OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

ORNL - TM - 535

STRESS-RUPTURE PROPERTIES OF TYPE 304 STAINLESS STEEL TUBING

J. T. Venard

ORNL-TM 535

Contract No. W-7405-eng-26

Metals and Ceramics Division

STRESS-RUPTURE PROPERTIES OF TYPE 304 STAINLESS STEEL TUBING

J. T. Venard

DATE ISSUED

JUN - 7 1963

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

STRESS-RUPTURE PROPERTIES OF TYPE 304 STAINLESS STEEL TUBING

J. T. Venard

ABSTRACT

A single heat of type 304 stainless steel tubing was burst tested in air to determine its stress-rupture properties at temperatures ranging from 1100 to 2200°F and times up to 4000 hr.

The data are presented in graphic form showing log stress vs log time-to-rupture and log strain vs log time-to-rupture. The effect of specimen size on stress-rupture behavior was examined as was the effect of testing in an atmosphere of 90 vol % He, 8 vol % N_2, 2 vol % O_2.

Correlation of the data up to 2000°F using the "Dorn Parameter" is shown to be valid. The data at 2200°F do not agree with this correlation. It is also shown that there is no "size effect" of 6.0-in. vs 2.5-in.-long specimens at temperatures of 1600°F and below. No difference was seen between stress-rupture tests run in air and those in 90 vol % He, 8 vol % N_2, 2 vol % O_2. Strain-at-rupture results indicate decreasing strains with increasing time. The strains observed at 1200 to 1600°F were similar and somewhat smaller strains were observed at 1100 and 1800°F.

INTRODUCTION

The fuel element cladding, type 304 stainless steel tubing, of the Experimental Gas-Cooled Reactor (EGCR) could be stressed due to internal gas pressure resulting from fission-gas release and/or due to thermal expansion of the fuel pellet column. These effects have been accounted for in the element design and the operating procedures for the reactor. However, it is important that the time-dependent strength and ductility of the cladding be known for use in hazards analysis, other failure analysis studies, and for cladding design studies on advanced gas-cooled reactor types.

Of particular interest in this investigation was the generation of base-line data for comparison in later studies on different heats of type 304 stainless steel subjected to varying heat treatments and tested in atmospheres other than air. The testing consisted of tube-burst experiments on a single heat of type 304 stainless steel seamless tubing at temperatures of 1100 to 2200°F for times up to 4000 hr.

Control tests on 2.5-in.-long specimens in air and in a mixture of 90 vol % He, 8 vol % N_2, 2 vol % O_2 were compared with tests on 6.0-in.-long specimens in air. These controls were done as support for an in-pile tube-burst program performed by the Solid State Division.[1]

SPECIMENS

A single heat of type 304 stainless steel obtained from the Superior Tube Company was used in the investigation. This tubing, designated as heat 23999X, was of nominal 0.750-in.-OD × 0.020-in. wall thickness.

A typical chemical analysis of this material is given below.

Superior 23999X

Element	C	Mn	P	S	Si	Ni	Cr	Mo	Cb	Fe
%	0.052	1.51	0.13	20 ppm	0.3	10.38	18.58	0.3	< 0.1	Bal

All specimens were cut to length, lightly polished, and fitted with slip-fit edge-fusion-type end plugs. A number of early tests at temperatures of 1300°F and below failed by separation of the end plug at the weld. This was eliminated in later tests by providing 0.020-in.-wall × 0.5-in.-long support rings which were included in the weld. The rings supported the tube wall and lowered the stress concentration at the weld root. A few typical specimen assemblies are shown in Fig. 1.

Atmospheres other than air were provided by canning the specimens in 1.0-in.-OD Inconel pipe and flowing the desired atmosphere past the specimen. The pressurizing gas was argon in all cases.

---

[1]N. E. Hinkle, "The Effect of Neutron Bombardment on the Stress Rupture Properties of Some Structural Alloys," paper presented at the Fourth Pacific Area National Meeting of the American Society for Testing and Materials, Los Angeles, California, October 1–5, 1962 (to be published).

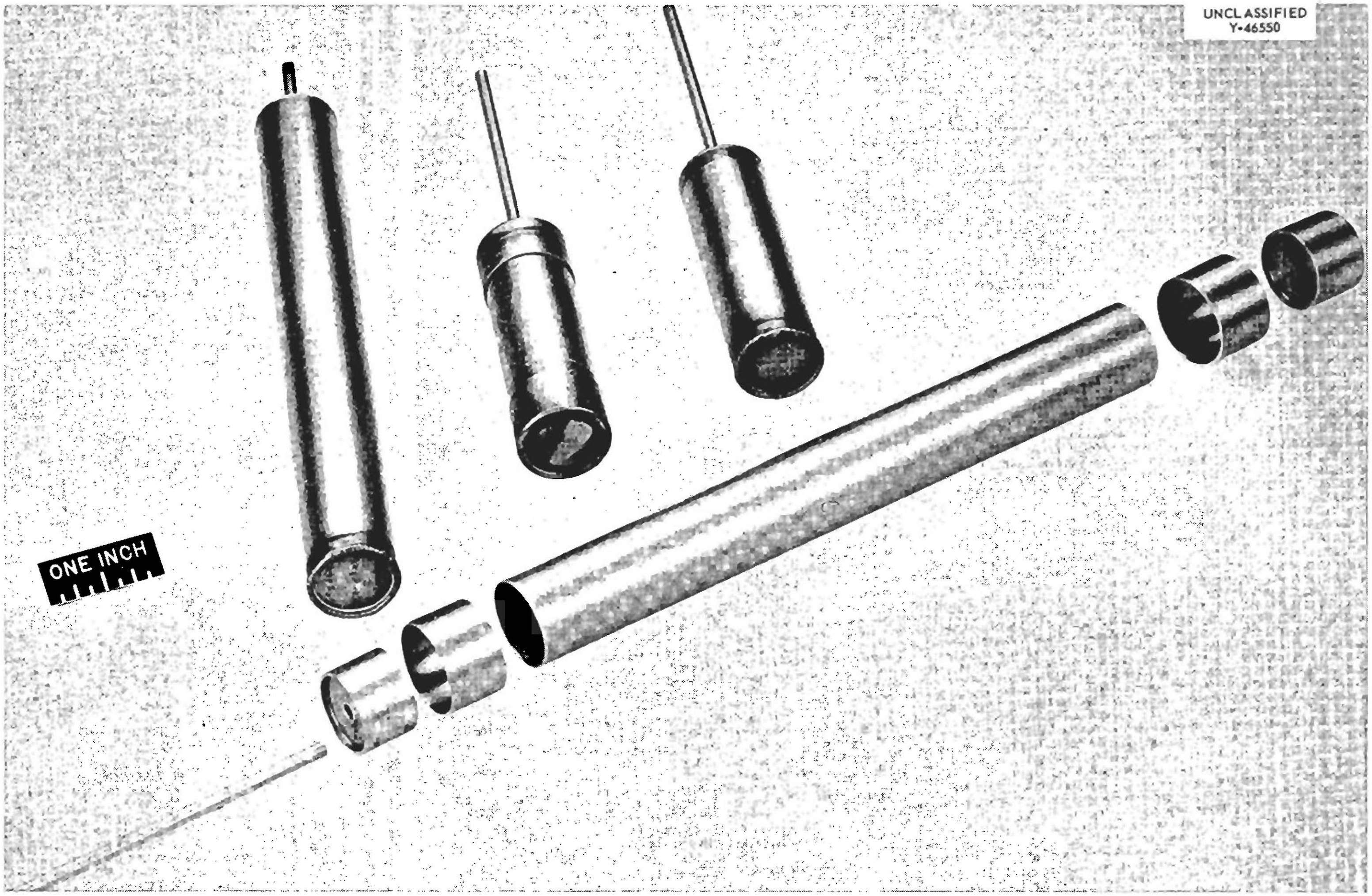

Fig. 1. Typical Specimen Assemblies.

EQUIPMENT

A schematic diagram of the test equipment is given in Fig. 2. Shown are the resistance-wound furnace, the Inconel block used to stabilize and reduce temperature gradients, and the pressurizing and timing systems.

EXPERIMENTAL RESULTS

Stress-rupture plots, log tangential stress vs log time-to-rupture, for air tests at 1100 to 1800°F appear as Fig. 3. Figure 4 is a stress-rupture plot of the 90 vol % He, 8 vol % N_2, 2 vol % O_2 tests. Results obtained at 2000 and 2200°F in vacuum are plotted in Fig. 5.

Figures 6 through 12 are log-log plots of maximum tangential strain at fracture vs time-to-rupture for air tests at 1100 to 1800°F.

The numerical data from which the foregoing figures were made are given in Tables 1 and 2 in the Appendix. Results of tests performed in air are tabulated in Table 1. Table 2 lists the results obtained by testing in an atmosphere of 90 vol % He, 8 vol % N_2, 2 vol % O_2.

Typical specimens after test and a closeup of a failure are shown in Fig. 13. Typical microstructures of as-received material and of specimens tested in air are shown in Fig. 14.

DISCUSSION

A closed-end tube internally pressurized is in the biaxial state of stress described below.

$$\sigma_\theta = \frac{PD}{2t} \tag{1}$$

$$\sigma_Z = \frac{PD}{4t} \tag{2}$$

$$\sigma_R \approx 0 \tag{3}$$

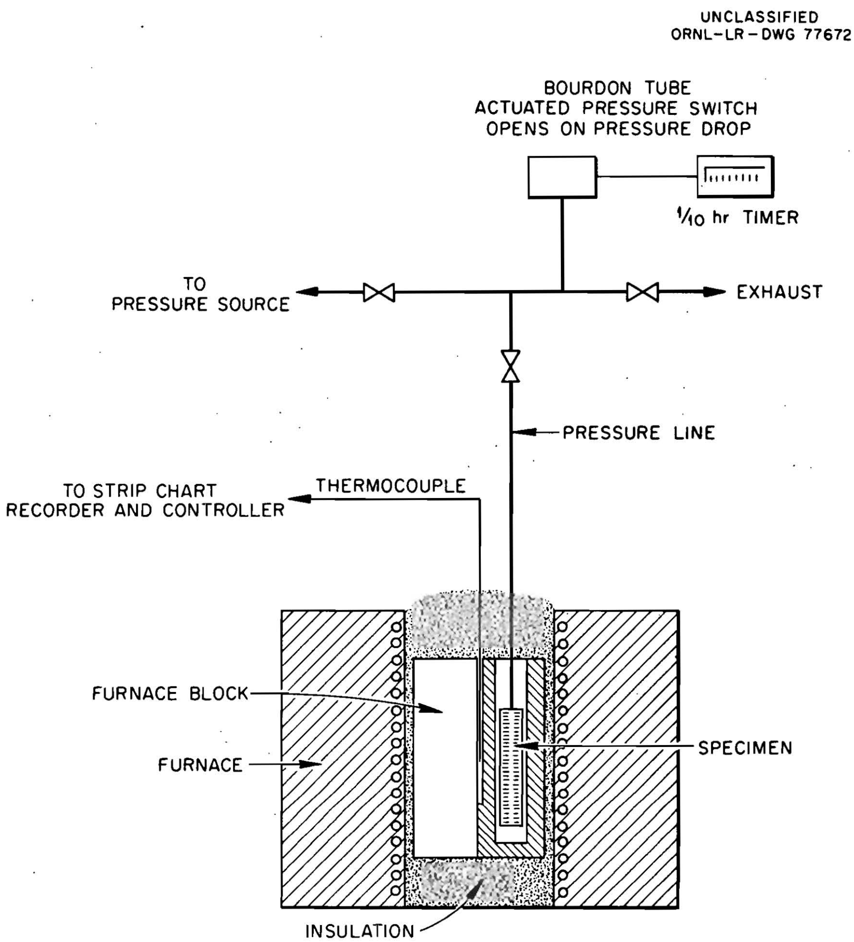

Fig. 2. Schematic of Tube-Burst Facility.

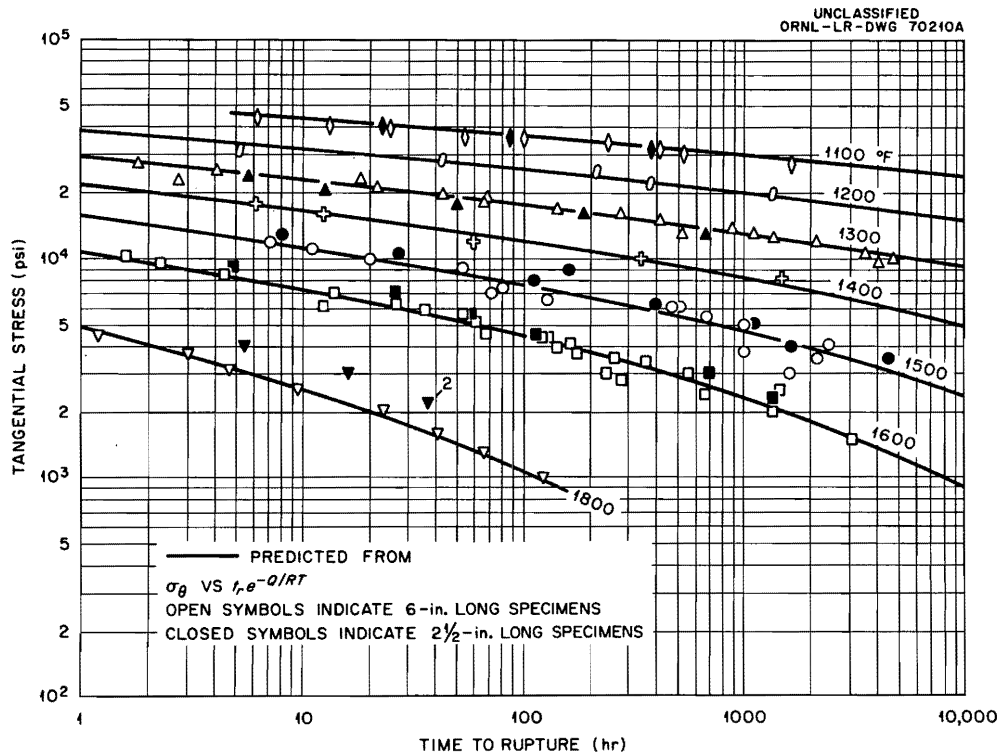

Fig. 3. Stress Rupture of Type 304 Stainless Steel Burst Tested in Air.

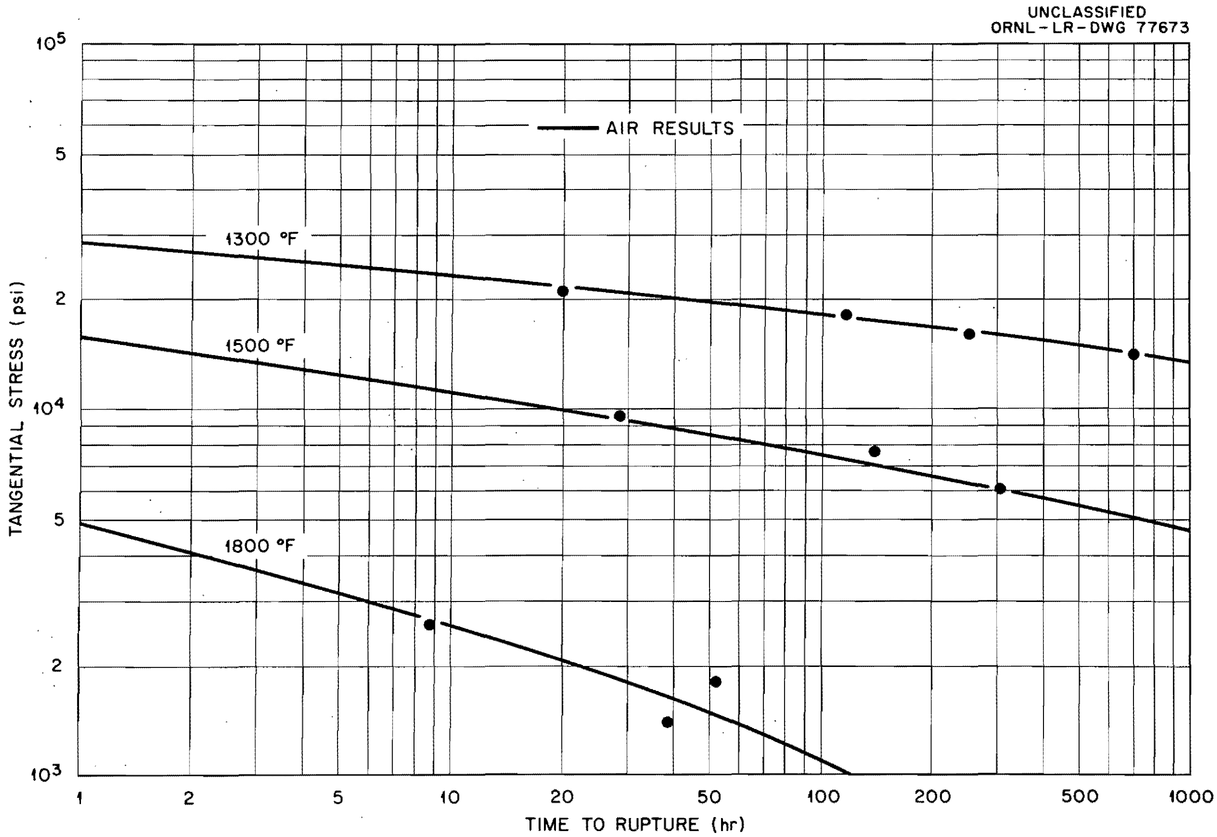

Fig. 4. Stress Rupture of Type 304 Stainless Steel Burst Tested in a 90 vol % He, 8 vol % N_2, 2 vol % O_2 Atmosphere.

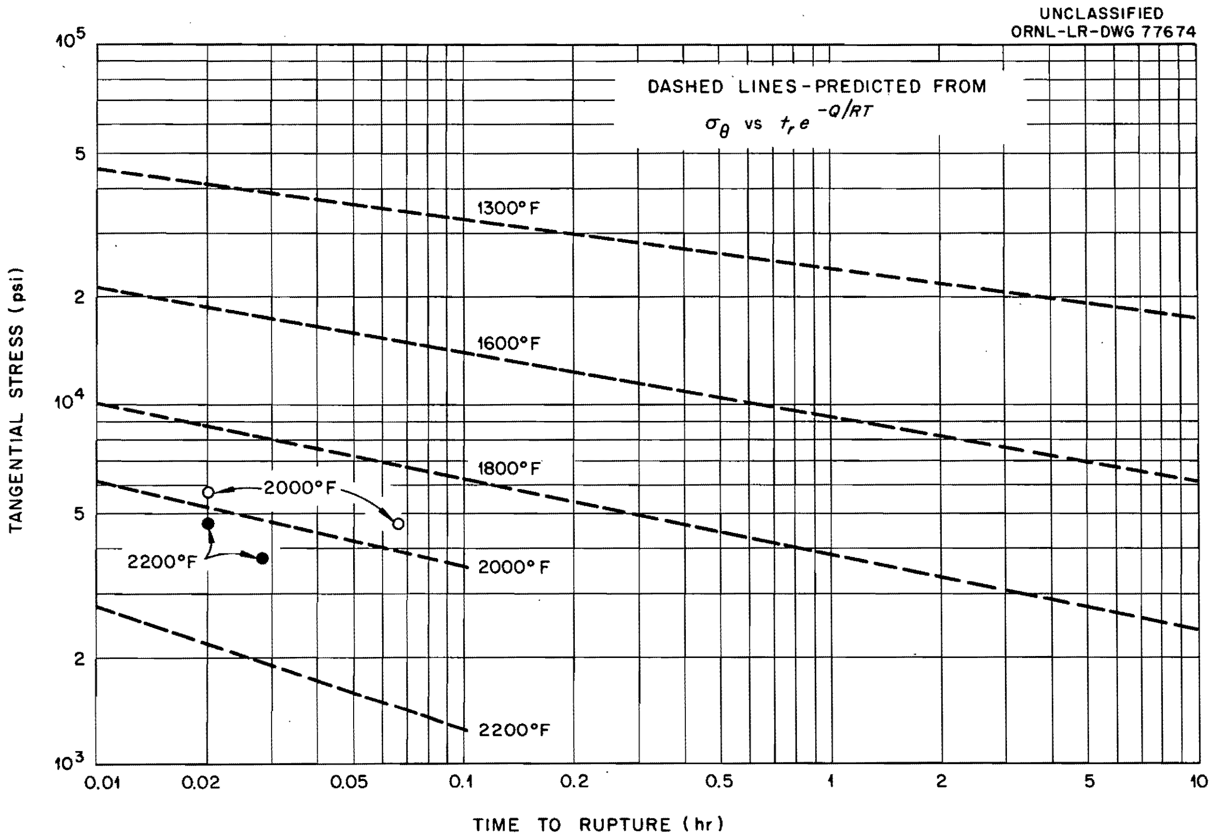

Fig. 5. Stress Rupture of Type 304 Stainless Steel Burst Tested in Vacuum.

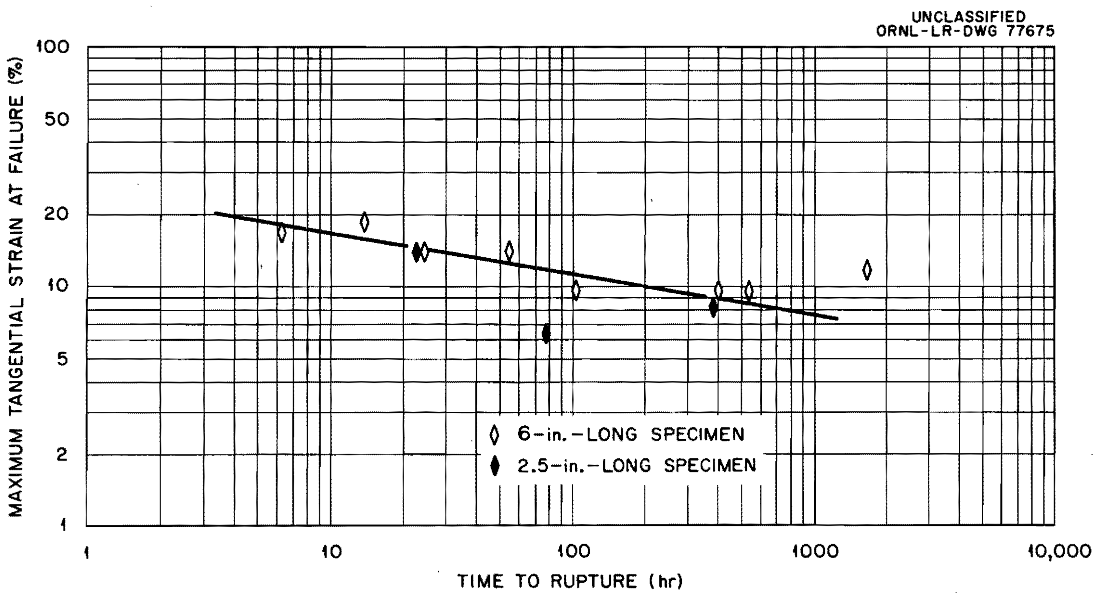

Fig. 6. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1100°F.

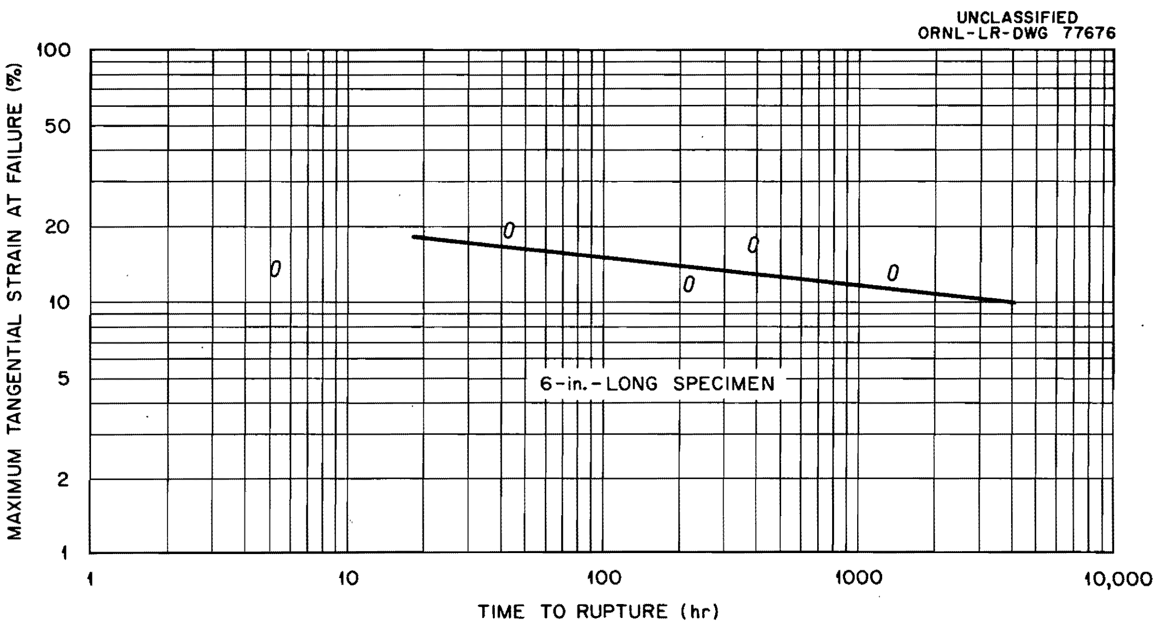

Fig. 7. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1200°F.

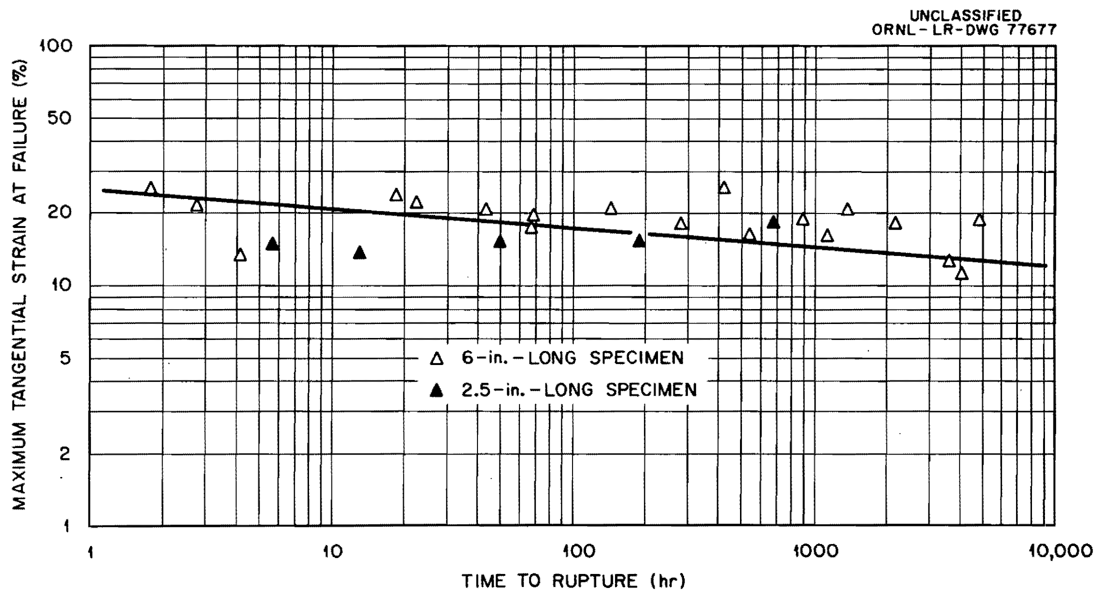

Fig. 8. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1300°F.

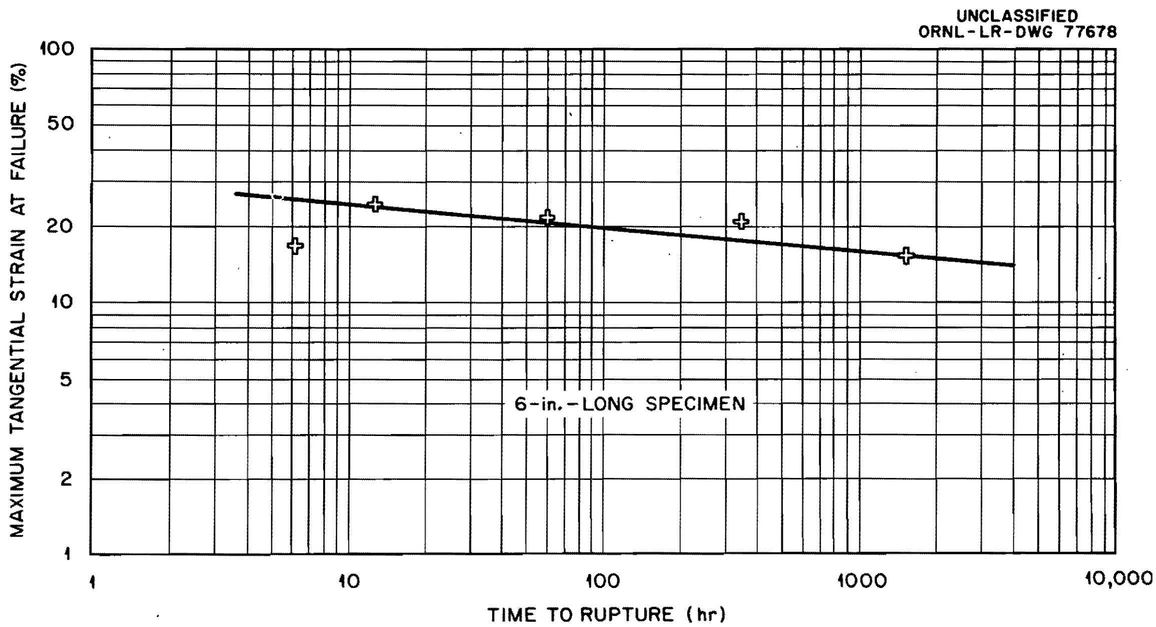

Fig. 9. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1400°F.

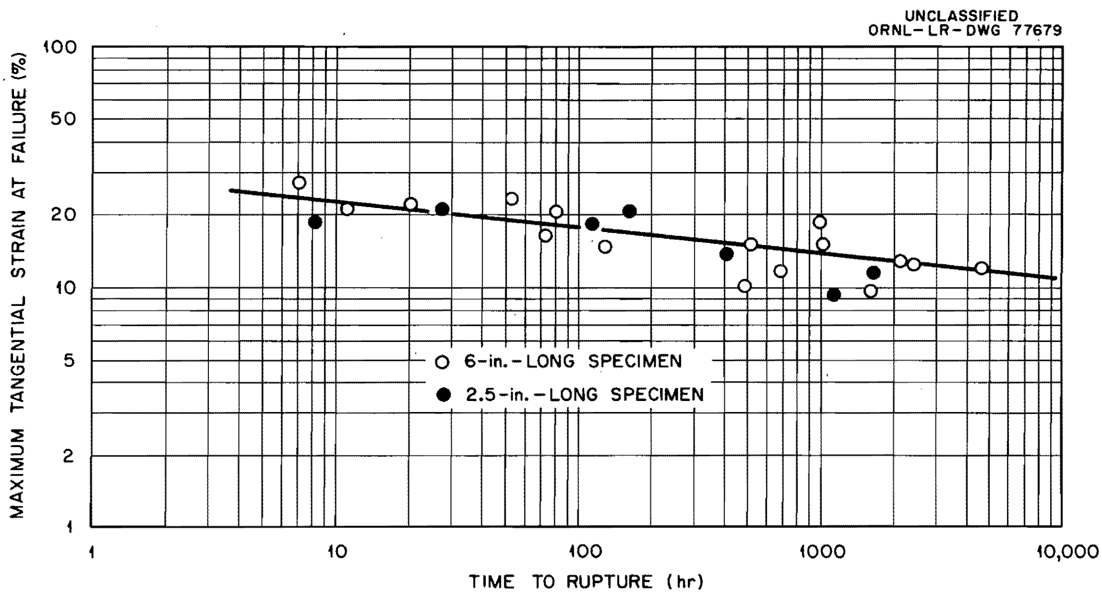

Fig. 10. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1500°F.

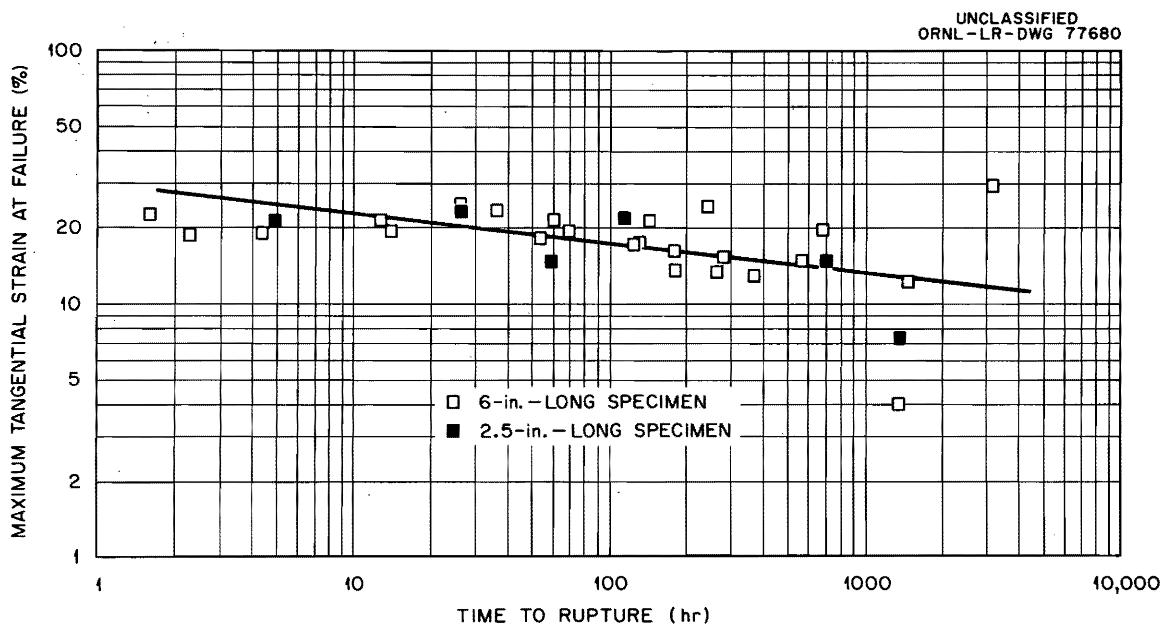

Fig. 11. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1600°F.

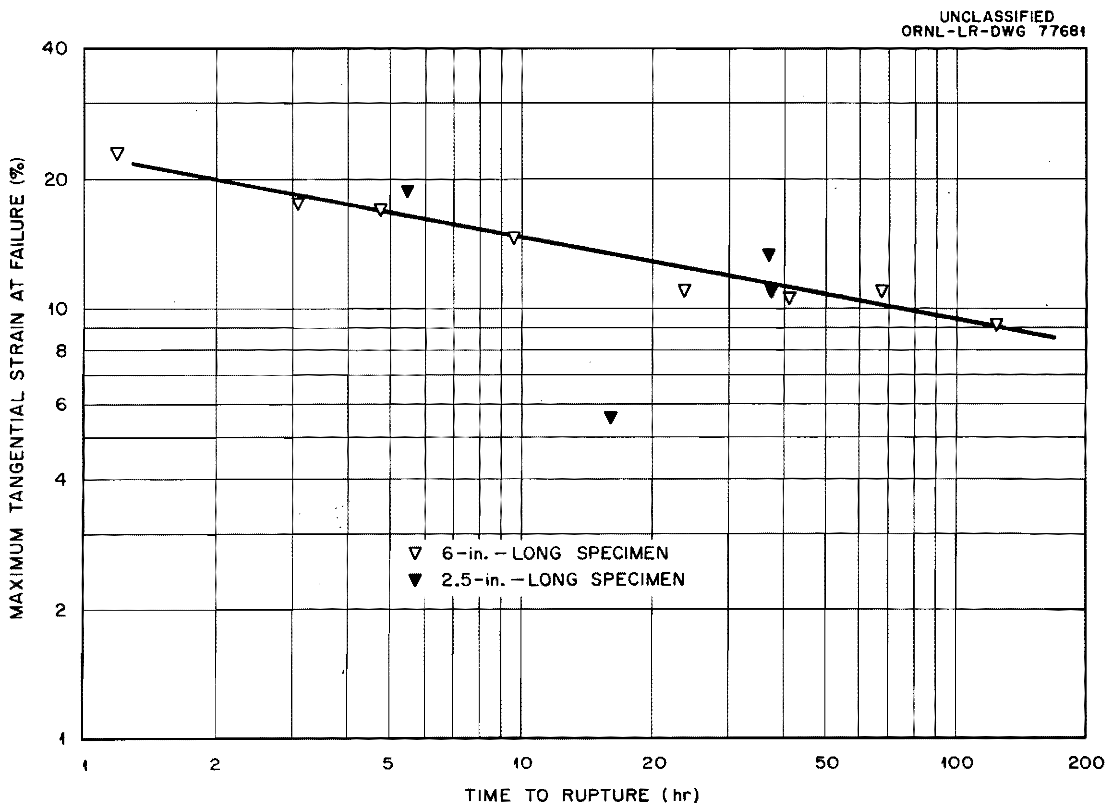

Fig. 12. Strain Vs Rupture Time of Type 304 Stainless Steel Burst Tested in Air at 1800°F.

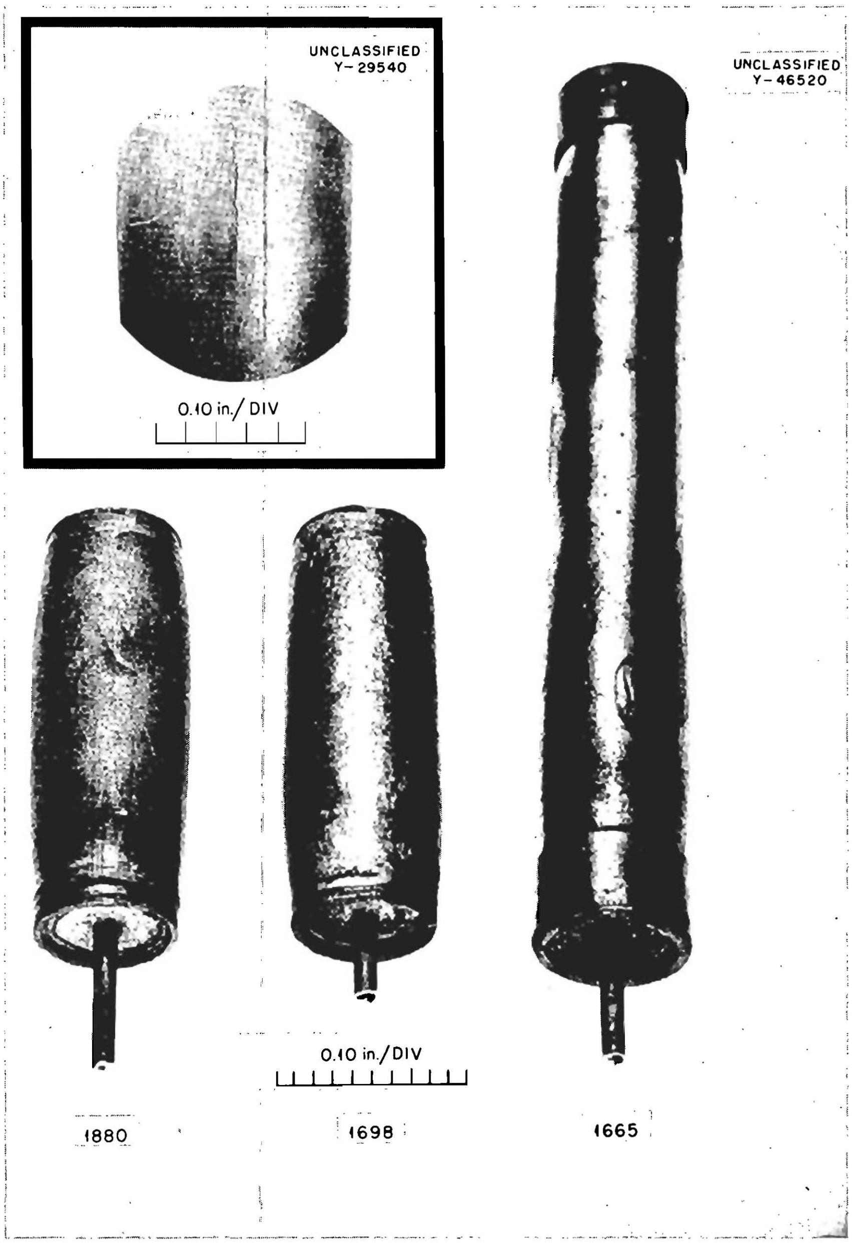

Fig. 13. Typical Specimens After Testing; also Closeup of a Failure.

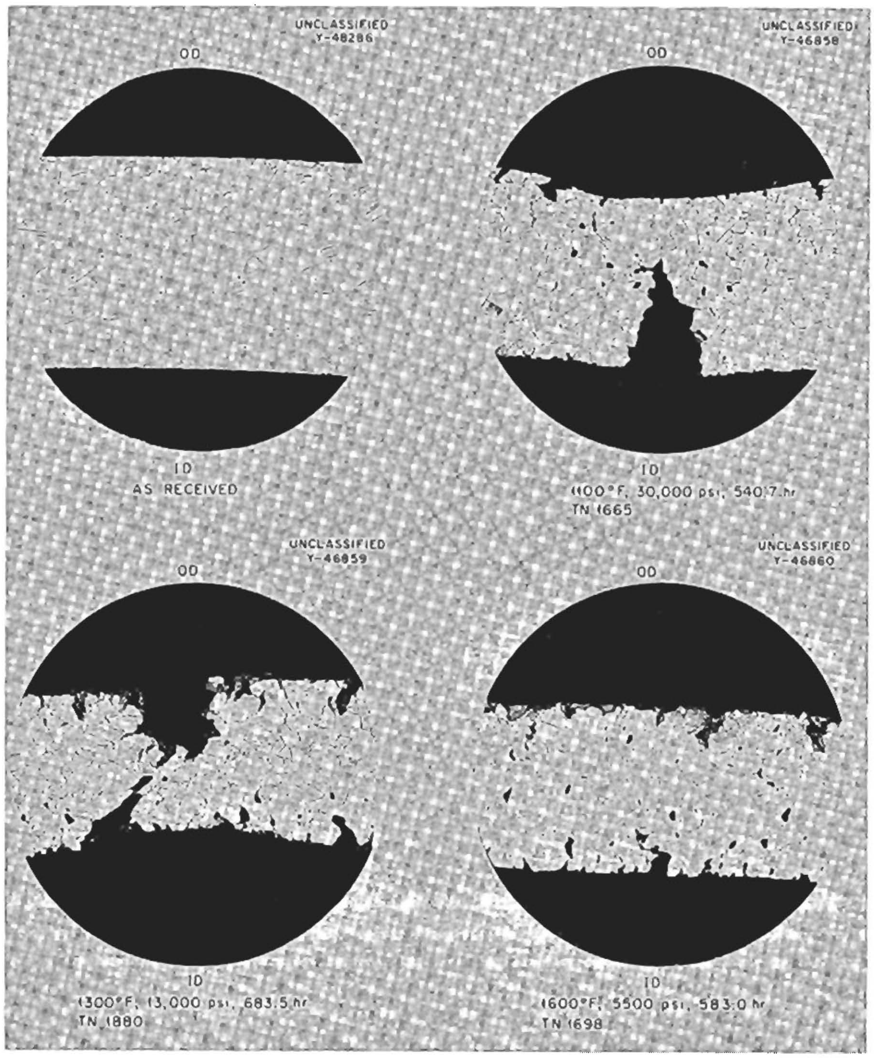

Fig. 14. Typical Microstructures of As-Received Material and of Specimens Tested in Air.

where

σ_θ = tangential stress in tube wall (psi),

σ_Z = axial stress in tube wall (psi),

σ_R = radial stress in tube wall (psi),

P = internal pressure applied (psig),

D = inside diameter of tube (in.),

t = average wall thickness (in.).

These expressions are approximations of the Lamé equations for the stress state in an internally pressurized cylinder and can be shown to be correct for thin-walled tubes.

Using the maximum principal stress criterion for fracture, the test results have been plotted as log σ_θ vs log t_r as in Fig. 3.

It has been proposed[2] that stress-rupture behavior at various temperatures can be related by plotting

$$\log \sigma \text{ vs } \log t_r e^{-Q/RT} \qquad (4)$$

where

σ = applied stress (psi),

t_r = time to rupture (hr),

e = Naperian base,

Q = activation energy for creep (cal/mole),

T = absolute temperature (°K),

R = gas constant (cal/mole-degree).

A master plot of the data has been made using this parameter and appears as Fig. 15. It is seen that using a value of Q = 110,000 cal/mole allows representation of all the data by a single line. Excellent agreement with a conventional stress-rupture plot is seen by fitting the data plotted in Fig. 3 with values taken from the master curve.

---

[2]R. L. Orr, O. D. Sherby, and J. E. Dorn, Am. Soc. Metals, Trans. Quart. 46, 113–28 (1954).

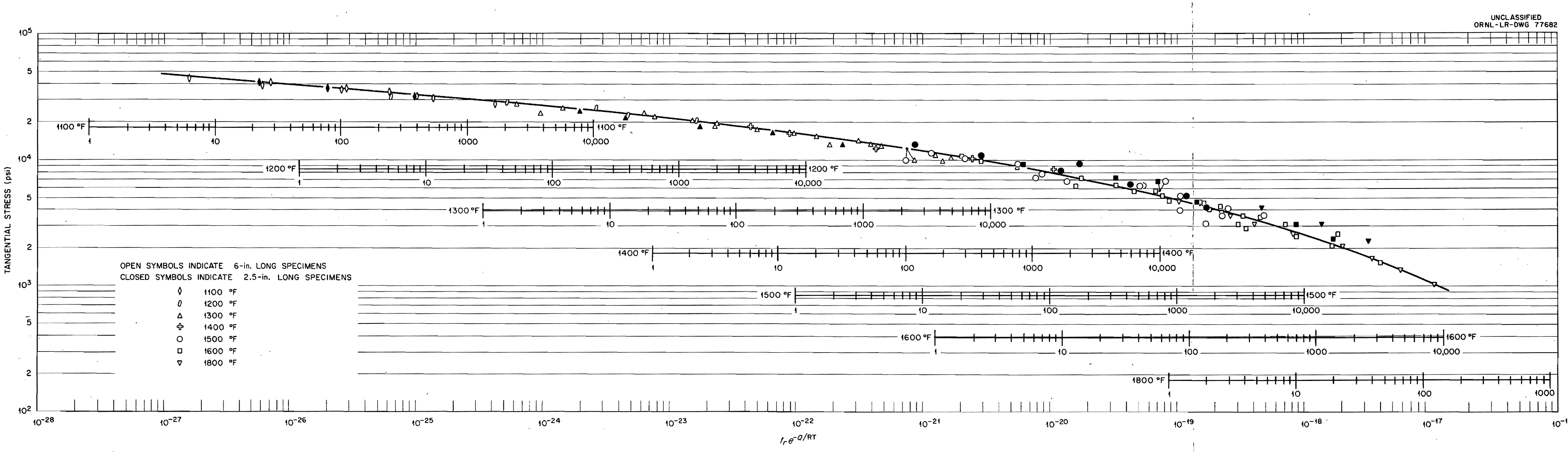

Fig. 15. "Dorn Parameter" Master Plot of Type 304 Stainless Steel Burst Tested in Air.

The use of any parameter fitting method for data such as these serves two purposes. First and most important here, a time-temperature parameter demonstrates the consistency of material behavior over a wide range of temperatures and times. Secondly, the use of such a relationship should allow for reasonably accurate extrapolations of material strength to temperatures and times not covered by experimental data. It can be argued that parameters other than the one used, which are less cumbersome to evaluate and manipulate, will achieve the same or better results. These points have been argued pro and con for all of the better known parameter methods until it has become a rhetorical question as to which is the better. It is the author's feeling that the use of the "Dorn Parameter" and a master plot such as Fig. 15 conveniently fulfills the criteria of data representation and extrapolation.

The comparison of stress-rupture behavior of 2.5 and 6.0-in.-long specimens afforded by Fig. 3 reveals no appreciable differences at temperatures up to 1600°F. At 1800°F, however, end effects in the shorter specimens become sufficient to lower the effective stress in the tube wall. The result is a greater apparent strength of the shorter specimens.

A few specimens were tested in an atmosphere of 90 vol % He, 8 vol % N_2, 2 vol % O_2. In-pile testing of the material was performed in this atmosphere to take advantage of the thermal conductivity of helium while still providing sufficient nitrogen and oxygen for comparison with the nitriding and oxidation observed in air tests. The results of the ex-pile testing in this atmosphere have been superimposed on the air results and reveal no difference in stress-rupture behavior.

Figures 6 through 12, which are plots of log maximum tangential strain at fracture vs log rupture time, reveal decreasing strain with increasing time-to-rupture. Note that strain levels are similar at 1200 to 1600°F with somewhat lower strains being observed at 1100 and 1800°F.

CONCLUSIONS

1. The "Dorn Parameter" is valid for correlation of tube-burst results within the temperature and time ranges examined.

2. No "size effect" between 2.5- and 6.0-in.-long specimens is seen at 1100 to 1600°F. At 1800°F, however, the shorter specimens experience end effects sufficient to lower the effective stress in the tube wall and thereby a "greater apparent strength" results.

3. An atmosphere of 90 vol % He, 8 vol % N_2, 2 vol % O_2 produces stress-rupture results equivalent to those obtained in air.

4. Strain-at-fracture data do not allow correlation on the basis of strain rates; however, the strains observed are consistent except for the somewhat lower values obtained at 1100 and 1800°F.

ACKNOWLEDGMENTS

The author wishes to express his thanks to J. W. Woods, C. W. Walker, and F. L. Beeler for their assistance in the experimental program.

APPENDIX

Table 1. Type 304 Stainless Steel Tube-Burst Tests in Air

Superior 23999X
As-Received Material

Temperature (°F)	Tangential Stress (psi)	Time to Rupture (hr)	Maximum Tangential Strain at Failure (%)	Specimen Length (in.)	Test No.
1100	43,000	6.3	16.9	6.0	1790
	40,000	13.8	18.6	6.0	1662
	40,000	22.9	14.0	2.5	1873
	38,000	24.2	14.0	6.0	1789
	36,000	54.5	14.0	6.0	1663
	36,000	79.0	6.4	2.5	1874
	35,000	101.7	9.7	6.0	1788
	34,000	244.2	-	6.0	1497
	31,000	397.4	9.7	6.0	1664
	31,000	385.4	8.4	2.5	1875
	30,000	540.7	9.6	6.0	1665
	27,000	1663.0	11.9	6.0	1785
1200	31,000	5.3	13.6	6.0	1795
	28,000	43.5	19.1	6.0	1794
	25,000	219.5	11.7	6.0	1793
	22,000	390.3	16.9	6.0	1792
	20,000	1371.6	13.0	6.0	1791
1300	27,000	1.8	25.4	6.0	1661
	25,000	4.2	13.4	6.0	1660
	24,000	5.7	14.9	2.5	1876
	23,000	2.8	21.6	6.0	1261
	23,000	18.4	23.7	6.0	1659
	21,500	22.3	22.0	6.0	1473
	21,000	13.0	13.5	2.5	1877
	20,000	44.1	21.2	6.0	1466
	19,000	68.5	19.6	6.0	1467
1300	18,000	66.7	17.2	6.0	1468
	18,000	50.9	15.1	2.5	1878
	17,000	143.9	21.1	6.0	1469
	16,000	280.6	18.0	6.0	1470
	16,000	189.9	15.0	2.5	1879
	15,000	420.9	25.0	6.0	1471
	14,000	905.4	18.8	6.0	1472
	13,000	539.9	16.2	6.0	430
	13,000	1129.7	16.3	6.0	1581
	13,000	683.5	18.3	2.5	1880
	12,500	1371.8	20.3	6.0	1582
	12,000	2178.4	18.3	6.0	1537
	10,500	3634.9	12.7	6.0	1306
	10,000	4844.4	18.6	6.0	1307
	9,500	4121.6	11.3	6.0	1308
1400	18,000	6.2	16.7	6.0	1799
	16,000	12.6	24.2	6.0	1798
	12,000	60.2	21.4	6.0	1752
	10,000	343.6	20.8	6.0	1751
	8,200	1514.2	15.3	6.0	1796
1500	13,000	8.3	18.6	2.5	1702
	12,000	7.2	27.1	6.0	1460
	11,000	11.2	21.0	6.0	1461
	10,500	27.6	21.0	2.5	1703
	10,000	20.5	22.1	6.0	1462
	9,000	53.5	23.1	6.0	1463

Table 1 (continued)

Temperature (°F)	Tangential Stress (psi)	Time to Rupture (hr)	Maximum Tangential Strain at Failure (%)	Specimen Length (in.)	Test No.
1500	9,000	163.0	20.6	2.5	1704
	8,000	115.6	18.0	2.5	1062
	7,500	82.2	20.4	6.0	1464
	7,000	73.9	16.2	6.0	1465
	6,500	130.4	14.7	6.0	1177
	6,200	409.7	13.9	2.5	1063
	6,000	517.4	15.0	6.0	310
	6,000	487.2	10.0	6.0	318
	5,500	690.9	11.7	6.0	319
	5,000	1024.6	15.0	6.0	239
	5,000	1133.6	9.3	2.5	73
	4,000	2453.6	12.4	6.0	240
	4,000	1667.4	11.5	2.5	72
	3,800	1009.0	18.7	6.0	1509
	3,500	2179.0	12.9	6.0	1508
	3,500	4621.0	12.0	6.0	1065
	3,000	1627.2	9.7	6.0	1111
1600	10,500	1.6	22.3	6.0	1238
	9,500	2.3	18.5	6.0	1240
	9,000	4.9	21.1	2.5	1881
	8,500	4.4	19.0	6.0	1241
	7,000	14.0	19.6	6.0	1227
	7,000	26.1	23.1	2.5	1882
	6,200	26.5	24.9	6.0	1507
	6,000	12.7	21.4	6.0	1434
	5,800	36.2	23.3	6.0	1506
	5,500	54.0	18.3	6.0	1208
	5,500	58.3	14.7	2.5	1698
	5,000	61.0	21.7	6.0	1209
	4,600	69.2	19.6	6.0	1511
	4,500	122.8	17.1	6.0	1505
1600	4,500	115.3	21.9	2.5	1883
	4,400	130.6	17.3	6.0	1510
	4,159	177.1	13.8	6.0	1205
	3,940	143.3	21.1	6.0	1206
	3,700	179.8	16.2	6.0	1204
	3,500	265.0	13.5	6.0	360
	3,400	366.6	13.0	6.0	1203
	3,000	243.1	24.2	6.0	718
	3,000	572.8	14.8	6.0	1433
	3,000	705.4	15.0	2.5	1884
	2,800	280.8	15.3	6.0	1459
	2,500	1479.4	12.3	6.0	1312
	2,400	689.9	19.9	6.0	1256
	2,300	1369.1	7.3	2.5	1701
	2,000	1352.3	4.0	6.0	1255
	1,500	3177.2	29.1	6.0	719
1800	4,500	1.2	23.0	6.0	1612
	4,000	5.5	18.8	2.5	1800
	3,600	3.1	17.8	6.0	1611
	3,000	4.8	17.0	6.0	1610
	3,000	16.1	5.6	2.5	1748
	2,500	9.7	14.7	6.0	1619
	2,200	37.8	10.9	2.5	1694
	2,200	37.2	13.2	2.5	1749
	2,000	23.7	11.0	6.0	1609
	1,600	40.6	10.5	6.0	1618
	1,300	67.5	10.9	6.0	1617
	1,000	124.6	9.1	6.0	1616
2000	5,700	0.02	-	2.5	-
	4,700	0.066	-	2.5	-
2200	4,700	0.02	-	2.5	-
	3,750	0.028	-	2.5	-

Table 2. Type 304 Stainless Steel Tube-Burst Tests in a 90 vol % He, 8 vol % N_2, 2 vol % O_2 Atmosphere

Superior 23999X
As-Received Material

Temperature (°F)	Tangential Stress (psi)	Time to Rupture (hr)	Maximum Tangential Strain at Failure (%)	Specimen Length (in.)	Test No.
1300	21,000	20.2	17.8	6.0	2012
	18,000	118.8	7.5	6.0	2011
	16,000	253.8	10.2	6.0	2010
	14,000	710.5	6.3	6.0	2009
1500	9,600	29.0	16.0	6.0	2016
	7,600	140.1	19.8	6.0	2015
	6,000	307.9	16.2	6.0	2014
1800	2,600	8.8	15.0	6.0	2034
	1,800	52.0	10.3	6.0	2033
	1,400	38.6	8.4	6.0	2032

DISTRIBUTION

1–2. Central Research Library
3. ORNL – Y-12 Technical Library Document Reference Section
4–16. Laboratory Records
17. Laboratory Records, ORNL, RC
18. ORNL Patent Office
19. G. M. Adamson
20. F. L. Beeler
21. B. S. Borie
22. J. H. Coobs
23. J. E. Cunningham
24. J. H. DeVan
25. D. A. Douglas, Jr.
26. J. H Frye, Jr.
27. A. Goldman
28–30. M. R. Hill
31. C. R. Kennedy
32. H. G. MacPherson
33. W. D. Manly
34. W. R. Martin
35. H. E. McCoy
36. C. J. McHargue
37. P. Patriarca
38. R. L. Stephenson
39. G. M. Tolson
40–45. J. T. Venard
46. C. W. Walker
47. J. R. Weir, Jr.
48–62. Division of Technical Information Extension (DTIE)
63. Research and Development Division (ORO)
64–65. D. F. Cope (ORO)