant temperature and a constant internal pressure. The following are the pertinent specifications and conditions for the seamless Hastelloy-X tube used in the sample calculations:

Material . . . . . . . . . . . . . . . . . . . . . . . . Hastelloy-X, seamless tubing

Tube size

  Outside diameter, cm (in.) . . . . . . . . . . . . . . . . . . . . . . . . 0.635 (0.250)

  Wall thickness, cm (in.) . . . . . . . . . . . . . . . . . . . . . . . . 0.076 (0.030)

  Ratio of outside diameter to inside diameter . . . . . . . . . . . . . . . . . 1.3158

Pressure, $N/m^2$ (psi) . . . . . . . . . . . . . . . . . . . . . . . . $10.3 \times 10^6$ (1500)

Temperature, K ($^oF$) . . . . . . . . . . . . . . . . . . . . . . . . 1089 (1500)

Stress exponent, n . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4.8

Safety factor, N . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1.5

The equivalent stress is calculated by equation (2):

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{4.8}(1.3158)^{2/4.8}}{(1.3158)^{2/4.8} - 1.0} p = 3.34 \; p = 34.40 \times 10^6 \; N/m^2 \; (5009 \text{ psi})$$

The ultimate equivalent strength $\bar{\sigma}_u$ is calculated by

$$\bar{\sigma}_u = N\bar{\sigma} = 1.5\,\bar{\sigma} = 51.60 \times 10^6 \; N/m^2 \; (7514 \text{ psi})$$

The parameter value of 38.1 for the equivalent stress of $51.60 \times 10^6$ newtons per square meter (7514 psi) is obtained from figure 3, and the parameter equation is solved for the lifetime t:

$$t = \text{antilog}\left(\frac{1000\ P}{1.8\ T} - 16.652\right) = 610 \text{ hr}$$

where the temperature T is in kelvins. Thus, for the given conditions, the service lifetime is 610 hours. The calculated lifetime for a tube without the safety factor is 2810 hours.

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TABLE I. - CHEMICAL COMPOSITION OF SPECIMENS

OF HASTELLOY-X

[Composition in wt. %.]

| Component | Aeronautical Material Specification 5536 | Tube test specimens as received (a) | Sheet tensile test specimens (b) | |
|---|---|---|---|---|
| | | | UCC109 | DMS006 and DMS010 |
| Chromium | 20.5 to 23.0 | 21.68 | 21.59 | 21.81 |
| Cobalt | 0.5 to 2.5 | 2.00 | 1.06 | 1.58 |
| Molybdenum | 8.0 to 10.0 | 8.81 | 9.74 | 8.92 |
| Iron | 17.0 to 20.0 | 18.09 | 17.80 | 18.05 |
| Tungsten | 0.2 to 1.0 | .40 | .34 | .57 |
| Silicon | 0 to 1.0 | .73 | (c) | (c) |
| Carbon | 0.05 to 0.15 | .07 | .13 | .10 |
| Manganese | 0 to 1.0 | .49 | (c) | (c) |
| Nickel | Balance | Balance | Balance | Balance |

[a]Analysis by an independent laboratory.

[b]Value for sheet tensile specimens from ref. 6; values for TMC2500 not reported.

[c]Not reported.

TABLE II. - EXPERIMENTAL DATA FOR HASTELLOY-X TUBES

| Specimen | Temperature, T | | Pressure, p | | Lifetime, hr | Outside diameter | | | | Wall thickness | | Stress exponent, n |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Before test | | After test | | | | |
| | K | °F | N/m$^2$ | psi | | cm | in. | cm | in. | cm | in. | |
| 1 | 1033.1 | 1400.0 | 9.65x10$^6$ | 1.40x10$^3$ | 3544.0 | 0.9578 | 0.3771 | 0.9624 | 0.3789 | 0.0638 | 0.0251 | 9.10 |
| 2 | 1033.1 | 1400.0 | 9.65 | 1.40 | 3600.0 | .9576 | .3770 | .9916 | .3904 | .0655 | .0258 | 9.10 |
| 3 | 1033.1 | 1400.0 | 9.65 | 1.40 | 3335.0 | .9578 | .3771 | .9855 | .3880 | .0645 | .0254 | 9.10 |
| 4 | 1033.1 | 1400.0 | 10.34 | 1.50 | 2579.0 | .9578 | .3771 | .9794 | .3856 | .0635 | .0250 | 9.10 |
| 5 | 1033.1 | 1400.0 | 10.34 | 1.50 | 2623.0 | .9578 | .3771 | .9870 | .3886 | .0635 | .0250 | 9.10 |
| 6 | 1033.1 | 1400.0 | 10.34 | 1.50 | 2435.0 | .9576 | .3770 | .9754 | .3840 | .0660 | .0260 | 9.10 |
| 7 | 1033.1 | 1400.0 | 11.03 | 1.60 | 2279.0 | .9578 | .3771 | .9876 | .3888 | .0676 | .0266 | 9.10 |
| 8 | 1033.1 | 1400.0 | 11.03 | 1.60 | 3115.0 | .9576 | .3770 | .9782 | .3851 | .0632 | .0249 | 9.10 |
| 9 | 1033.1 | 1400.0 | 11.03 | 1.60 | 3166.0 | .9581 | .3772 | .9883 | .3891 | .0640 | .0252 | 9.10 |
| 10 | 1033.1 | 1400.0 | 11.72 | 1.70 | 2696.0 | .9576 | .3770 | 1.0173 | .4005 | .0653 | .0257 | 9.10 |
| 11 | 1033.1 | 1400.0 | 11.72 | 1.70 | 2470.0 | .9578 | .3771 | .9901 | .3898 | .0643 | .0253 | 9.10 |
| 12 | 1033.1 | 1400.0 | 11.72 | 1.70 | 2755.0 | .9578 | .3771 | .9825 | .3868 | .0653 | .0257 | 9.10 |
| 13 | 1033.1 | 1400.0 | 12.41 | 1.80 | 1884.0 | .9578 | .3771 | .9896 | .3896 | .0643 | .0253 | 9.10 |
| 14 | 1033.1 | 1400.0 | 12.41 | 1.80 | 2475.0 | .9576 | .3770 | .9947 | .3916 | .0671 | .0264 | 9.10 |
| 15 | 1033.1 | 1400.0 | 12.41 | 1.80 | 1879.3 | .9591 | .3776 | 1.0069 | .3964 | .0660 | .0260 | 9.10 |
| 16 | 1033.1 | 1400.0 | 12.41 | 1.80 | 1868.2 | .9578 | .3771 | 1.0206 | .4018 | .0665 | .0262 | 9.10 |
| 17 | 1038.7 | 1410.0 | 12.41 | 1.80 | 952.2 | .9586 | .3774 | .9876 | .3888 | .0726 | .0286 | 7.50 |
| 18 | 1038.7 | 1410.0 | 12.41 | 1.80 | 898.0 | .9581 | .3772 | 1.0018 | .3944 | .0653 | .0257 | 7.50 |
| 19 | 1060.9 | 1450.0 | 7.58 | 1.10 | 3007.0 | .9581 | .3772 | .9842 | .3875 | .0640 | .0252 | 5.90 |
| 20 | 1060.9 | 1450.0 | 7.58 | 1.10 | 2869.0 | .9578 | .3771 | .9888 | .3893 | .0658 | .0259 | 5.90 |
| 21 | 1060.9 | 1450.0 | 7.58 | 1.10 | 2615.0 | .9578 | .3771 | .9881 | .3890 | .0632 | .0249 | 5.90 |
| 22 | 1060.9 | 1450.0 | 8.27 | 1.20 | 1900.0 | .9576 | .3770 | .9840 | .3874 | .0663 | .0261 | 5.90 |
| 23 | 1060.9 | 1450.0 | 8.27 | 1.20 | 1880.0 | .9578 | .3771 | .9804 | .3860 | .0635 | .0250 | 5.90 |
| 24 | 1060.9 | 1450.0 | 8.27 | 1.20 | 2387.0 | .9581 | .3772 | 1.0079 | .3968 | .0653 | .0257 | 5.90 |
| 25 | 1060.9 | 1450.0 | 8.96 | 1.30 | 1590.0 | .9581 | .3772 | 1.0000 | .3937 | .0635 | .0250 | 5.90 |
| 26 | 1060.9 | 1450.0 | 8.96 | 1.30 | 2144.5 | .9581 | .3772 | .9873 | .3887 | .0648 | .0255 | 5.90 |
| 27 | 1060.9 | 1450.0 | 8.96 | 1.30 | 2011.0 | .9578 | .3771 | .9825 | .3868 | .0648 | .0255 | 5.90 |
| 28 | 1060.9 | 1450.0 | 9.65 | 1.40 | 1560.0 | .9581 | .3772 | .9822 | .3867 | .0640 | .0252 | 5.90 |
| 29 | 1060.9 | 1450.0 | 9.65 | 1.40 | 1759.0 | .9578 | .3771 | .9972 | .3926 | .0638 | .0251 | 5.90 |
| 30 | 1060.9 | 1450.0 | 10.34 | 1.50 | 1476.0 | .9581 | .3772 | .9962 | .3922 | .0650 | .0256 | 5.90 |
| 31 | 1060.9 | 1450.0 | 10.34 | 1.50 | 1392.0 | .9581 | .3772 | .9992 | .3934 | .0648 | .0255 | 5.90 |
| 32 | 1088.7 | 1500.0 | 6.21 | .90 | 2771.0 | .9576 | .3770 | .9957 | .3920 | .0665 | .0262 | 4.80 |
| 33 | 1088.7 | 1500.0 | 6.21 | .90 | 3210.0 | .9581 | .3772 | 1.0069 | .3964 | .0638 | .0251 | 4.80 |
| 34 | 1088.7 | 1500.0 | 6.89 | 1.00 | 1748.0 | .9578 | .3771 | .9980 | .3929 | .0645 | .0254 | 4.80 |
| 35 | 1088.7 | 1500.0 | 6.89 | 1.00 | 1871.0 | .9581 | .3772 | .9972 | .3926 | .0638 | .0251 | 4.80 |
| 36 | 1088.7 | 1500.0 | 6.89 | 1.00 | 1410.0 | .9576 | .3770 | .9898 | .3897 | .0648 | .0255 | 4.80 |
| 37 | 1088.7 | 1500.0 | 7.58 | 1.10 | 1079.0 | .9581 | .3772 | 1.0038 | .3952 | .0645 | .0254 | 4.80 |
| 38 | 1088.7 | 1500.0 | 7.58 | 1.10 | 1082.0 | .9576 | .3770 | 1.0071 | .3965 | .0632 | .0249 | 4.80 |
| 39 | 1116.5 | 1550.0 | 5.52 | .80 | 1030.0 | .9576 | .3770 | 1.0043 | .3954 | .0658 | .0259 | 4.40 |
| 40 | 1116.5 | 1550.0 | 5.52 | .80 | 847.0 | .9576 | .3770 | .9715 | .3825 | .0645 | .0254 | 4.40 |
| 41 | 1116.5 | 1550.0 | 6.21 | .90 | 910.0 | .9581 | .3772 | 1.0028 | .3948 | .0635 | .0250 | 4.40 |
| 42 | 1116.5 | 1550.0 | 6.21 | .90 | 830.0 | .9578 | .3771 | 1.0003 | .3938 | .0653 | .0257 | 4.40 |
| 43 | 1116.5 | 1550.0 | 6.21 | .90 | 845.0 | .9578 | .3771 | 1.0096 | .3975 | .0706 | .0278 | 4.40 |
| 44 | 1116.5 | 1550.0 | 6.21 | .90 | 833.0 | .9581 | .3772 | 1.0010 | .3941 | .0640 | .0252 | 4.40 |
| 45 | 1138.7 | 1590.0 | 5.52 | .80 | 396.8 | .9583 | .3773 | .9990 | .3933 | .0673 | .0265 | 4.10 |
| 46 | 1138.7 | 1590.0 | 5.52 | .80 | 380.2 | .9586 | .3774 | .9820 | .3866 | .0665 | .0262 | 4.10 |
| 47 | 1149.8 | 1610.0 | 6.89 | 1.00 | 115.0 | .9578 | .3771 | .9886 | .3892 | .0643 | .0253 | 3.90 |
| 48 | 1149.8 | 1610.0 | 6.89 | 1.00 | 123.0 | .9583 | .3773 | 1.0081 | .3969 | .0638 | .0251 | 3.90 |
| 49 | 1149.8 | 1610.0 | 8.27 | 1.20 | 61.0 | .9581 | .3772 | .9802 | .3859 | .0658 | .0259 | 3.90 |
| 50 | 1149.8 | 1610.0 | 8.27 | 1.20 | 58.0 | .9586 | .3774 | .9853 | .3879 | .0660 | .0260 | 3.90 |
| 51 | 1172.0 | 1650.0 | 5.52 | .80 | 105.0 | .9614 | .3785 | 1.0013 | .3942 | .0678 | .0267 | 3.70 |
| 52 | 1172.0 | 1650.0 | 5.52 | .80 | 88.0 | .9591 | .3776 | .9876 | .3888 | .0653 | .0257 | 3.70 |

TABLE III. - CALCULATED RESULTS FOR HASTELLOY-X TUBES

| Specimen | Equivalent stress, $\sigma$ | | Larson-Miller parameter, P (a) | Strain | Ultimate equivalent bore strain | Equivalent bore strain rate, $\epsilon_a$, $hr^{-1}$ |
|---|---|---|---|---|---|---|
| | $N/m^2$ | psi | | | | |
| 1 | $59.44 \times 10^6$ | $8.62 \times 10^3$ | 43.80 | $0.4773 \times 10^{-2}$ | $0.7334 \times 10^{-2}$ | $0.2070 \times 10^{-5}$ |
| 2 | 57.72 | 8.37 | 43.81 | $.3554 \times 10^{-1}$ | $.5509 \times 10^{-1}$ | $.1530 \times 10^{-4}$ |
| 3 | 58.70 | 8.51 | 43.75 | .2890 | .4458 | .1337 |
| 4 | 63.96 | 9.28 | 43.55 | .2254 | .3459 | .1341 |
| 5 | 63.96 | 9.28 | 43.56 | .3050 | .4680 | .1784 |
| 6 | 61.34 | 8.90 | 43.50 | .1857 | .2885 | .1185 |
| 7 | 63.88 | 9.26 | 43.45 | .3103 | .4856 | .2131 |
| 8 | 68.49 | 9.93 | 43.70 | .2149 | .3294 | .1057 |
| 9 | 67.67 | 9.81 | 43.71 | .3155 | .4853 | .1533 |
| 10 | 70.37 | 10.21 | 43.58 | .6233 | .9650 | .3579 |
| 11 | 71.57 | 10.38 | 43.51 | .3368 | .5188 | .2100 |
| 12 | 70.39 | 10.21 | 43.60 | .2572 | .3982 | .1445 |
| 13 | 75.78 | 10.99 | 43.29 | .3315 | .5106 | .2710 |
| 14 | 72.42 | 10.50 | 43.51 | .3873 | .6047 | .2443 |
| 15 | 73.73 | 10.69 | 43.29 | .4979 | .7732 | .4114 |
| 16 | 73.03 | 10.59 | 43.28 | .6550 | $.1020 \times 10^{0}$ | .5461 |
| 17 | 66.84 | 9.69 | 42.97 | .3021 | $.4845 \times 10^{-1}$ | .5089 |
| 18 | 74.81 | 10.85 | 42.92 | .4560 | .7058 | .7859 |
| 19 | 46.92 | 6.80 | 44.84 | .2731 | .4201 | .1397 |
| 20 | 45.57 | 6.61 | 44.80 | .3235 | .5020 | .1750 |
| 21 | 47.50 | 6.89 | 44.73 | .3156 | .4837 | .1850 |
| 22 | 49.30 | 7.15 | 44.46 | .2759 | .4292 | .2259 |
| 23 | 51.60 | 7.48 | 44.45 | .2360 | .3622 | .1927 |
| 24 | 50.14 | 7.27 | 44.65 | .5196 | .8043 | .3369 |
| 25 | 55.91 | 8.11 | 44.31 | .4374 | .6713 | .4222 |
| 26 | 54.76 | 7.94 | 44.56 | .3049 | .4707 | .2195 |
| 27 | 54.75 | 7.94 | 44.51 | .2572 | .3972 | .1975 |
| 28 | 59.71 | 8.66 | 44.30 | .2519 | .3874 | .2484 |
| 29 | 59.94 | 8.69 | 44.40 | .4110 | .6316 | .3591 |
| 30 | 62.93 | 9.13 | 44.25 | .3977 | .6147 | .4165 |
| 31 | 63.19 | 9.16 | 44.20 | .4295 | .6631 | .4764 |
| 32 | 37.04 | 5.37 | 45.95 | .3979 | .6197 | .2236 |
| 33 | 38.76 | 5.62 | 46.07 | .5090 | .7821 | .2436 |
| 34 | 42.52 | 6.17 | 45.56 | .4190 | .6462 | .3697 |
| 35 | 43.07 | 6.25 | 45.61 | .4083 | .6273 | .3353 |
| 36 | 42.34 | 6.14 | 45.37 | .3369 | .5202 | .3689 |
| 37 | 46.79 | 6.79 | 45.14 | .4772 | .7359 | .6820 |
| 38 | 47.74 | 6.92 | 45.15 | .5172 | .7929 | .7328 |
| 39 | 33.42 | 4.85 | 46.26 | .4881 | .7574 | .7353 |
| 40 | 34.10 | 4.95 | 46.09 | .1459 | .2250 | .2657 |
| 41 | 39.03 | 5.66 | 46.15 | .4666 | .7160 | .7868 |
| 42 | 37.91 | 5.50 | 46.07 | .4429 | .6855 | .8259 |
| 43 | 34.93 | 5.07 | 46.08 | .5410 | .8594 | $.1017 \times 10^{-3}$ |
| 44 | 38.70 | 5.61 | 46.07 | .4480 | .6892 | $.8274 \times 10^{-4}$ |
| 45 | 32.74 | 4.75 | 46.33 | .4241 | .6628 | $.1670 \times 10^{-3}$ |
| 46 | 33.14 | 4.81 | 46.29 | .2438 | .3796 | $.9983 \times 10^{-4}$ |
| 47 | 42.99 | 6.24 | 45.67 | .3209 | .4942 | $.4298 \times 10^{-3}$ |
| 48 | 43.37 | 6.29 | 45.73 | .5195 | .7981 | .6489 |
| 49 | 50.37 | 7.30 | 45.10 | .2306 | .3579 | .5867 |
| 50 | 50.19 | 7.28 | 45.05 | .2782 | .4321 | .7451 |
| 51 | 32.72 | 4.75 | 46.46 | .4148 | .6492 | .6183 |
| 52 | 33.95 | 4.92 | 46.30 | .2966 | .4589 | .5215 |

[a] Larson-Miller parameter constant, 20.

TABLE IV. - CREEP-RUPTURE DATA FOR SHEET SPECIMENS OF HASTELLOY-X

[From ref. 6.]

| Specimen | Temperature, T | | Stress, σ | | Lifetime, hr | Strain | Strain rate, $\bar{\epsilon}$, $hr^{-1}$ | Larson-Miller parameter, P (a) |
|---|---|---|---|---|---|---|---|---|
| | K | °F | $N/m^2$ | psi | | | | |
| TMC250 | 1033.1 | 1400.0 | $189.61\times10^{6}$ | $27.50\times10^{3}$ | 12.7 | $0.1300\times10^{0}$ | $0.1024\times10^{-1}$ | 39.25 |
| | 1033.1 | 1400.0 | 189.61 | 27.50 | 9.1 | .1100 | .1209 | 38.98 |
| | 1033.1 | 1400.0 | 144.79 | 21.00 | 64.0 | .1000 | $.1562\times10^{-2}$ | 40.56 |
| | 1033.1 | 1400.0 | 144.79 | 21.00 | 70.0 | .1100 | .1571 | 40.63 |
| | 1033.1 | 1400.0 | 144.79 | 21.00 | 69.2 | .2600 | .3757 | 40.62 |
| | 1033.1 | 1400.0 | 144.79 | 21.00 | 69.1 | .2500 | .3618 | 40.62 |
| UCC109 | 922.0 | 1200.0 | 275.79 | 40.00 | 190.5 | $0.1400\times10^{0}$ | $0.7349\times10^{-3}$ | 36.98 |
| | 922.0 | 1200.0 | 241.32 | 35.00 | 647.7 | .1600 | .2470 | 37.87 |
| | 1005.4 | 1350.0 | 172.37 | 25.00 | 111.3 | .2600 | $.2336\times10^{-2}$ | 39.90 |
| | 1005.4 | 1350.0 | 137.90 | 20.00 | 392.9 | .1800 | $.4581\times10^{-3}$ | 40.90 |
| | 1088.7 | 1500.0 | 124.11 | 18.00 | 28.2 | .4700 | $.1667\times10^{-1}$ | 42.04 |
| | 1088.7 | 1500.0 | 103.42 | 15.00 | 209.0 | .2200 | $.1053\times10^{-2}$ | 43.75 |
| | 1088.7 | 1500.0 | 82.74 | 12.00 | 159.5 | .1200 | $.7524\times10^{-3}$ | 43.52 |
| | 1088.7 | 1500.0 | 68.95 | 10.00 | 482.2 | .1300 | .2696 | 44.46 |
| | 1172.0 | 1650.0 | 41.37 | 6.00 | 216.3 | .1500 | .6935 | 47.13 |
| | 1255.4 | 1800.0 | 20.68 | 3.00 | 103.2 | .1800 | $.1744\times10^{-2}$ | 49.75 |
| DMS006 | 1144.3 | 1600.0 | 106.87 | 15.50 | 1.3 | $0.1600\times10^{0}$ | $0.1231\times10^{0}$ | 41.43 |
| | 1144.3 | 1600.0 | 106.87 | 15.50 | .9 | .2300 | .2556 | 41.11 |
| | 1144.3 | 1600.0 | 79.98 | 11.60 | 2.5 | 0 | 0 | 42.02 |
| | 1144.3 | 1600.0 | 79.29 | 11.50 | 2.7 | $.8000\times10^{-1}$ | $.2963\times10^{-1}$ | 42.09 |
| | 1144.3 | 1600.0 | 74.46 | 10.80 | 1.4 | 0 | 0 | 41.50 |
| | 1144.3 | 1600.0 | 74.46 | 10.80 | 4.6 | 0 | 0 | 42.57 |
| | 1144.3 | 1600.0 | 68.95 | 10.00 | 10.5 | $.1000\times10^{0}$ | $.9524\times10^{-2}$ | 43.30 |
| | 1144.3 | 1600.0 | 68.95 | 10.00 | 7.6 | .1100 | $.1447\times10^{-1}$ | 43.01 |
| DMS010 | 1144.3 | 1600.0 | 106.87 | 15.50 | 3.7 | $0.1200\times10^{0}$ | $0.3243\times10^{-1}$ | 42.37 |
| | 1144.3 | 1600.0 | 106.87 | 15.50 | 3.6 | .1200 | .3333 | 42.35 |
| | 1144.3 | 1600.0 | 90.32 | 13.10 | 9.7 | .1200 | .1237 | 43.23 |
| | 1144.3 | 1600.0 | 88.94 | 12.90 | 11.6 | .1100 | $.9483\times10^{-2}$ | 43.39 |
| | 1144.3 | 1600.0 | 82.74 | 12.00 | 15.8 | $.9000\times10^{-1}$ | .5696 | 43.67 |
| | 1144.3 | 1600.0 | 82.74 | 12.00 | 15.6 | .9000 | .5769 | 43.66 |
| | 1144.3 | 1600.0 | 77.22 | 11.20 | 20.6 | .8000 | .3883 | 43.91 |
| | 1310.9 | 1900.0 | 55.16 | 8.00 | .5 | .8000 | $.1600\times10^{0}$ | 46.49 |
| | 1310.9 | 1900.0 | 41.37 | 6.00 | 1.4 | .6000 | $.4286\times10^{-1}$ | 47.54 |
| | 1310.9 | 1900.0 | 41.37 | 6.00 | 2.0 | $.1200\times10^{0}$ | .6000 | 47.91 |
| | 1310.9 | 1900.0 | 27.58 | 4.00 | 7.4 | $.9000\times10^{-1}$ | .1216 | 49.25 |
| | 1310.9 | 1900.0 | 27.58 | 4.00 | 7.0 | .9000 | .1286 | 49.19 |
| | 1310.9 | 1900.0 | 24.13 | 3.50 | 11.2 | $.1400\times10^{0}$ | .1250 | 49.68 |
| | 1310.9 | 1900.0 | 19.99 | 2.90 | 27.7 | .2400 | $.8664\times10^{-2}$ | 50.60 |

[a]Larson-Miller parameter constant, 20.

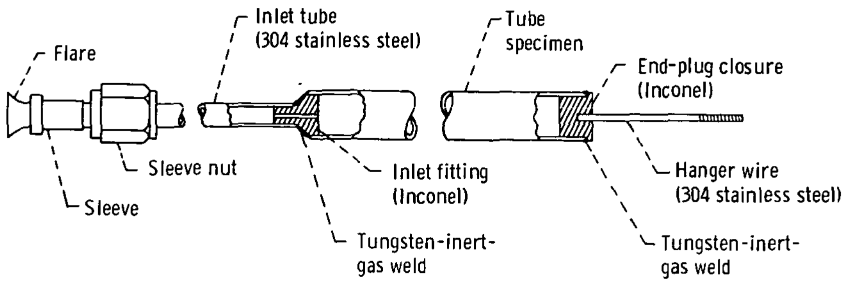



Figure 1. - Test specimen assembly.

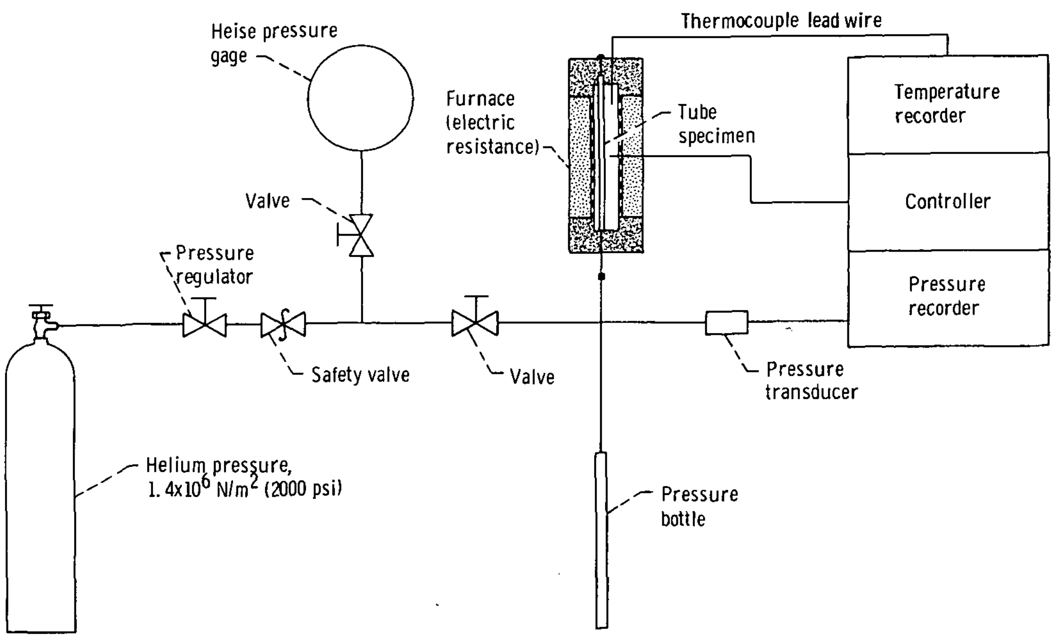



Figure 2. - Heat-exchanger-tube test rig. Maximum test temperature, 1233 K (1760° F); maximum test pressure, $12.41 \times 10^6$ newtons per square meter (1800 psi).

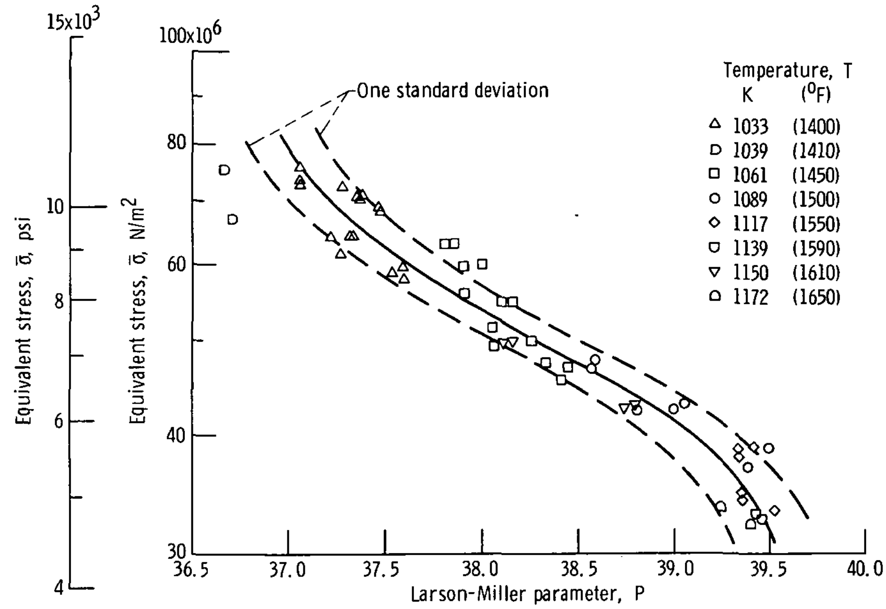



Figure 3. - Equivalent stress as function of Larson-Miller parameter for tube specimens of Hastelloy-X. Larson-Miller parameter constant, 16.652.

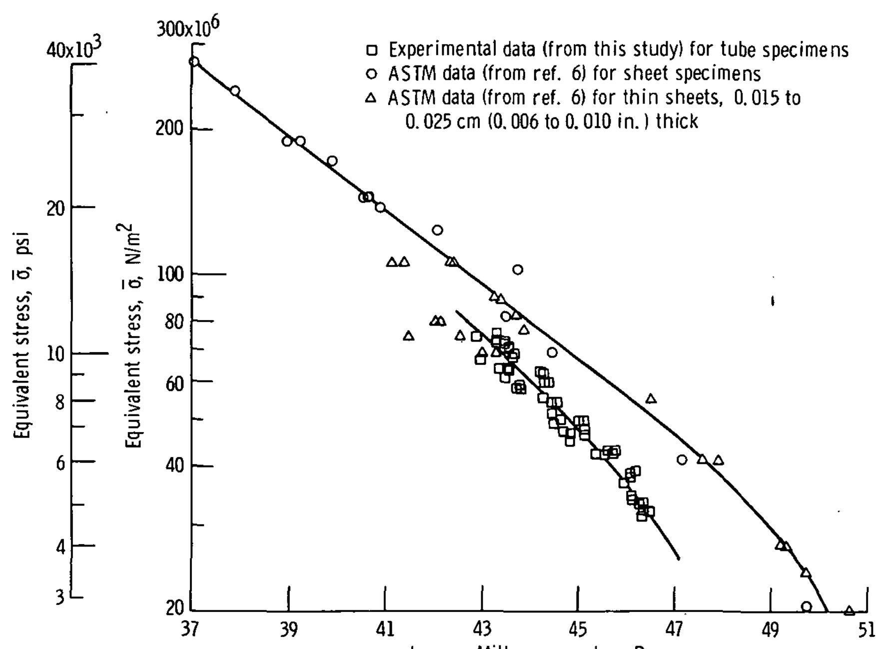



Figure 4. - Equivalent stress as function of Larson-Miller parameter for sheet and tube specimens of Hastelloy-X. Larson-Miller parameter constant, 20.

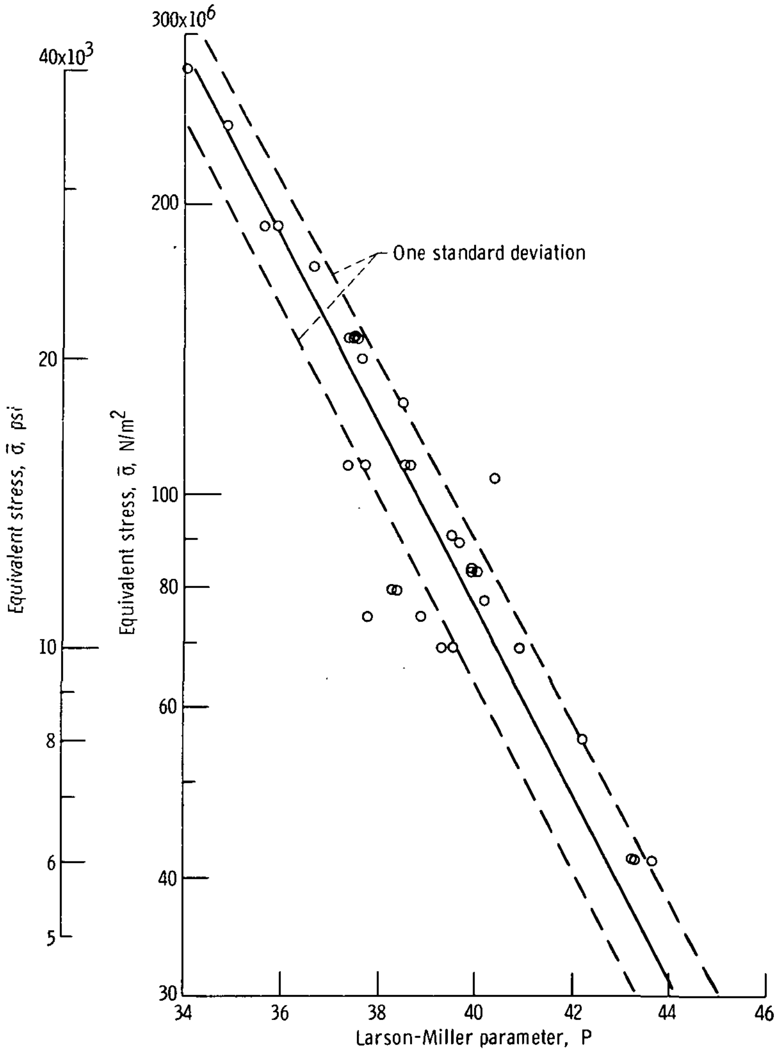



Figure 5. - Equivalent stress as function of Larson-Miller parameter for sheet specimens of Hastelloy-X (from ref. 6). Larson-Miller parameter constant, 18. 186.

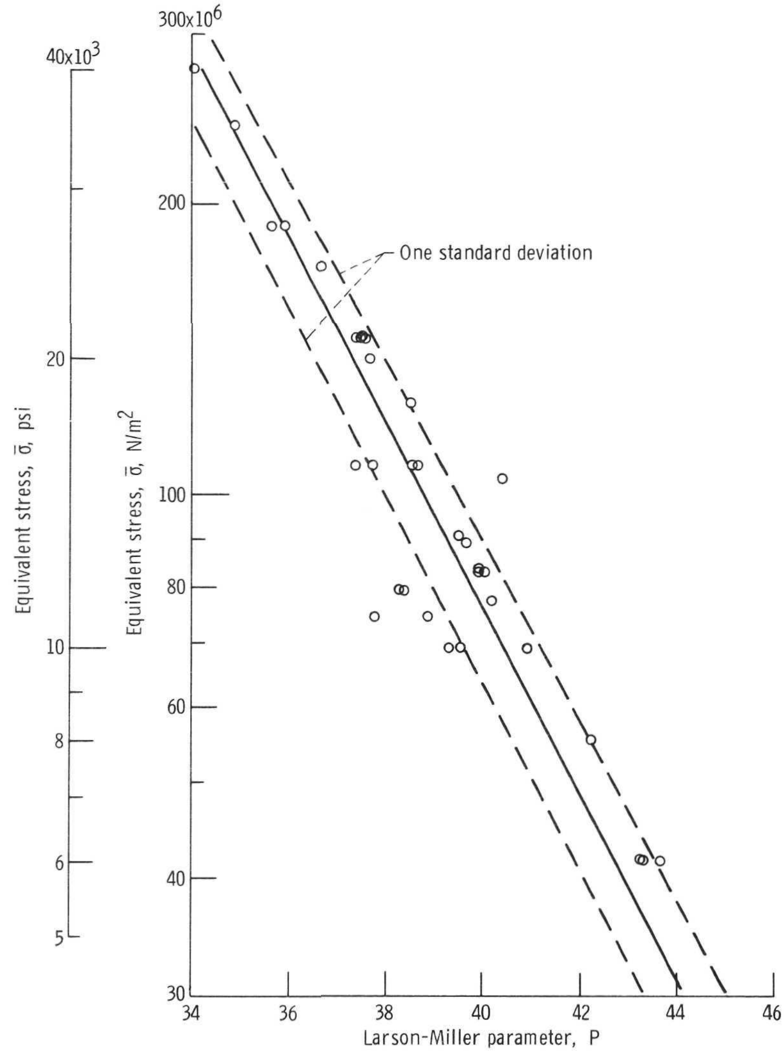
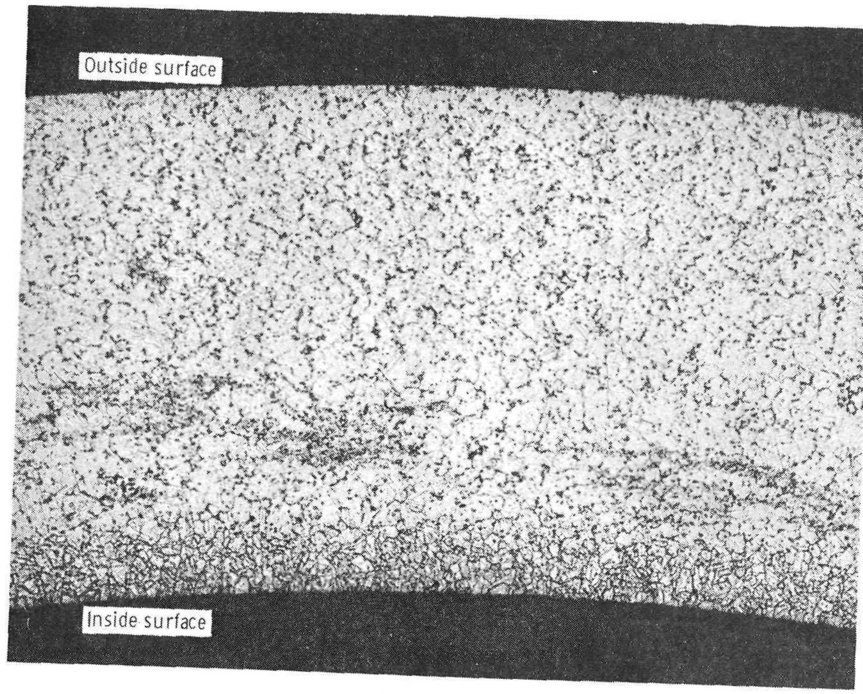
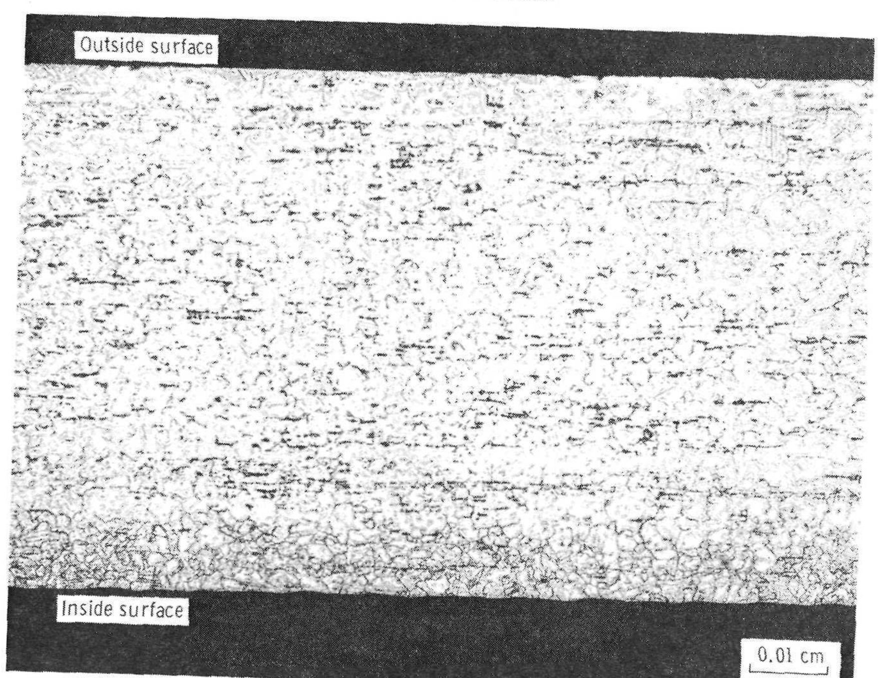



Figure 5. - Equivalent stress as function of Larson-Miller parameter for sheet specimens of Hastelloy-X (from ref. 6). Larson-Miller parameter constant, 18. 186.

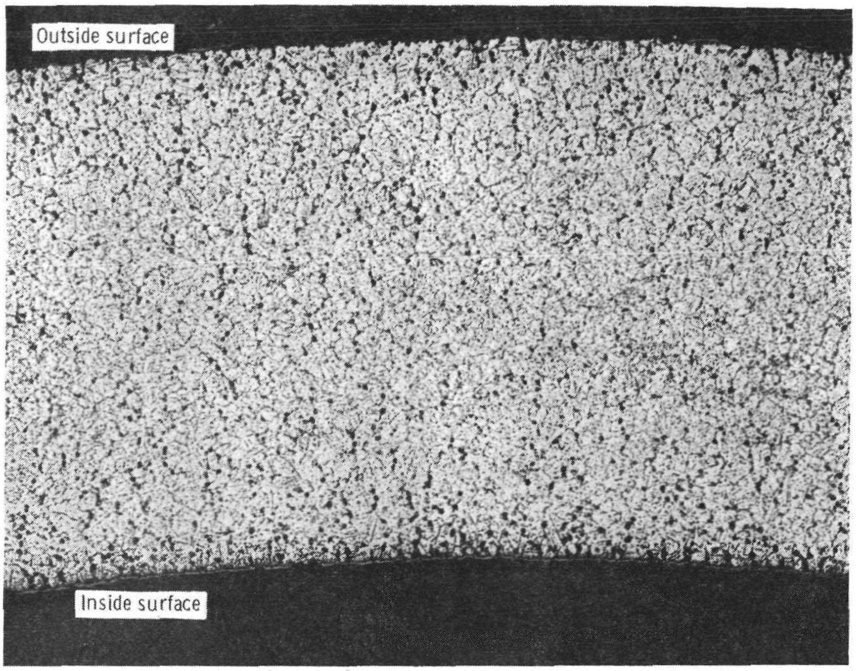



(a) Transverse section.

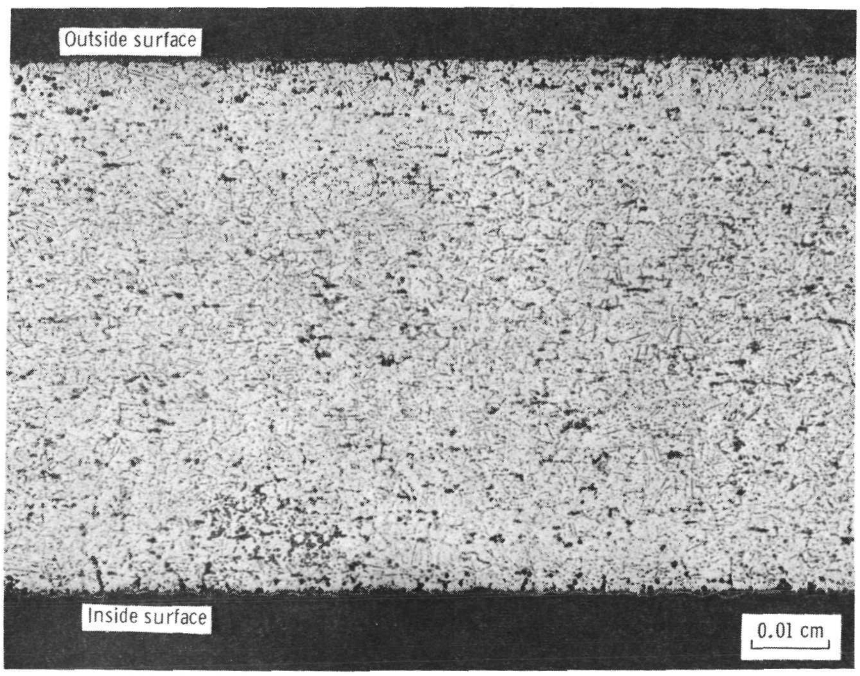



(b) Longitudinal section.

Figure 6. - Sections of as-received tube specimen of Hastelloy-X showing parent metal. Etched, X100.

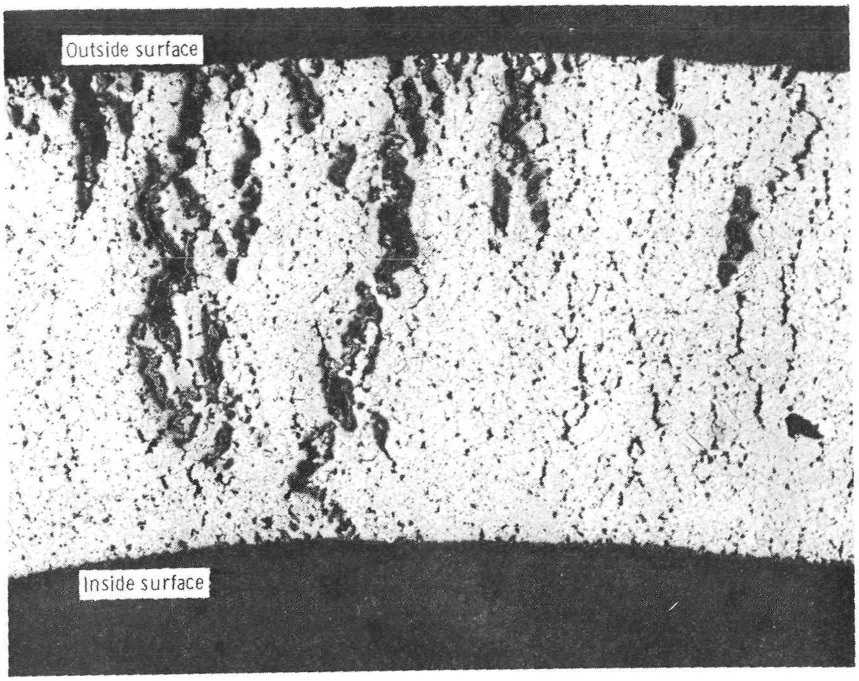



(a) Transverse section.

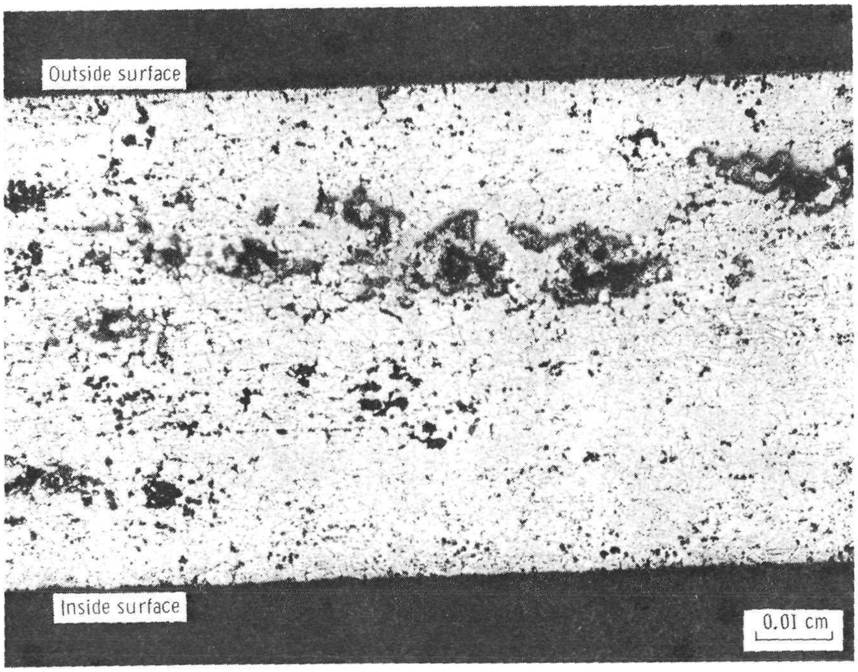



(b) Longitudinal section.

Figure 7. - Sections of tube specimen 2 failure area after 3600 hours at 1033 K (1400° F) and $9.65 \times 10^6$ newtons per square meter (1400 psi). Etched, X100.




(a) Transverse section.




(b) Longitudinal section.

Figure 8. - Sections of tube specimen 45 failure area after 396 hours at 1139 K ($1590^0$ F) and $5.52 \times 10^6$ newtons per square meter (800 psi). Etched, X100.



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