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CREEP-RUPTURE TESTS OF INTERNALLY PRESSURIZED INCONEL 702 TUBES

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16. Abstract

Thirty-four seamless Inconel 702 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 1028 to 1130 K (1390° to 1575° F) and internal helium pressures from 4.8×10^{6} to 12.4×10^{6} N/m^2 (700 to 1800 psi). Lifetimes ranged from 29 to 1561 hr. The creep-rupture strength of the tubes was about 70 percent lower than that of sheet specimens. Larson-Miller correlations and photomicrographs of some specimens are presented.

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SUMMARY

In order to obtain creep-rupture data for designing a helium-to-air heat exchanger, 34 seamless Inconel 702 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. Inconel 702 is a nickel-base superalloy and was selected for its strength at high temperatures and its resistance to oxidation.

The test temperatures and pressures were chosen to simulate the proposed service conditions. The test temperatures ranged from 1028 to 1172 K (1390° to 1575° F), with helium pressures from 4.8×10^{6} to 12.4×10^{6} newtons per square meter (700 to 1800 psi) corresponding to equivalent stresses from 27.05×10^{6} to 82.67×10^{6} newtons per square meter (4.0 to 12.0 ksi). The lifetimes for the tubes ranged from 29 to 1561 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 about 70 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 10.3×10^{6} newtons per square meter (1500 psi) and a temperature of 1089 K (1500° F). For these conditions, the predicted life of the tube is 450 hours, and with a safety factor of 1.5 on the stress, the predicted lifetime is 112 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° F) and pressures up to 12.41×10^{6} newtons per square meter (1800 psi).

One of the materials selected as a candidate was Inconel 702. This is a nickel-base superalloy and is available commercially in seamless tube form. This alloy was chosen because it is oxidation resistant at temperatures up to 1590 K (2400° F) because of its high aluminum content. The uniaxial test data show that Inconel 702 has good strength at the heat-exchanger temperatures and can be welded and fabricated. Inconel 702 is the fifth 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}

ρ ratio of outside diameter to inside diameter of tube

$\bar{\sigma}$ equivalent stress, N/m^2 (ksi)

PROCEDURES

Material

Thirty-four seamless tubes of Inconel 702 (refs. 4 and 5) were tested. This alloy is a nickel-base superalloy. Because it is oxidation resistant and has strength at high temperatures, this alloy is used for furnace and jet engine parts exposed to high temperatures. Inconel 702 keeps its excellent oxidation resistance at temperatures up to 1590 K (2400° F) and can be welded and machined.

Table I lists the chemical analysis of the as-received tube samples as well as the Aeronautical Material Specification for Inconel 702. An independent laboratory performed the analysis of the tube specimens.

Test Specimens

The Inconel 702 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 8.3×10^{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 4.8×10^{6} to 12.4×10^{6} newtons per square meter (700 to 1800 psi), the temperatures ranged from 1028 to 1130 K (1390° to 1575° F), and the test times varied from 29 to 1561 hours. The effective stresses at the tube bore were from 27.05×10^{6} to 82.67×10^{6} newtons per square meter (4.0 to 12.0 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 ±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 (±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 ±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. 6).

(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 7, applies:

$$\dot{\epsilon} = B\bar{\sigma}^n \qquad (1)$$

(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

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{n} \rho^{2/n}}{\rho^{2/n} - 1} p \qquad (2)$$

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

$$\dot{\epsilon}_{\theta a} = \rho^2 \dot{\epsilon}_{\theta b} \quad (3)$$

The equivalent strain rate at the tube bore is

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

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° 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 end at four places spaced 45° apart. The four measurements were averaged to obtain the tube wall thickness.

RESULTS AND DISCUSSION

Thirty-four creep-rupture test specimens were fabricated from commercially purchased, seamless Inconel 702 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 4.8×10^6 to 12.4×10^6 newtons per square meter (700 to 1800 psi), while the test temperatures ranged from 1028 to 1130 K (1390° to 1575° F). The effective stresses at the tube bore varied from 27.05×10^6 to 82.67×10^6 newtons per square meter (4.0 to 12.0 ksi), and the lifetimes ranged from 29 to 1561 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. 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 2.08 at 1028 K (1390° F) to 1.57 at 1130 K (1575° F). The method used to calculate n is described in reference 3.

The test results for the tubes were used as input for the computer program of Mendelson, Roberts, and Manson (ref. 8). This program correlated the stress, lifetime, and temperature data by means of the Larson-Miller parameter. The program selected a parameter constant of 10.671 for the tubes. The results are plotted in figure 3, which shows the fitted parameter curves with ± 1 standard deviation.

Since the parameter constants for the tubes and sheet data from reference 5 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 table III and are shown in figure 4. This figure shows that the rupture strength of the tubes for a given value of P is about 70 percent lower than that of the sheet creep-rupture specimens (ref. 5) over the range of the parameter values used in this test.

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 an Inconel 702 tube wih 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 10.3×10^{6} newtons per square meter (1500 psi), and the temperature is 1089 K (1500° F). For these conditions, the lifetime is predicted to be 450 hours, and with a safety factor of 1.5 on the stress, the service life is predicted to be 112 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 40 to 900 minutes, with most of the tubes falling into the 120- to 480-minute range.

Metallography

Figures 5 to 7 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 5 shows a tube in the as-received condition. Figure 5(a) shows a transverse section, while figure 5(b) shows a longitudinal section. These photographs show carbides as stringers in the direction of work during the tube forming process.

Figure 6 shows tube specimen 7 after 700 hours at 1033 K (1400° F) and an internal pressure of 6.89×10^{6} newtons per square meter (1000 psi). Precipitates within the grains and changes in grain size are not apparent. Some precipitates, probably carbides, and voids are visible at the grain boundaries. Both the inside and the outside surfaces of the tube show a thin layer of oxidation.

Figure 7 shows tube specimen 32 after 92 hours at 1130 K (1575° F) and 5.52×10^{6} newtons per square meter (700 psi). The transverse section (fig. 7(a)) shows a crack penetrating the tube wall and propagating along the grain boundaries. Again, the voids and precipitates appear along the grain boundaries only. The number of voids is larger in this specimen than in the one shown in figure 6. The inside and outside surfaces of the tube as well as the crack surfaces show a thin layer of oxidation. The grain size has increased over the as-received tube grain size.

The oxidation visible at the inside surfaces of both tubes 7 and 32 results from the tubes remaining in the furnaces for a relatively long time following failure. During this time, air was able to diffuse through the fractures into the tubes.

SUMMARY OF RESULTS

Thirty-four seamless Inconel 702 tubes, pressurized internally with helium, were tested in an electric resistance furnace until failure. The tests in an air atmosphere ranged from 29 to 1561 hours. The test temperatures ranged from 1028 to 1130 K (1390° to 1575° F), and the pressures ranged from 4.8×10^6 to 12.4×10^6 newtons per square meter (700 to 1800 psi). The pressures resulted in equivalent stresses at the tube bore of 27.05×10^6 to 82.67×10^6 newtons per square meter (4.0 to 12.0 ksi). The pressures were converted to equivalent stresses and correlated with the test temperatures and lifetimes by the Larson-Miller parameter. The parameter constant for the tubes was selected by a computer program. A graph is shown for the tube correlation. The tube data were also correlated by the Larson-Miller parameter with a constant of 20.0, which permits comparison with published sheet tensile test data by using a parameter constant of 20.0 also. A graph is presented showing this comparison.

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

1. Tests of the seamless Inconel 702 tubes showed that the creep-rupture strength was about 70 percent lower than that of the sheet specimens over the range of test conditions.

2. Reliable predictions of the creep-rupture lifetimes for seamless Inconel 702 tubes under given temperature and stress conditions can not be made on the basis of sheet creep-rupture data.

3. Failures of the seamless Inconel 702 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 40 to more than 900 minutes 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° F) and an internal helium pressure of 10.3×10^{6} newtons per square meter (1500 psi) would have a predicted lifetime of 450 hours. With a safety factor of 1.5, the predicted service life would be 112 hours.

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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 Inconel 702 tube used in the sample calculations:

Material	Inconel 702, 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)	$10.3\text{x}10^6$ (1500)
Temperature, K ($^\circ F$)	1089 (1500)
Stress exponent, n	1.59
Safety factor, N	1.5

The equivalent stress is calculated by equation (2):

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{1.59}(1.3158)^{2/1.59}}{(1.3158)^{2/1.59} - 1.0} p = 6.89 \; p = 71.00\text{x}10^6 \; N/m^2 \; (10\ 320 \text{ psi})$$

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

$$\bar{\sigma}_u = N\bar{\sigma} = 1.5\,\bar{\sigma} = 106.6\text{x}10^6 \; N/m^2 \; (15\ 500 \text{ psi})$$

The parameter value of 22.96 for the equivalent stress of $106.6\text{x}10^6$ newtons per square meter (15 500 psi) is obtained from figure 3, and the parameter equation is solved for the lifetime t:

$$t = \text{antilog}\left(\frac{1000 \text{ P}}{1.8 \text{ T}} - 10.671\right) = 112 \text{ hr}$$

where the temperature T is in kelvins. Thus, for the given conditions, the service lifetime is 112 hours. Similarly, the calculated lifetime for a tube without the safety factor is 450 hours.

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TABLE I. - CHEMICAL COMPOSITION OF

SPECIMENS OF INCONEL 702

[Composition in wt. %.]

Component	Aeronautical Material Specification 5550	Tube test specimens (a)
Chromium	14.0 to 17.0	15.66
Titanium	0.25 to 1.0	.52
Aluminum	2.75 to 3.75	3.11
Iron	0.0 to 2.0	.60
Copper	0.0 to 0.5	.03
Silicon	0.0 to 0.7	.21
Carbon	0.0 to 0.10	.03
Manganese	0.0 to 1.0	1.30
Nickel	Balance	Balance

[a]Analysis by an independent laboratory.

TABLE II. - EXPERIMENTAL DATA FOR INCONEL 702 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	1027.6	1390.0	12.41×10^6	1.80×10^3	194.3	0.9599	0.3779	0.9708	0.3822	0.0635	0.0250	2.08
2	1027.6	1390.0	4.83	.70	1561.0	.9609	.3783	.9764	.3844	.0653	.0257	2.08
3	1027.6	1390.0	12.41	1.80	191.7	.9599	.3779	.9662	.3804	.0640	.0252	2.08
4	1027.6	1390.0	12.41	1.80	184.0	.9601	.3780	.9695	.3817	.0655	.0258	2.08
5	1027.6	1390.0	12.41	1.80	184.5	.9594	.3777	.9649	.3799	.0668	.0263	2.08
6	1033.1	1400.0	6.89	1.00	662.0	.9606	.3782	.9708	.3822	.0635	.0250	2.02
7	1033.1	1400.0	6.89	1.00	700.0	.9604	.3781	.9688	.3814	.0668	.0263	2.02
8	1033.1	1400.0	8.27	1.20	423.0	.9606	.3782	.9672	.3808	.0635	.0250	2.02
9	1033.1	1400.0	8.27	1.20	486.0	.9609	.3783	.9680	.3811	.0655	.0258	2.02
10	1033.1	1400.0	8.96	1.30	158.7	.9606	.3782	1.0104	.3978	.0653	.0257	2.02
11	1033.1	1400.0	8.96	1.30	341.5	.9606	.3782	.9962	.3922	.0650	.0256	2.02
12	1060.9	1450.0	6.21	.90	362.0	.9604	.3781	.9710	.3823	.0638	.0251	1.92
13	1060.9	1450.0	5.52	.80	464.0	.9606	.3782	.9675	.3809	.0630	.0248	1.92
14	1060.9	1450.0	6.89	1.00	281.0	.9606	.3782	.9688	.3814	.0643	.0253	1.92
15	1060.9	1450.0	8.27	1.20	229.0	.9606	.3782	.9713	.3824	.0655	.0258	1.92
16	1060.9	1450.0	8.27	1.20	216.5	.9604	.3781	.9698	.3818	.0635	.0250	1.92
17	1060.9	1450.0	8.96	1.30	147.6	.9606	.3782	.9715	.3825	.0658	.0259	1.92
18	1060.9	1450.0	8.96	1.30	162.3	.9609	.3783	.9693	.3816	.0645	.0254	1.92
19	1088.7	1500.0	4.83	.70	230.7	.9627	.3790	.9728	.3830	.0643	.0253	1.59
20	1088.7	1500.0	4.83	.70	243.3	.9599	.3779	.9771	.3847	.0660	.0260	1.59
21	1088.7	1500.0	12.41	1.80	35.3	.9596	.3778	.9695	.3817	.0635	.0250	1.59
22	1088.7	1500.0	12.41	1.80	29.3	.9596	.3778	.9675	.3809	.0635	.0250	1.59
23	1088.7	1500.0	6.89	1.00	112.0	.9606	.3782	.9685	.3813	.0665	.0262	1.59
24	1088.7	1500.0	6.89	1.00	136.0	.9606	.3782	.9721	.3827	.0648	.0255	1.59
25	1088.7	1500.0	8.27	1.20	68.5	.9609	.3783	.9715	.3825	.0645	.0254	1.59
26	1088.7	1500.0	8.27	1.20	91.0	.9604	.3781	.9703	.3820	.0635	.0250	1.59
27	1088.7	1500.0	4.14	.60	501.0	.9606	.3782	.9728	.3830	.0638	.0251	1.59
28	1088.7	1500.0	4.14	.60	345.5	.9606	.3782	.9754	.3840	.0648	.0255	1.59
29	1088.7	1500.0	5.52	.80	165.0	.9606	.3782	.9672	.3808	.0635	.0250	1.59
30	1088.7	1500.0	5.52	.80	228.0	.9604	.3781	.9799	.3858	.0653	.0257	1.59
31	1130.4	1575.0	4.83	.70	86.8	.9596	.3778	.9685	.3813	.0635	.0250	1.57
32	1130.4	1575.0	4.83	.70	91.8	.9601	.3780	.9685	.3813	.0658	.0259	1.57
33	1130.4	1575.0	4.83	.70	75.8	.9601	.3780	.9708	.3822	.0660	.0260	1.57
34	1130.4	1575.0	4.83	.70	86.9	.9619	.3787	.9700	.3819	.0648	.0255	1.57

TABLE III. - CALCULATED RESULTS FOR INCONEL 702 TUBES

Speci-men	Equivalent stress, σ		Larson-Miller parameter, P (a)	Strain	Ultimate equivalent bore strain	Equivalent bore strain rate, ϵ_a, hr^{-1}
	N/m^2	psi				
1	81.02×10^6	11.75×10^3	41.23	0.1138×10^{-1}	0.1745×10^{-1}	0.8982×10^{-4}
2	30.68	4.45	42.91	.1612	.2493	.159[illegible]
3	80.37	11.66	41.22	$.6616 \times 10^{-2}$	.1017	.5306
4	78.52	11.39	41.19	.9788	.1516	.8238
5	76.96	11.16	41.19	.5825	$.9078 \times 10^{-2}$	.4920
6	45.13	6.55	42.45	$.1058 \times 10^{-1}$	$.1622 \times 10^{-1}$	.2450
7	42.89	6.22	42.49	$.8728 \times 10^{-2}$	.1360	.1943
8	54.16	7.86	42.08	.6875	.1054	.2492
9	52.49	7.61	42.20	.7402	.1146	.2358
10	57.08	8.28	41.29	$.5182 \times 10^{-1}$	.8015	$.5050 \times 10^{-3}$
11	57.30	8.31	41.91	.3702	.5718	.1674
12	40.59	5.89	43.09	.1111	.1705	$.4711 \times 10^{-4}$
13	36.53	5.30	43.29	$.7139 \times 10^{-2}$	.1092	.2353
14	44.76	6.49	42.88	.8461	.1302	.4634
15	52.67	7.64	42.71	$.1111 \times 10^{-1}$	.1720	.7509
16	54.34	7.88	42.66	$.9786 \times 10^{-2}$	.1501	.6931
17	56.84	8.24	42.34	$.1137 \times 10^{-1}$	.1763	$.1194 \times 10^{-3}$
18	57.97	8.41	42.42	$.8723 \times 10^{-2}$	.1344	$.8281 \times 10^{-4}$
19	31.87	4.62	43.83	$.1055 \times 10^{-1}$	.1623	.7036
20	30.94	4.49	43.88	.1799	.2794	$.1148 \times 10^{-3}$
21	82.67	11.99	42.23	.1032	.1583	.4485
22	82.67	11.99	42.08	$.8205 \times 10^{-2}$	.1259	.4295
23	43.91	6.37	43.22	.8197	.1275	.1139
24	45.09	6.54	43.38	$.1190 \times 10^{-1}$	.1836	.1350
25	54.33	7.88	42.80	.1110	.1711	.2497
26	55.16	8.00	43.04	.1031	.1582	.1738
27	27.48	3.99	44.49	.1269	.1948	$.3889 \times 10^{-4}$
28	27.05	3.92	44.18	.1534	.2366	.6848
29	36.78	5.33	43.55	$.6875 \times 10^{-2}$	.1054	.6388
30	35.79	5.19	43.82	.2036	.3150	$.1381 \times 10^{-3}$
31	32.19	4.67	44.64	$.9264 \times 10^{-2}$	.1421	.1637
32	31.10	4.51	44.69	.8730	.1354	.1475
33	30.99	4.49	44.53	$.1111 \times 10^{-1}$	.1725	.2276
34	31.64	4.59	44.65	$.8450 \times 10^{-2}$	.1303	.1499

[a]Larson-Miller parameter constant, 20.

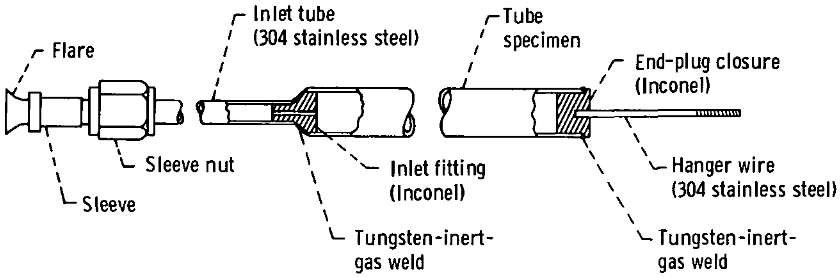


Figure 1. - Test specimen assembly.

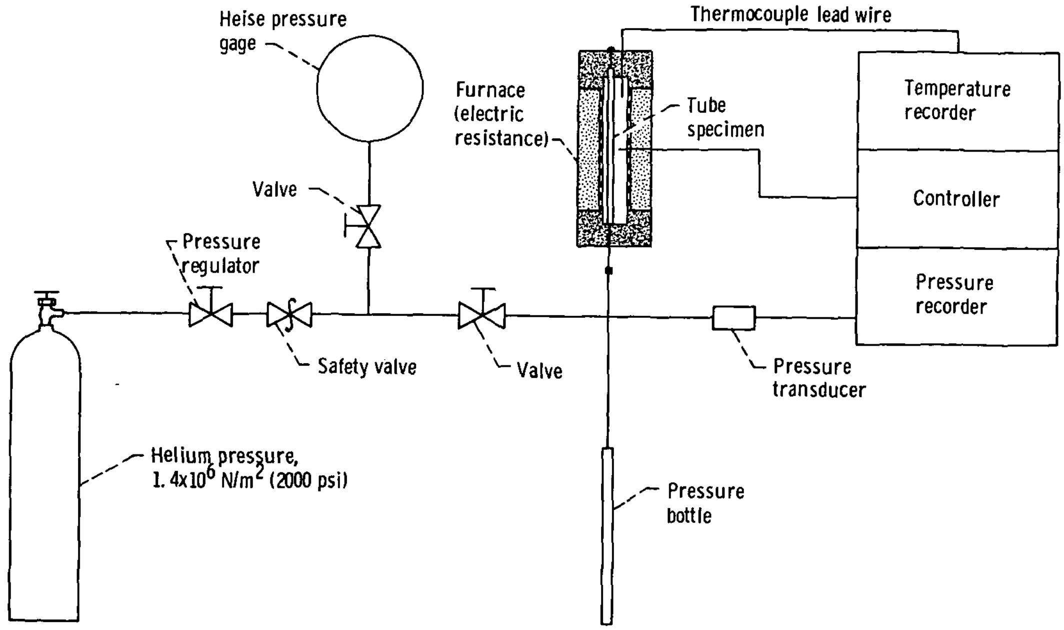


Figure 2. - Heat-exchanger-tube test rig. Maximum test temperature, 1233 K (1760° F); maximum test pressure, 12.41×10^6 newtons per square meter (1800 psi).

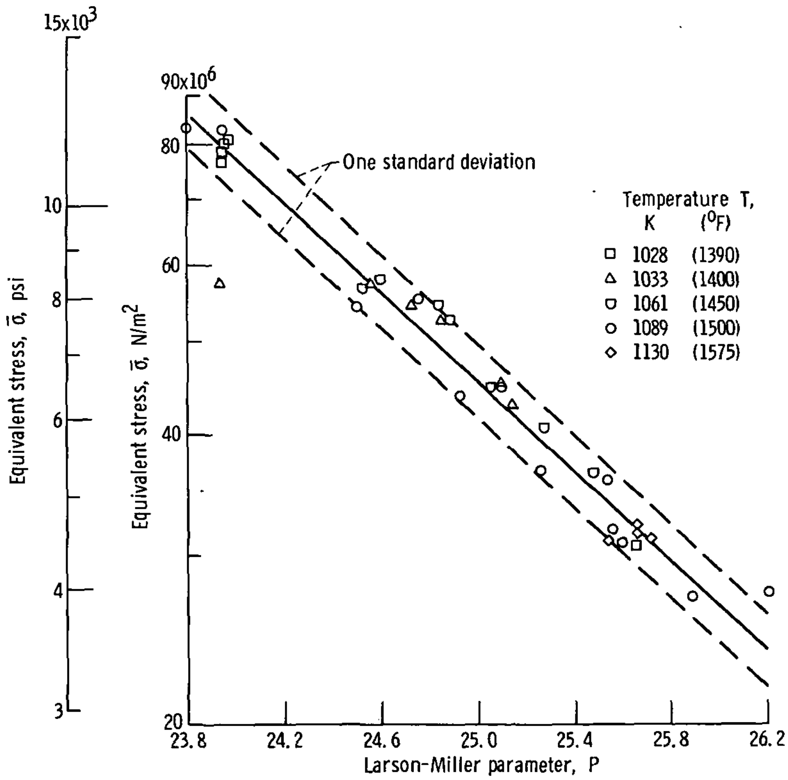


Figure 3. - Equivalent stress as function of Larson-Miller parameter for Inconel 702 tubes. Larson-Miller parameter constant, 10.671.

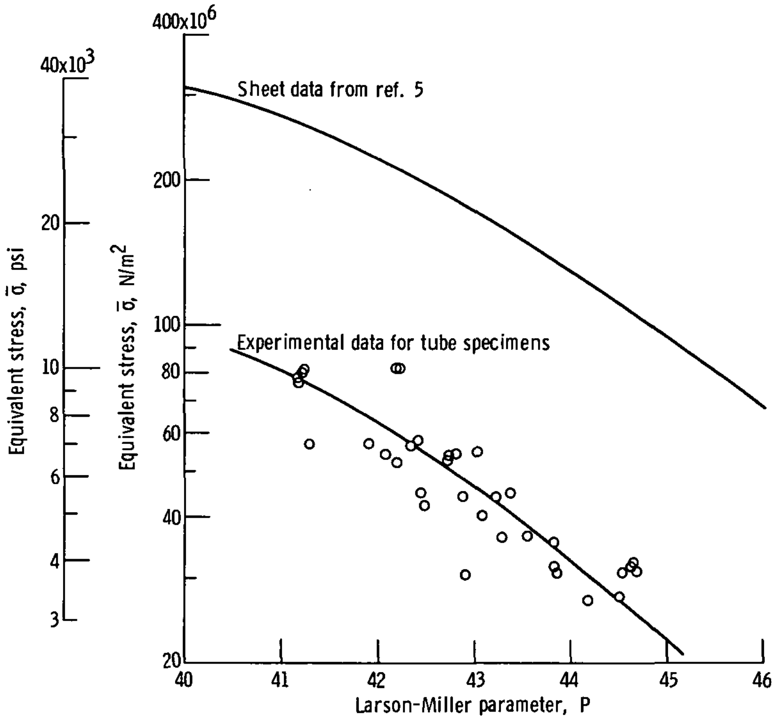
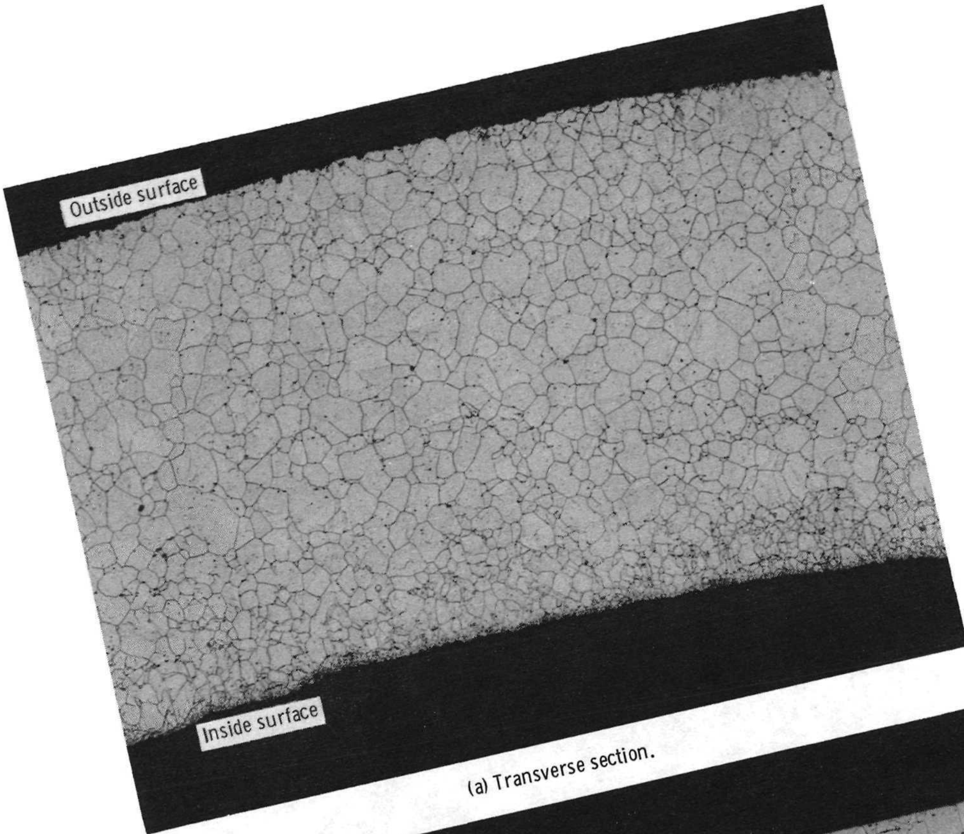
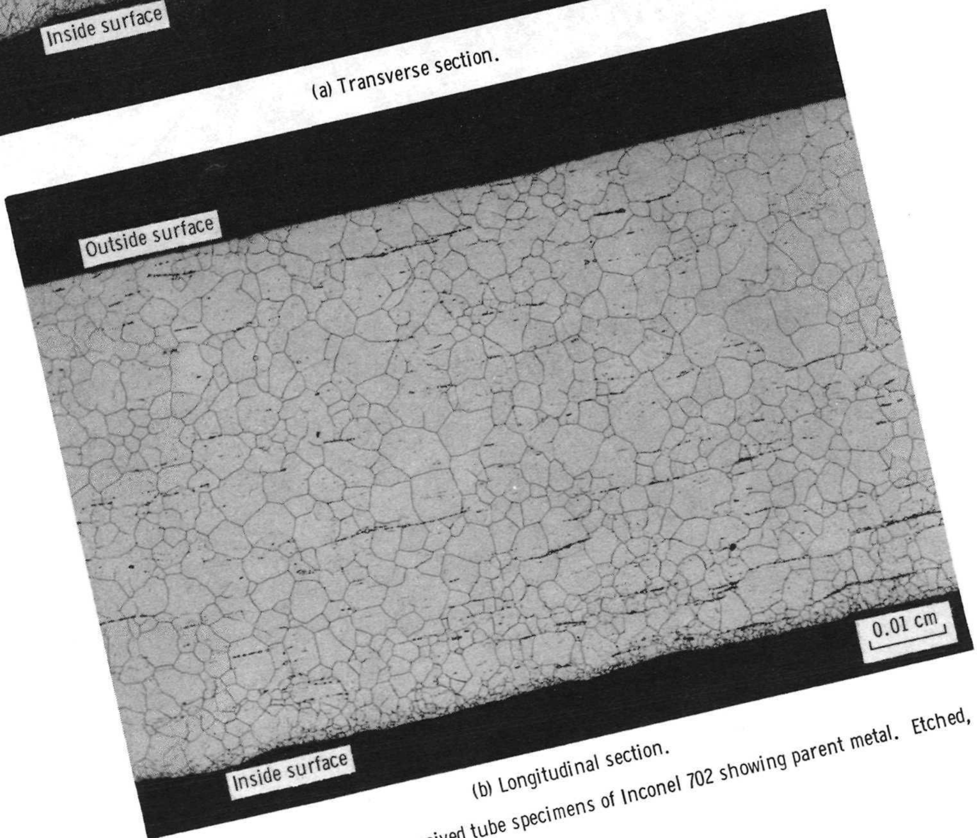


Figure 4. - Equivalent stress as function of Larson-Miller parameter for sheet and tube specimens of Inconel 702. Larson-Miller parameter constant, 20.

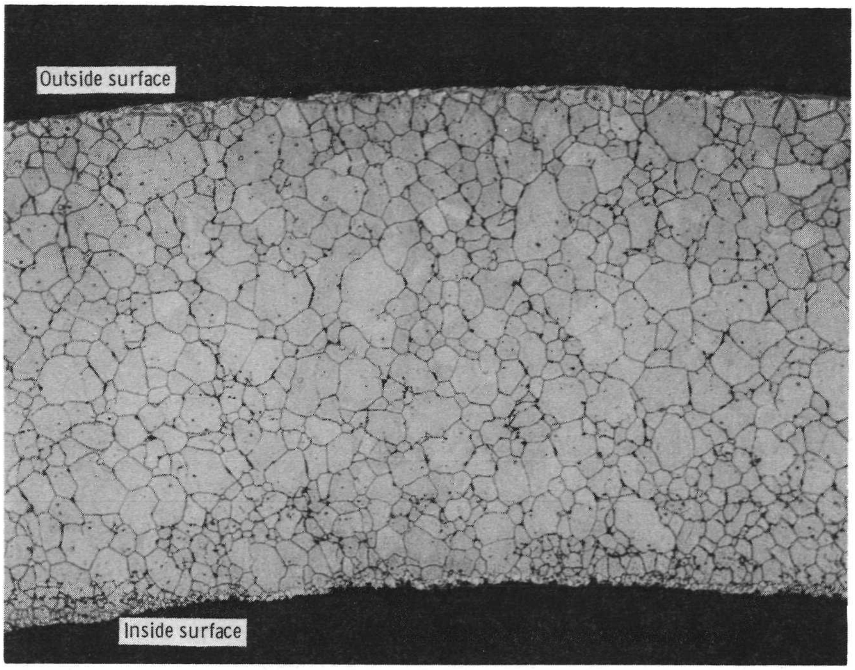


(a) Transverse section.

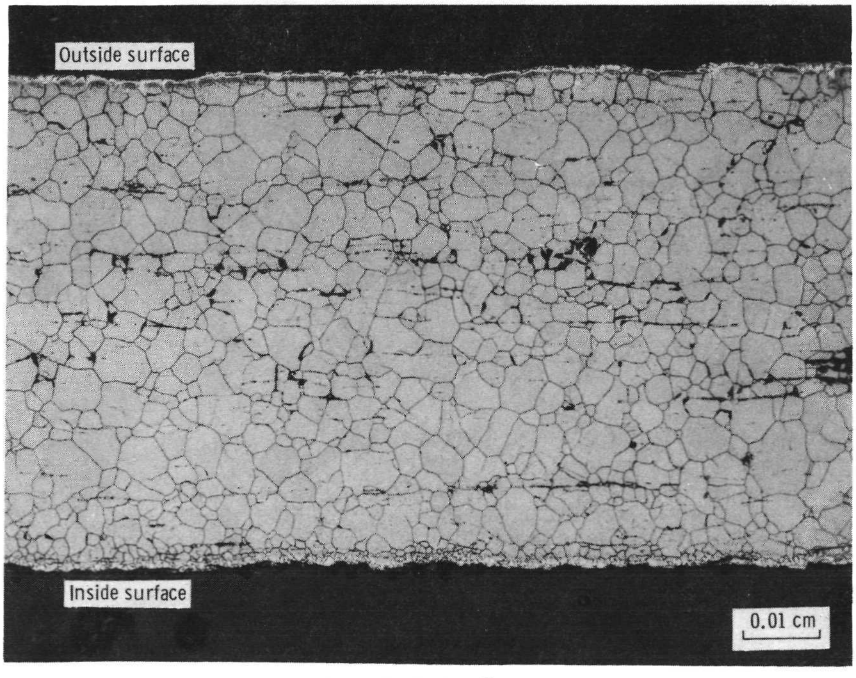


(b) Longitudinal section.

Figure 5. - Sections of as-received tube specimens of Inconel 702 showing parent metal. Etched, X100.

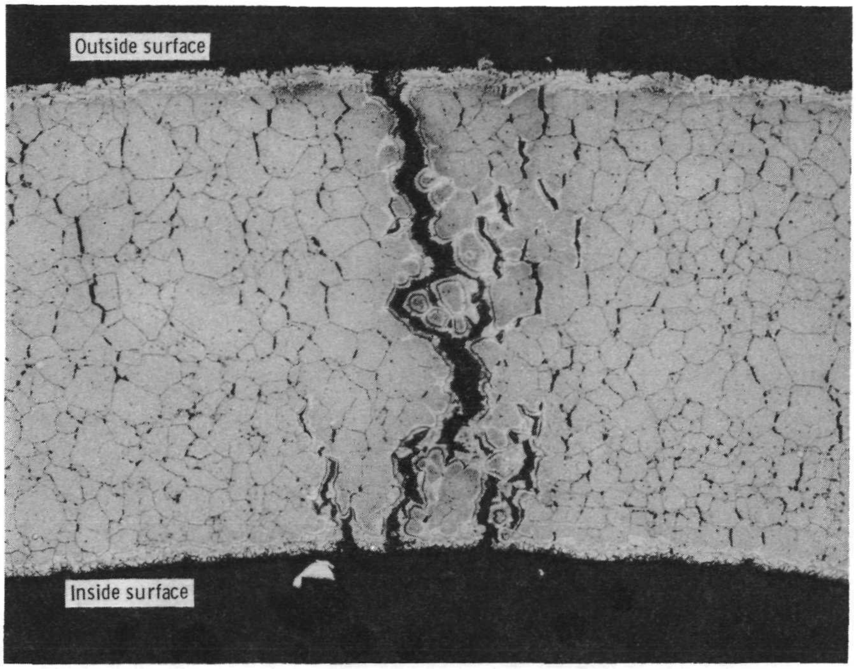


(a) Transverse section.

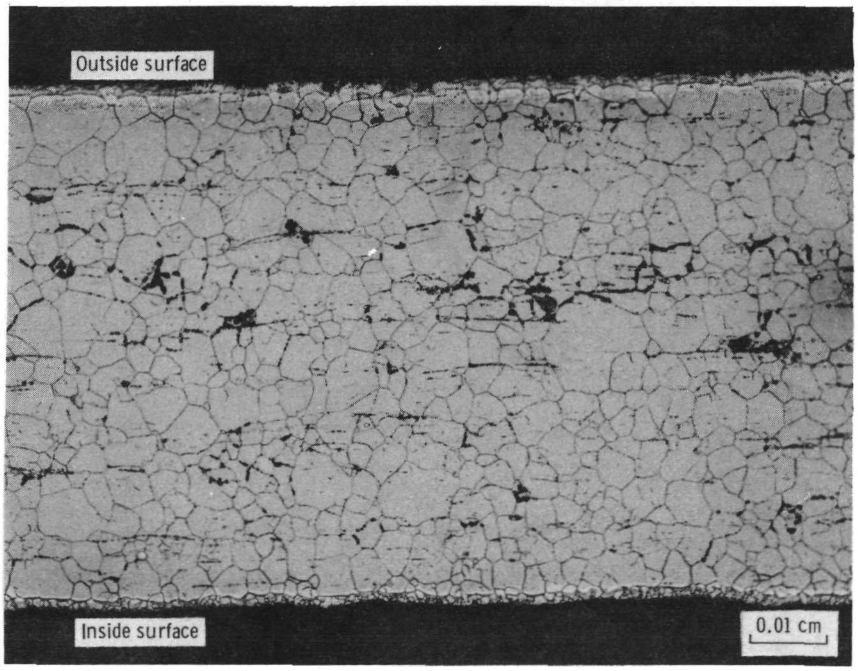


(b) Longitudinal section.

Figure 6. - Sections of tube specimen 7 failure area after 700 hours at 1033 K (1400° F) and 6.89×10^6 newtons per square meter (1000 psi). Etched, X100.



(a) Transverse section.



(b) Longitudinal section.

Figure 7. - Sections of tube specimen 32 failure area after 92 hours at 1130 K (1575° F) and 4.83×10^6 newtons per square meter (700 psi). Etched, X100.

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