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ANALYSIS OF AVAILABLE CREEP AND CREEP-RUPTURE DATA FOR COMMERCIALLY HEAT-TREATED ALLOY 718

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ABSTRACT

The Ni-Cr-Fe-Nb alloy 718 is a widely used material in elevated-temperature applications. Currently, it is approved by the American Society of Mechanical Engineers *ASME Boiler and Pressure Vessel Code* only as a bolting material for elevated-temperature nuclear service. This report presents analyses of available creep and creep-rupture data for commercially heat-treated alloy 718 toward the development of allowable stress levels for this material in general elevated-temperature nuclear service.

Available data came from 14 heats of bar, plate, and forging material over the temperature range from 538 to 704°C. The longest rupture time encompassed by the data was almost 87,000 h. Generalized regression analyses were performed to yield an analytical expression for rupture life as a function of stress and temperature. Heat-to-heat variations were accounted for by "lot-centering" the data. Effects of different solution heat treatment temperatures (T_s) were accounted for by normalizing the creep stresses to the data for T_s = 954°C. Thus, the results are strictly applicable only for material with this solution treatment.

Time and strain to tertiary creep were predicted as functions of rupture life. Creep strain-time data were represented by normalization to the time and strain to tertiary creep and development of "master creep curves." The results allow estimation of time-dependent allowable stress per American Society of Mechanical Engineers Code Case N-47, and the creep strain-time relationships can be used to develop isochronous stress-strain curves.

INTRODUCTION

Alloy 718 is a widely used structural material in elevated-temperature applications. This popularity is due to several excellent

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features of the behavior of this material, including high creep and creep-rupture strength, good oxidation resistance, and exceptional high-cycle fatigue strength. Current designs of the reactor upper internals and control rod drive line for the proposed Clinch River Breeder Reactor (CRBR) involve extensive use of alloy 718 in the commercially heat-treated condition. (This treatment consists of a solution anneal at 954°C plus a duplex aging treatment of 718 and 621°C.) However, with the exception of bolting material, alloy 718 has not been approved by the American Society of Mechanical Engineers (ASME) code for high-temperature nuclear applications. Recent research programs have been aimed at the generation of necessary information to allow such code approval for commercially heat-treated alloy 718 in high-temperature, nonwelded application. This report presents an analysis of available creep and creep-rupture data as of July 1979, when the analysis was performed. The goal of the present analysis is to summarize the data in such a fashion as to allow determination of time-dependent allowable stresses for elevated-temperature applications per ASME Code Case N-47.[1] This work is part of a larger effort toward compilation of a Code Case N-47 package for alloy 718 being coordinated by EG&G Idaho, Inc., through the Idaho National Engineering Laboratory. The work presented herein was performed through funding obtained from EG&G by subcontract. The EG&G program is in turn funded by the United States Department of Energy.

MATERIAL

Alloy 718 is a high-strength Ni-Cr-Fe-Nb material with significant creep and rupture strength up to 704°C (1300°F). Common nonproprietary specifications for this material are given in refs. 2–7. In addition, applicable RDT standards exist for bars and forgings,[8] seamless tube,[9] and plate, sheet, or strip.[10] Tables 1 through 4 compare several aspects of the various specifications.

Table 1. Product Check Analysis Limits

Element	Content, %		
	ASTM A670	ASTM A637	AMS 5589, 5596, 5662
Carbon	0.09 max	0.09 max	0.09 max
Manganese	0.38 max	0.38 max	0.38 max
Silicon	0.38 max	0.38 max	0.38 max
Phosphorus	0.02 max	0.02 max	0.02 max
Sulfur	0.018 max	0.02 max	0.018 max
Chromium	16.75–21.25	16.75–21.25	16.75–21.25
Cobalt	1.03 max	1.20 max	1.03 max
Molybdenum	2.70–3.40	2.70–3.40	2.70–3.40
Ni + Ta	4.55–5.70	4.55–5.70	4.55–5.70
Titanium	0.60–1.20	0.60–1.20	0.60–1.20
Aluminum	0.10–0.90	0.10–0.90	0.10–0.90
Iron	remainder	remainder	remainder
Copper	0.33 max	0.33 max	0.33 max
Ni + Co	49.65–55.35	49.65–55.35	49.65–55.35
Boron	0.008 max	0.008 max	0.008 max

Table 2. Melting Requirements

ASTM A 670	ASTM A 637	AMS 5589, 5596, 5562
Consumable electrode remelt,[a] or	Electric furnace, or	Not specified
induction melt in vacuum	vacuum induction, or	
	multiple melt using consumable electrode remelt practice	

[a]If the consumable electrode remelt is not performed in a vacuum, then the electrode shall have been produced by vacuum induction melting.

Table 3. Specified Minimum Tensile and Other Properties of Alloy 718

Specification	Strength, MPa (ksi) Tensile	Strength, MPa (ksi) Yield	Total Elongation (%)	Reduction of Area (%)	Hardness	Predominant Grain Size
Room Temperature						
ASTM A 670[a,b]	1240 (180)	1035 (150)	12			
ASTM A 637[c]	1274 (185)	1035 (150)	12[d]	15[d]	331 BHN	
AMS 5589[a,e]	1274 (185)	1035 (150)	12		36 C	5
AMS 5596C[a,b]	1240 (180)	1035 (150)	12		36 C	6
AMS 5662C[a,f]						
Longitudinal	1274 (185)	1035 (150)	12	15		4–5
Long transverse	1240 (180)	1035 (150)	10	12		4–5
Transverse	1240 (180)	1035 (150)	6	8		4–5
649°C (1200°F)						
AMS 5596[a]						
up to 0.635 mm	964 (140)	792 (115)	5			
over 0.635 mm	999 (145)	827 (120)	5			
AMS 5662[a]						
Longitudinal	999 (145)	861 (125)	12	15		
Long transverse	964 (140)	861 (125)	10	12		
Transverse	964 (140)	861 (125)	6	8		

[a]Although precipitation hardening is not explicitly required by the specification, it is required to achieve the properties specified.

[b]Plate, sheet, strip.

[c]Bar, forgings.

[d]Lower values (6% total elongation, 8% reduction of area) apply to specimens machined tangentially from near the center of large disk forgings over 0.032 m^2 (50 $in.^2$) in cross section or radially from rings 76 mm (3 in.) or more in thickness.

[e]Tubing.

[f]Bar, forgings, rings.

Table 4. Heat Treatment Requirements for Solution Treated and Duplex Aged Alloy 718

Treatment	Specification	Temperature (°C)	Temperature (°F)	Time (h)	Cooling
Solution	ASTM A 670	*a*	*a*	*a*	*a*
	ASTM A 637	924–1010	1700–1850	0.5	air cool or faster
	AMS 5589[b]	940–968	1725–1775	0.5	air cool or faster
	AMS 5596[b]	924–1010	1700–1850		air cool or faster
	AMS 5662C	924–1010	1700–1850	≥1	air cool or faster
First aging	all	718	1325	8	furnace cool
Alternate	5596, 5662C	718	1325	8	55°C/h (100°F/h)
Second aging	all	621	1150	10[c]	air cool
Alternate	5596, 5662C	621	1150	8	air cool

[a]Not specified.

[b]Recommendations, not requirements.

[c]Including cooling time from 718°C.

STRESS CRITERIA

The time-dependent allowable design stress intensity limit, S_t , is defined for a given temperature and a given time, t , as the lowest of:

1. 2/3 of the minimum stress to cause rupture in time t;
2. 80% of the minimum stress to cause onset of tertiary creep in time t; and
3. the minimum stress to produce 1% total strain in time t.

In addition, Code Case N-47 includes average isochronous stress-strain curves representing the behavior of the materials that it encompasses. Therefore, the scope of this investigation included both analysis of the properties directly required to define values of S_t and the development of an analytical representation for creep strain-time behavior to be used in isochronous stress-strain curve development.

DATA

A survey of available data revealed information from 14 heats of plate, bar, and forging material meeting applicable standards. Tables 5 and 6 summarize the characteristics of these heats of material. Table 7 presents the actual data used in the analyses. The data were obtained from testing programs at ORNL, EG&G, and Huntington Alloy Products Division of the International Nickel Company,[11] General Electric Company,[12] Allegheny Ludlum Steel Corporation,[13] and the Hanford Engineering Development Laboratory (HEDL).[14]

The maximum expected use temperature for alloy 718 in nuclear applications is 649°C (1200°F). Therefore, in accordance with usual ASME procedures data obtained above 704°C (1300°F) were excluded from the analysis. Analytical results above 649°C were extended only to 10,000 h to avoid the large uncertainties in long-time extrapolations due to the potential metallurgical instability of this alloy at high temperatures.

ANALYSIS OF RUPTURE DATA

The first step in the analysis of available creep-rupture data was to plot the data in terms of stress versus log rupture life in order to identify general trends in behavior. The general trend that emerged from this evaluation was that all heats given a 954°C solution treatment showed fairly similar behavior (Figs. 1–3). The two heats given a 982°C solution treatment appeared similar to each other (Fig. 4) but different from the behavior of the 954°C solution-treated heats. At short times, the 982°C-treated material shows inferior creep rupture resistance to the 954°C-treated material. At longer times, the service exposure appears to negate the effects of the solution treating and the two sets of data converge. The time required for convergence increases as temperature decreases.

The above effects clearly indicate that the differences in behavior are due to the different solution treatment temperatures. The actual physical nature of the effect (grain size, etc.) could not be determined

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Subject: Analysis of Available Creep and Creep-Rupture Data for Commercially Heat-Treated Alloy 718.

Attached are corrected pages 7 and 21 for subject report. They have been printed on self-adhesive stock. Just peel off the backing and affix to the original pages in your copy(ies) of report.

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Table 5. Chemical Compositions of Heats of Alloy 718 Tested

Heat	Chemical composition, wt %														
	C	Mn	P	S	Si	Cr	Ni	Co	Mo	Cu	Al	Nb + Ta	To	Fe	B
C56445	0.05	0.21	*a*	0.006	0.05	18.18	52.16	0.06	3.03	*a*	0.56	5.31	0.76	Bal.	0.004
Y8509	0.06	0.28	*a*	0.007	0.27	18.24	55.61	*a*	2.81	*a*	0.49	4.94	0.77	16.43	*a*
04A4EY	0.04	0.09	*a*	0.007	0.19	19.02	54.01	0.05	3.16	0.04	0.53	5.27	0.97	16.60	*a*
04A9EY	0.04	0.11	*a*	0.007	0.19	19.07	54.06	0.06	3.12	0.05	0.50	5.15	1.06	16.56	*a*
05A3EY	0.04	0.11	*a*	0.007	0.23	18.87	53.87	0.05	3.16	0.05	0.41	5.31	0.93	16.93	*a*
05A5EY	0.04	0.13	*a*	0.007	0.25	18.50	53.95	0.08	3.09	0.10	0.57	5.41	0.98	16.87	*a*
52C9EK	0.07	0.08	0.007	0.007	0.17	18.11	53.44	0.03	3.00	0.11	0.59	5.10	1.08	18.19	0.0034
8-232	0.05	<0.1	0.01	0.004	<0.1	18.30	53.10	0.36	2.95	<0.1	0.51	5.28	1.02	18.40	0.0042
2180-5-9419	0.05	0.23	<0.005	<0.002	0.10	18.02	52.63	0.27	3.02	0.05	0.54	5.13	1.06	Bal.	0.003
2180-5-9422	0.05	0.23	0.005	0.002	0.07	17.71	Bal.	0.33	3.07	0.03	0.52	5.11	1.02	19.02	0.003
2180-6-9457	0.05	0.29	<0.005	<0.002	0.15	18.24	52.17	<0.05	3.05	0.02	0.55	5.16	1.06	19.18	0.003
2180-6-9458	0.05	0.30	<0.005	<0.002	0.19	18.22	52.18	0.06	3.04	0.08	0.64	5.17	0.98	19.29	0.002
2180-4-9478	0.05	0.21	0.005	0.005	0.10	18.21	52.63	0.30	3.05	0.02	0.54	5.08	0.97	Bal.	0.002
2180-4-9497	0.05	0.17	<0.005	<0.005	0.03	18.15	52.37	0.42	3.10	<0.02	0.57	5.08	0.98	Bal.	0.006

[a]Not reported.

Table 6. Characterization of Heats of Alloy 718 Tested

Heat	Product Form	Vendor	Melting Practice	ASTM Grain Size Number	Solution Treatment			Post-Age[a] Cooling
					(°C)	(°F)	(h)	
C56445	25.2-mm pancake	Latrobe	unknown	unknown	982	1800	2	air cool
Y8509	16-mm bar	Huntington	unknown	unknown	982	1800	1	water quench[b]
04A4EY	13-mm forged bar	Huntington	unknown	unknown	954	1750	unknown	air cool
04A9EY	13-mm forged bar	Huntington	unknown	unknown	954	1750	unknown	air cool
05A3EY	13-mm forged bar	Huntington	unknown	unknown	954	1750	unknown	air cool
05A5EY	13-mm forged bar	Huntington	unknown	unknown	954	1750	unknown	air cool[c]
52C9EK	13-mm plate	Huntington	unknown	unknown	954	1750	0.5	unknown
8-232	16-mm bar	Allegheny	unknown	unknown	954	1750	1	air cool
9419	13-mm plate	Cabot	VIM-ESR	8[d]	954	1750	1	air cool[e]
9422	130 × 200 × 460-mm forging	Cabot	VIM-ESR	2–8[d]	954	1750	1	air cool[e]
9457	13-mm plate	Cabot	VIM-ESR	8–9	954	1750	1	air cool[e]
9458	19-mm plate	Cabot	VIM-ESR	8–9	954	1750	1	air cool[e]
9478	13-mm plate	Cabot	VIM-ESR	7[d]	954	1750	1	air cool[e]
9497	19-mm plate	Cabot	VIM-ESR	8[d]	954	1750	1	air cool[e]

[a]All material after solution treatment aged 8 h at 718°C (1325°F), then cooled 56°C/h to 621°C (1150°F), held 8 h, air cooled, except as noted.

[b]Cooling rate from 718°C to 621°C 11°C/h; no hold at 621°C.

[c]Furnace cooled between 718 and 621°C at unknown rate. Held at 621°C to give total aging time of 18 h.

[d]Mill-annealed.

[e]To below 500°C (932°F).

Table 7. Data Used in Analyses of Creep behavior[a]

HEAT	FORM	TEMP (C)	STRESS (MPA)	TIME TO % CREEP STRAIN (H) 0.01	0.1	0.2	0.5	1.0	TIME TO TERTIARY CREEP (H)	CREEP STRAIN TO TERTIARY (%)	RUPTURE LIFE (H)	TOTAL ELONG (%)	RED. AREA (%)
9478	P	538.	1034.	0.	9.	42.	308.	1156.	1400.	1.35	2047.	2.80	9.40
9478	P	538.	965.	0.	59.	640.	3200.	5060.	4550.	0.79	6879.	4.10	13.40
9419	P	538.	1034.	0.	5.	19.	135.	587.	1085.	1.75	1413.	6.00	11.80
9419	P	538.	965.	0.	400.	2700.	7295.	9470.	8025.	0.03	11385.	2.70	9.50
9458	P	538.	1096.	0.	0.	1.	4.	14.	86.	0.90	90.	9.00	17.00
9458	P	538.	1034.	0.	1.	4.	20.	135.	416.	2.30	561.	6.00	12.00
9458	P	538.	1006.	0.	0.	0.	0.	0.	0.	0.0	1029.	9.00	15.00
9458	P	538.	896.	0.	828.	3013.	7505.	9491.	3365.	0.03	11799.	4.00	14.00
9458	P	538.	965.	1.	136.	638.	1501.	2167.	1801.	0.64	2633.	5.00	13.00
9458	P	538.	929.	0.	34.	283.	1351.	2000.	1713.	0.73	3014.	6.00	15.00
8-232	F	538.	827.	0.	0.	0.	0.	0.	0.	0.0	83121.	0.0	0.0
52C9EK	P	538.	965.	0.	0.	5.	100.	1250.	1580.	1.30	1909.	4.10	7.30
Y8509	B	538.	896.	0.	0.	0.	0.	0.	0.	0.0	3791.	5.00	5.00
Y8509	B	538.	896.	0.	0.	0.	0.	1500.	2320.	1.40	2876.	3.50	9.50
C56445	F	538.	1089.	0.	0.	0.	0.	0.	27.	15.30	28.	16.20	23.00
C56445	F	538.	1034.	0.	0.	0.	10.	35.	85.	2.15	133.	7.00	19.00
C56445	F	538.	1000.	0.	0.	0.	18.	45.	0.	0.0	256.	4.30	19.00
C56445	F	538.	965.	0.	50.	195.	720.	0.	805.	0.03	115.	3.40	25.00
C56445	F	538.	924.	0.	17.	37.	1030.	1700.	1500.	0.90	1731.	2.60	28.00
C56445	F	538.	855.	14.	1250.	3600.	5700.	7700.	6200.	0.01	8473.	2.70	17.00
C56445	F	538.	814.	50.	4300.	8600.	14500.	17800.	13200.	0.43	21524.	3.40	23.00
9478	P	593.	1034.	0.	0.	1.	3.	8.	18.	2.22	28.	7.00	14.40
9478	P	593.	931.	0.	8.	29.	85.	135.	120.	0.89	218.	5.00	14.70
9478	P	593.	827.	0.	70.	300.	720.	970.	947.	0.92	1363.	5.80	13.20
9478	P	593.	793.	0.	165.	462.	1035.	1320.	1148.	0.64	1860.	5.90	11.60
9478	P	593.	793.	0.	235.	628.	1355.	1710.	1498.	0.64	2423.	8.00	16.90
9478	P	593.	724.	15.	1050.	2930.	5900.	7238.	6250.	0.58	9830.	10.00	18.80
9419	P	593.	793.	0.	292.	808.	1430.	1725.	1424.	0.47	2421.	11.00	22.30
9419	P	593.	793.	0.	350.	1000.	1750.	2155.	1735.	0.49	2885.	9.20	25.80
9419	P	593.	724.	0.	1160.	2990.	4600.	5420.	4425.	0.44	6791.	6.80	27.30
9497	P	593.	793.	0.	75.	388.	766.	975.	770.	0.53	1447.	6.90	17.10
9497	P	593.	724.	0.	882.	2182.	3455.	4120.	3415.	0.43	5478.	7.10	17.80
9497	P	593.	655.	66.	2240.	6700.	13750.	15640.	13900.	0.56	20900.	6.10	23.20
9422	F	593.	793.	0.	334.	487.	685.	830.	585.	0.32	1092.	4.10	15.20
9422	F	593.	724.	19.	1000.	1480.	2135.	2610.	1845.	0.33	3756.	5.20	14.90
9457	P	593.	793.	0.	198.	610.	1231.	1515.	1315.	0.57	1986.	6.40	21.20
9457	P	593.	793.	0.	192.	660.	1413.	1755.	1490.	0.57	2367.	9.00	24.70
9458	P	593.	863.	0.	11.	34.	137.	194.	177.	0.30	309.	7.00	16.00
9458	P	593.	813.	0.	0.	0.	0.	0.	0.	0.0	1190.	11.00	22.00
9458	P	593.	759.	2.	553.	986.	1452.	1695.	1384.	0.40	2222.	10.00	26.00
9458	P	593.	725.	1.	253.	1239.	2433.	2953.	2392.	0.48	4133.	14.00	30.00
8-232	F	593.	827.	0.	0.	0.	0.	0.	0.	0.0	3875.	6.40	11.60
8-232	F	593.	690.	0.	0.	0.	0.	0.	0.	0.0	19918.	6.60	24.40
52C9EK	P	593.	1034.	0.	0.	0.	1.	2.	0.	0.0	11.	11.10	13.90
52C9EK	P	593.	965.	0.	0.	0.	5.	12.	0.	0.0	20.	5.40	3.50

[a]An entry of 0. in any column indicates no data available.

Table 7. (Continued)[a]

HEAT	FORM	TEMP (C)	STRESS (MPA)	TIME TO % CREEP STRAIN (H) 0.01	0.1	0.2	0.5	1.0	TIME TO TERTIARY CREEP (H)	CREEP STRAIN TO TERTIARY (%)	RUPTURE LIFE (H)	TOTAL ELONG (%)	RED. AREA (%)
52C9EK	P	593.	896.	0.	0.	7.	47.	97.	99.	1.05	168.	5.00	6.40
52C9EK	P	593.	848.	0.	0.	5.	130.	325.	375.	1.23	487.	3.90	4.70
52C9EK	P	593.	800.	0.	0.	8.	90.	600.	780.	1.30	1571.	9.20	14.40
Y8509	B	593.	896.	0.	2.	7.	20.	44.	58.	1.50	87.	5.50	4.50
Y8509	B	593.	827.	0.	7.	29.	72.	144.	0.	0.0	194.	3.50	19.50
Y8509	B	593.	758.	0.	170.	235.	394.	519.	266.	0.25	788.	5.00	10.00
Y8509	B	593.	724.	0.	25.	330.	965.	1360.	1235.	0.69	2705.	6.00	8.00
Y8509	B	593.	690.	0.	510.	1000.	2000.	2840.	2750.	0.80	6189.	16.00	18.00
C56445	F	593.	931.	0.	0.	0.	0.	9.	25.	1.90	28.	3.90	13.00
C56445	F	593.	896.	0.	0.	12.	32.	40.	47.	1.00	62.	4.00	28.00
C56445	F	593.	848.	0.	15.	33.	75.	113.	112.	0.95	152.	4.10	28.00
C56445	F	593.	807.	0.	25.	68.	172.	256.	190.	0.56	368.	4.70	22.00
C56445	F	593.	724.	35.	550.	850.	1350.	1731.	1520.	0.70	2328.	4.20	17.00
C56445	F	593.	648.	40.	4700.	8300.	13000.	10600.	10200.	0.40	10606.	4.10	18.00
C56445	F	593.	593.	165.	8700.	16500.	24000.	28000.	24600.	0.50	33991.	6.50	16.00
9478	P	649.	882.	0.	1.	2.	4.	7.	5.	0.80	12.	4.70	11.90
9478	P	649.	758.	0.	6.	14.	35.	48.	42.	0.71	87.	15.80	21.00
9478	P	649.	690.	0.	23.	69.	130.	160.	134.	0.52	246.	9.90	24.70
9478	P	649.	620.	2.	150.	335.	558.	695.	548.	0.43	1023.	15.90	30.80
9478	P	649.	579.	19.	746.	1020.	1368.	1640.	1188.	0.32	1991.	10.00	24.90
9478	P	649.	552.	18.	485.	1005.	1720.	2175.	1705.	0.40	2767.	8.20	35.90
9478	P	649.	448.	9.	220.	1300.	6000.	8708.	7950.	0.78	11254.	8.90	38.10
9419	P	649.	758.	0.	10.	18.	35.	45.	42.	0.62	90.	9.90	21.80
9419	P	649.	620.	0.	127.	310.	571.	737.	582.	0.52	1089.	13.70	45.70
9419	P	649.	579.	2.	210.	470.	888.	1218.	904.	0.52	1860.	13.40	47.50
9419	P	649.	448.	35.	3264.	5260.	7862.	9482.	6850.	0.35	11076.	8.20	52.20
9497	P	649.	758.	0.	6.	13.	28.	36.	28.	0.54	68.	9.30	15.20
9497	P	649.	620.	0.	140.	282.	455.	558.	435.	0.44	869.	10.00	29.60
9497	P	649.	620.	0.	109.	248.	440.	548.	443.	0.51	868.	12.00	27.60
9497	P	649.	579.	1.	310.	711.	1240.	1560.	1251.	0.51	2178.	10.00	32.90
9422	F	649.	620.	1.	128.	245.	444.	600.	436.	0.48	1019.	9.10	23.10
9457	P	649.	620.	0.	72.	192.	342.	446.	343.	0.51	681.	10.60	23.00
9457	P	649.	620.	0.	111.	234.	381.	470.	367.	0.47	677.	10.90	37.50
9458	P	649.	759.	0.	3.	7.	12.	16.	13.	0.52	26.	8.00	18.00
9458	P	649.	689.	0.	11.	29.	62.	80.	68.	0.70	128.	12.00	24.00
9458	P	649.	621.	1.	70.	157.	251.	314.	250.	0.0	466.	20.00	31.00
9458	P	649.	580.	0.	0.	0.	0.	0.	0.	0.0	932.	18.00	35.00
9458	P	649.	510.	0.	0.	0.	0.	0.	0.	0.0	2707.	15.00	31.70
8-232	F	649.	690.	0.	0.	0.	0.	0.	0.	0.0	221.	9.00	16.80
8-232	F	649.	586.	0.	0.	0.	0.	0.	0.	0.0	2366.	12.90	20.50
8-232	F	649.	552.	0.	0.	0.	0.	0.	0.	0.0	5684.	10.40	16.10
8-232	F	649.	483.	0.	0.	0.	0.	0.	0.	0.0	11023.	10.10	21.20
8-232	F	649.	448.	0.	0.	0.	0.	0.	0.	0.0	13367.	6.50	17.40
8-232	F	649.	345.	0.	2500.	5400.	12700.	20000.	19000.	0.88	28817.	15.00	16.80
8-232	F	649.	276.	0.	0.	0.	0.	0.	0.	0.0	58056.	20.50	33.00

[a]An entry of 0. in any column indicates no data available.

Table 7. (Continued)[a]

HEAT	FORM	TEMP (C)	STRESS (MPA)	TIME TO % CREEP STRAIN (H) 0.01	0.1	0.2	0.5	1.0	TIME TO TERTIARY CREEP (H)	CREEP STRAIN TO TERTIARY (%)	RUPTURE LIFE (H)	TOTAL ELONG (%)	RED. AREA (%)
8-232	F	649.	207.	0.	5000.	12500.	42500.	57500.	51000.	0.73	86776.	34.00	37.10
52C9EK	P	649.	827.	0.	0.	0.	0.	0.	0.	0.0	6.	3.90	9.60
52C9EK	P	649.	758.	0.	0.	1.	10.	19.	19.	0.94	31.	3.70	5.50
52C9EK	P	649.	690.	0.	0.	4.	35.	63.	59.	0.90	121.	8.00	7.80
52C9EK	P	649.	662.	0.	0.	1.	38.	63.	60.	0.80	110.	4.50	9.00
52C9EK	P	649.	634.	0.	0.	4.	70.	157.	172.	1.10	364.	12.30	21.00
52C9EK	P	649.	593.	0.	0.	10.	230.	680.	750.	1.20	1315.	14.30	28.00
05A3EY	F	649.	620.	0.	0.	0.	0.	0.	78.	1.20	170.	32.00	45.00
05A3EY	F	649.	552.	0.	0.	0.	0.	0.	90.	0.70	296.	21.00	45.00
05A3EY	F	649.	448.	0.	0.	0.	0.	0.	550.	0.90	1533.	33.00	46.00
04A4EY	F	649.	620.	0.	0.	0.	0.	0.	80.	1.20	166.	30.00	68.50
04A4EY	F	649.	483.	0.	0.	0.	0.	0.	360.	2.00	739.	30.00	72.50
04A9EY	F	649.	827.	0.	0.	0.	0.	0.	0.	0.0	23.	14.00	18.00
04A9EY	F	649.	620.	0.	0.	0.	0.	0.	146.	0.40	240.	25.00	25.50
04A9EY	F	649.	483.	0.	0.	0.	0.	0.	550.	1.00	977.	8.00	19.50
05A5EY	F	649.	620.	0.	0.	0.	0.	0.	70.	0.45	161.	24.00	63.00
05A5EY	F	649.	483.	0.	0.	0.	0.	0.	425.	1.45	1006.	28.00	68.50
Y8509	B	649.	690.	0.	6.	14.	30.	49.	0.	0.0	138.	19.00	30.00
Y8509	B	649.	690.	0.	8.	14.	27.	40.	0.	0.0	126.	17.00	21.50
Y8509	B	649.	620.	0.	34.	82.	183.	251.	214.	0.68	573.	19.00	40.00
Y8509	B	649.	552.	0.	87.	345.	1200.	1600.	1416.	0.58	2067.	8.50	40.00
Y8509	B	649.	483.	0.	2170.	3650.	5100.	5800.	4680.	0.30	6951.	15.50	44.00
Y8509	B	649.	414.	0.	4000.	7000.	10750.	11900.	10700.	0.30	14024.	13.50	35.00
Y8509	B	649.	414.	0.	3700.	10000.	11400.	12300.	10000.	0.20	13248.	5.00	35.00
C56445	F	649.	793.	0.	0.	0.	0.	0.	5.	0.55	11.	4.30	13.00
C56445	F	649.	745.	0.	0.	0.	1.	24.	20.	0.65	31.	3.20	19.00
C56445	F	649.	662.	0.	15.	32.	54.	85.	68.	0.60	150.	5.40	17.00
C56445	F	649.	630.	16.	102.	220.	380.	500.	417.	0.57	747.	7.00	17.00
C56445	F	649.	538.	0.	135.	830.	2000.	2520.	2230.	0.68	3132.	7.10	19.00
C56445	F	649.	469.	0.	450.	1550.	4800.	5566.	4800.	0.73	7263.	3.10	19.00
C56445	F	649.	434.	0.	770.	1850.	4500.	7200.	5700.	0.69	10232.	8.10	31.00
9478	P	704.	690.	0.	0.	1.	2.	4.	5.	1.17	8.	12.70	18.10
9478	P	704.	586.	0.	3.	8.	17.	23.	19.	0.64	49.	20.20	27.00
9478	P	704.	476.	0.	27.	77.	180.	240.	210.	0.67	338.	9.80	38.30
9478	P	704.	414.	0.	66.	186.	403.	530.	438.	0.59	744.	18.10	39.70
9478	P	704.	365.	6.	345.	480.	717.	863.	745.	0.63	1205.	19.60	35.90
9478	P	704.	241.	6.	221.	522.	1577.	2720.	1980.	0.55	4959.	23.70	56.30
9419	P	704.	365.	0.	66.	217.	554.	773.	668.	0.70	1148.	16.80	55.00
9497	P	704.	414.	1.	100.	198.	475.	623.	529.	0.63	355.	13.60	41.90
9497	P	704.	365.	0.	40.	257.	773.	1027.	388.	0.66	1416.	13.80	35.50
9422	F	704.	365.	0.	140.	426.	939.	1248.	1042.	0.62	1742.	11.10	39.90
9457	P	704.	365.	0.	28.	90.	267.	410.	366.	0.81	708.	14.50	33.70
9457	P	704.	365.	0.	25.	95.	302.	462.	412.	0.79	745.	12.10	33.90
9458	P	704.	621.	0.	0.	1.	3.	4.	3.	0.62	9.	17.00	27.00
9458	P	704.	552.	0.	1.	4.	8.	11.	9.	0.65	27.	20.00	36.00

[a]An entry of 0. in any column indicates no data available.

Table 7. (Continued)[a]

HEAT	FORM	TEMP (C)	STRESS (MPA)	TIME TO % CREEP STRAIN (H) 0.01	0.1	0.2	0.5	1.0	TIME TO TERTIARY CREEP (H)	CREEP STRAIN TO TERTIARY (%)	RUPTURE LIFE (H)	TOTAL ELONG (%)	RED. AREA (%)
9458	P	704.	496.	2.	7.	13.	22.	36.	28.	0.60	76.	16.00	37.00
9458	P	704.	414.	0.	9.	55.	153.	218.	185.	0.67	394.	18.00	32.00
9458	P	704.	345.	0.	0.	0.	0.	0.	0.	0.0	713.	28.00	44.00
9458	P	704.	276.	0.	0.	0.	0.	0.	0.	0.0	1697.	25.00	38.00
8-232	F	704.	517.	0.	0.	0.	0.	0.	0.	0.0	142.	15.90	24.20
8-232	F	704.	345.	0.	0.	0.	0.	0.	0.	0.0	1829.	11.20	18.90
8-232	F	704.	276.	0.	0.	0.	0.	0.	0.	0.0	5099.	17.20	30.50
8-232	F	704.	207.	0.	0.	0.	0.	0.	0.	0.0	7674.	34.10	40.70
8-232	F	704.	172.	0.	0.	0.	0.	0.	0.	0.0	8857.	38.30	50.10
8-232	F	704.	103.	0.	0.	0.	0.	0.	0.	0.0	25135.	41.70	80.00
Y8509	B	704.	483.	0.	4.	10.	45.	91.	0.	0.0	174.	25.00	46.50
Y8509	B	704.	414.	0.	60.	259.	337.	389.	295.	0.30	598.	12.50	41.50
Y8509	B	704.	345.	0.	375.	642.	997.	1050.	925.	0.38	1346.	20.00	42.00
Y8509	B	704.	310.	0.	310.	796.	1167.	1400.	1045.	0.38	1923.	18.50	46.00
Y8509	B	704.	241.	0.	80.	1350.	2600.	3300.	2600.	0.50	5260.	41.00	54.00
C56445	F	704.	469.	0.	0.	12.	36.	61.	80.	1.40	183.	14.60	32.60
C56445	F	704.	414.	0.	37.	110.	270.	350.	310.	0.70	477.	7.10	29.30
C56445	F	704.	379.	0.	14.	95.	400.	593.	580.	0.98	308.	7.50	26.00
C56445	F	704.	303.	0.	21.	410.	1650.	2250.	2120.	0.80	2071.	18.70	34.00
C56445	F	704.	255.	17.	899.	1750.	3500.	4979.	4350.	0.70	6048.	8.70	33.00
C56445	F	704.	593.	0.	0.	0.	0.	6.	7.	1.25	18.	10.20	24.00
C56445	F	704.	524.	0.	0.	0.	0.	38.	0.	0.0	71.	8.10	22.10

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[a]An entry of 0. in any column indicates no data available.

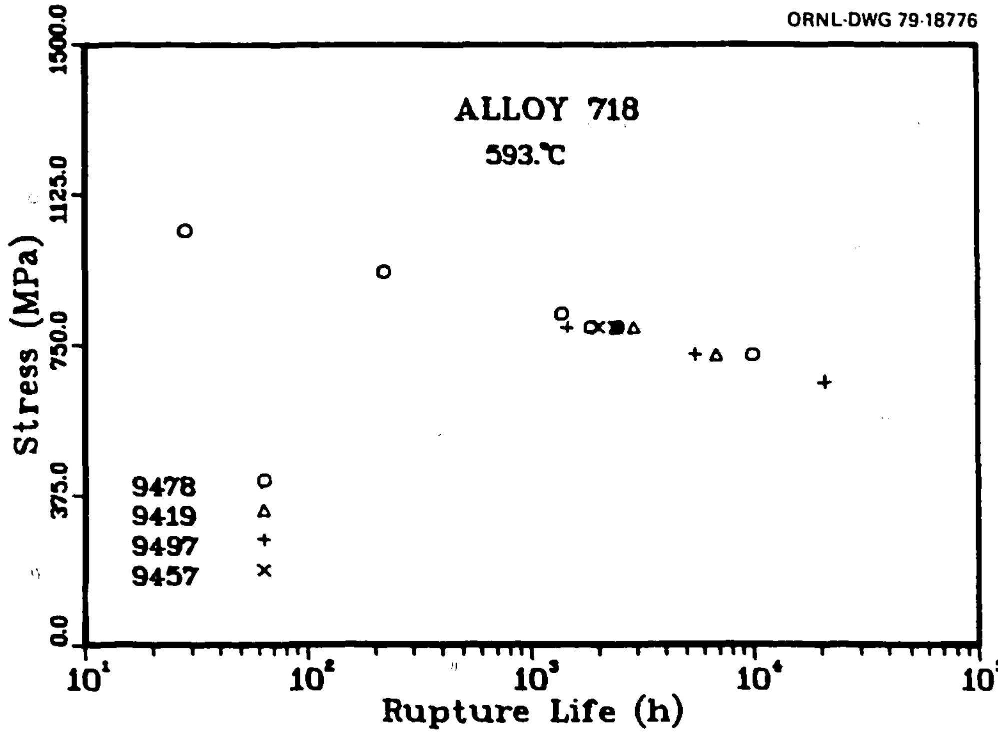

Fig. 1. Creep-Rupture Behavior of Four Heats of Alloy 718 at 593°C (1100°F). All heats solution treated at 954°C (1750°F).

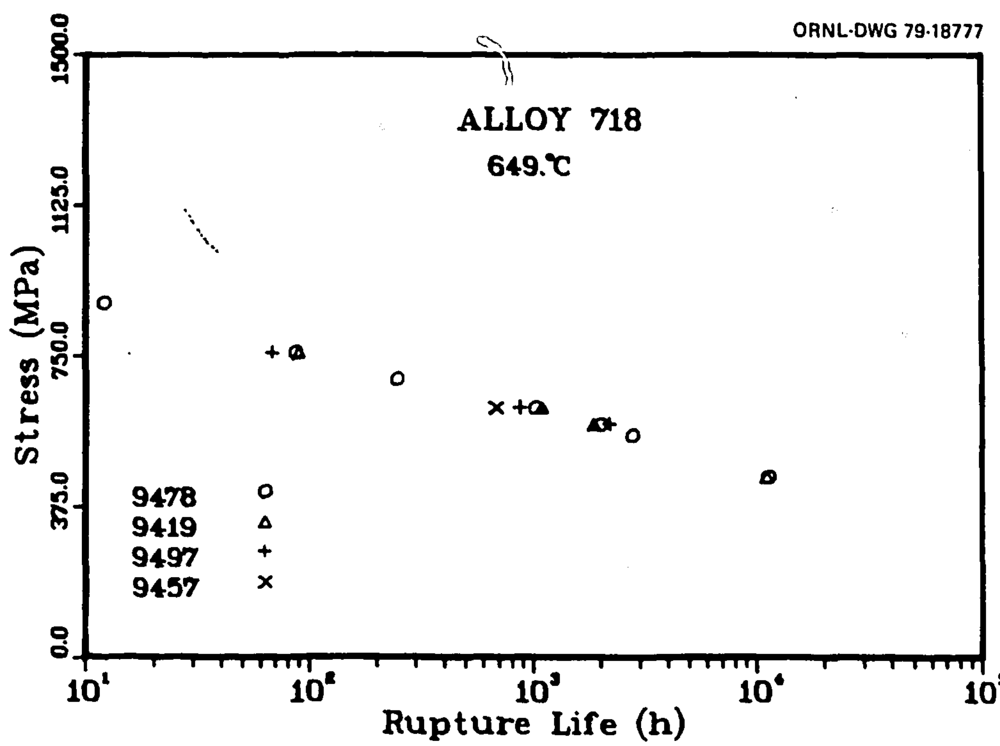

Fig. 2. Creep-Rupture Behavior of Four Heats of Alloy 718 at 649°C (1200°F). All heats solution treated at 954°C (1750°F).

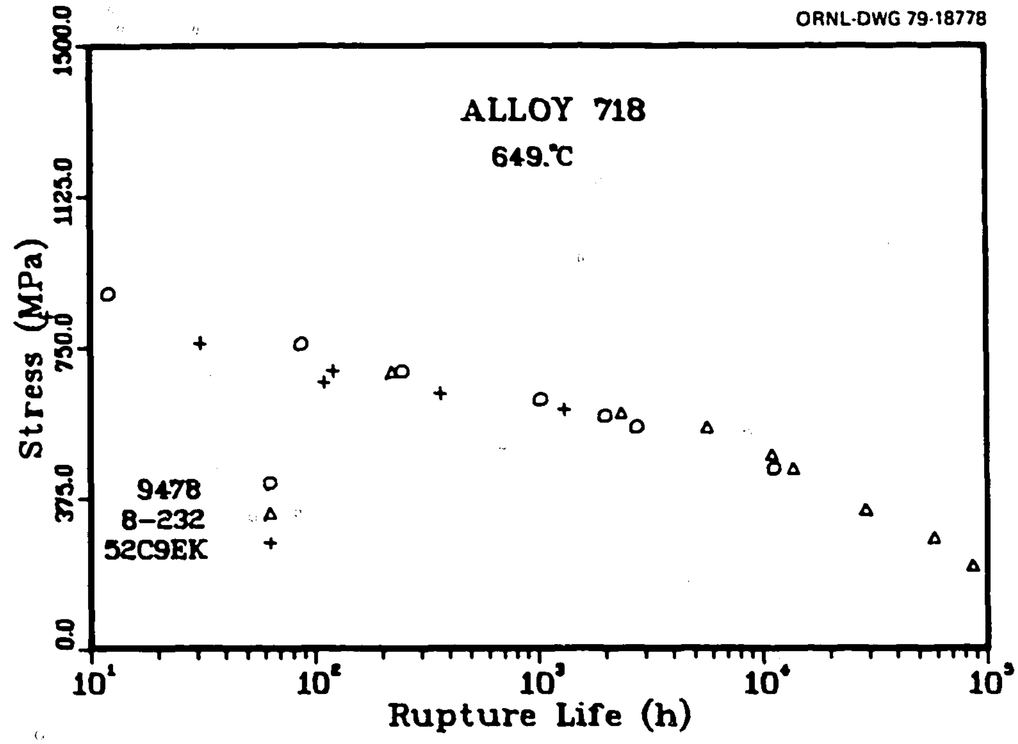

Fig. 3. Creep-Rupture Behavior of Three Heats of Alloy 718 at 649°C (1200°F). All heats solution treated at 954°C (1750°F).

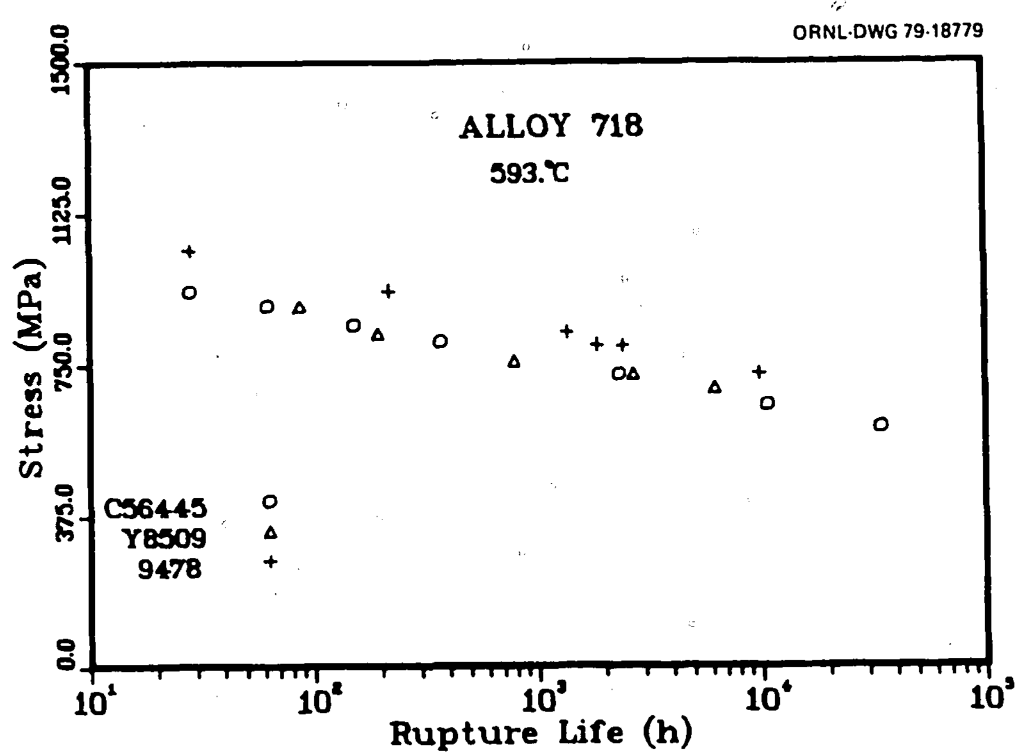

Fig. 4. Comparison of Behavior for Heat 9478 (Solution Treated at 954°C) and Two Heats Solution Treated at 982°C.

from available information. Thus, we attempted to resolve the differences in terms of solution treatment temperature, T_s, alone. Figure 5 shows the relationship that we found between stress for a given rupture life for T_s = 954°C and T_s = 982°C at various test temperatures. The difference between the stress for T_s = 954°C (σ_{954}) and the stress for T_s = 982°C (σ_{982}) is given by

$$\sigma_{954} - \sigma_{982} = \Delta\sigma = \frac{\log \sigma_{982} - 2.7}{0.00242} \qquad (1)$$

for $\sigma_{982} \geq 500$ MPa. For lower stresses, $\sigma_{954} = \sigma_{982}$.

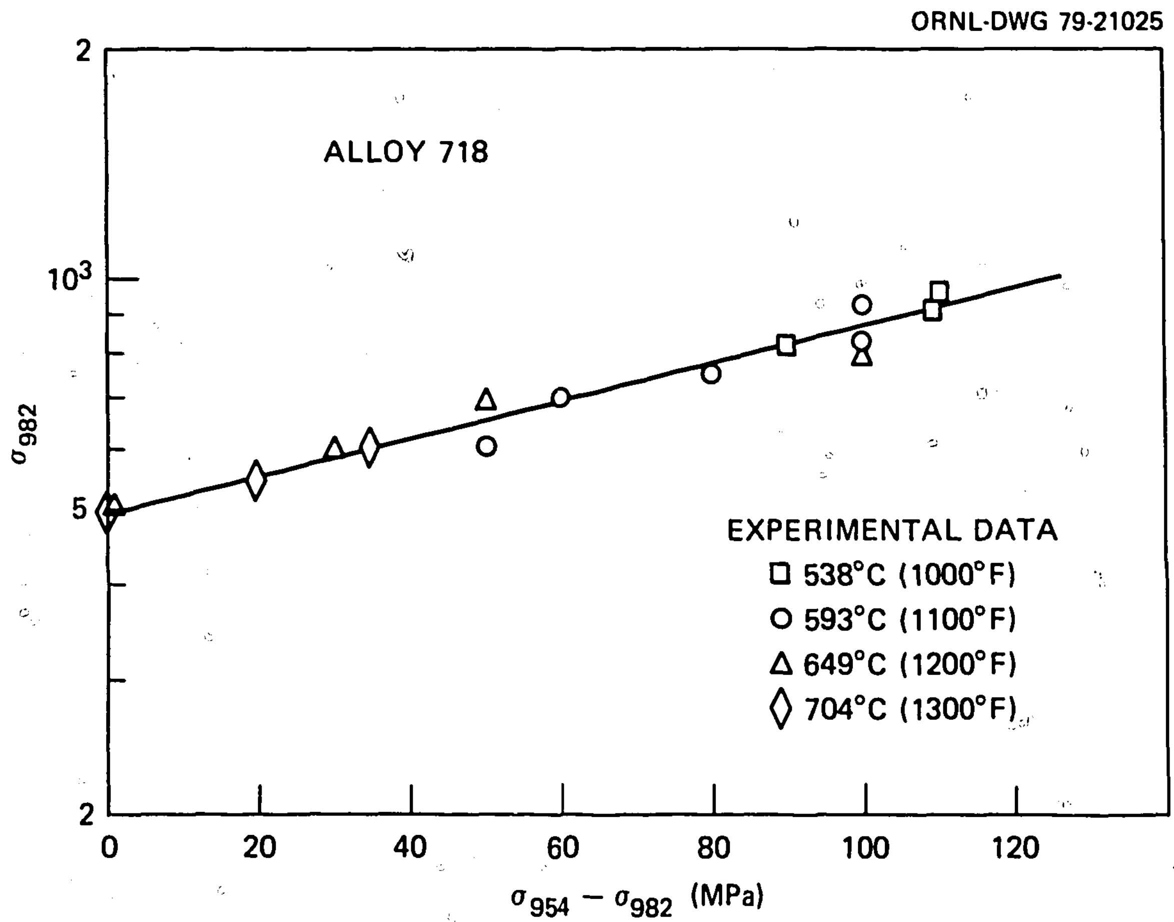

Fig. 5. Relationship Between Rupture Strength of Alloy 718 Solution Treated at Two Different Temperatures. σ_{954} = rupture stress for material solution treated at 954°C; σ_{982} = rupture stress for material solution treated at 982°C.

Equation (1) can be generalized by adding a term involving T_s, but the data available are not sufficient to verify such a relationship. Equation (1) works well for the data used to develop it, but those data are insufficient to provide faith in its general application. We used Eq. (1) to normalize the available T_s = 982°C data to be consistent with the T_s = 954°C data. As a result, the results obtained in these analyses are strictly applicable only to material receiving the 954°C solution treatment even though available specifications generally allow higher solution treatment temperatures.

Initial data fits using the above modification identified five data as being outliers, all from Heat 52C9EK tested at HEDL. These included a test at 649°C, which lasted 4 times as long as a replicate test, and four tests at 538°C for which the time to tertiary creep was approximately equal to the rupture life, indicating a rather sudden brittle-type failure. These five tests were excluded from further analysis.

Once a final data set had been settled upon, the data were analyzed by generalized regression analysis procedures such as have been described elsewhere.[15–17] The different heats (with the above T_s normalization) display only small heat-to-heat variation in strength compared with type 304 stainless steel,[18–19] for example. Still, these variations do exist and could cause significant biases in the fits to this nonhomogeneous data base. The data for various heats do appear to be approximately parallel in terms of log rupture life as plotted against stress at various temperatures. Thus, it is possible to account for the heat-to-heat variations in strength by using the technique of "lot-centering" the data.[17,20] This method provides excellent protection against biases caused by inhomogeneous data distributions.

First assume that the logarithm of rupture life (log t_r)* is the dependent variable for the analysis. Label log t_r as Y. Next assume

*Debate has sometimes arisen as to whether time or stress should be the dependent variable in creep-rupture data analyses. The authors frankly can see no legitimate question over this choice in fitting the data, and it will not be addressed here. References 17, 20, 21, and 22 discuss the subject. The question of which variable one should use in applying design safety factors is somewhat different, however. That question will be addressed later in this report.

that Y can be expressed as a linear function (in the regression sense) of terms involving stress (σ) and temperature (T). Label these terms as X_i. In general form, we thus have

$$\hat{Y}_K = \sum_{i=0}^{N} a_i X_{iK} , \qquad (2)$$

where the a_i are constants estimated by least squares analysis, and $\hat{Y}_K$ is the predicted value of log rupture life at the Kth level of the independent or predictor variables, X_{iK}. Note that X_0 is always unity and that a_0 is a constant intercept term.

As the next step, each variable (Y_K and all X_{iK}) is "lot-centered," and the equation becomes

$$\hat{Y}_{Kh} - \overline{Y}_h = \sum_{i=1}^{N} a_i'(X_{iKh} - \overline{X}_{ih}) , \qquad (3)$$

where the barred variables represent average values for a given lot and h represents the index of the lot involved.* The prediction of log rupture life itself will then be given by

$$\hat{Y}_{Kh} = \overline{Y}_h - \sum_{i=1}^{N} a_i'\overline{X}_{ih} + \sum_{i=1}^{N} a_i'X_{iKh} . \qquad (4)$$

The quantity $Y_h - \sum a_i'\overline{X}_{iKh}$ is a constant for a given lot and replaces the intercept term a_0 in the uncentered analysis. Thus each lot will have a different intercept term, but all other coefficients a_i will be common to all lots.

Lot centering of the data involves no complicated mathematics and can be done by anyone who can add, substract, and divide. However, for large data sets these simple operations can become quite tedious and the

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*In this treatment, a lot is all material that is expected to have the same properties, so one equation will fit a property to an independent variable. In this report a lot corresponds to one heat, but in other cases it may be different, such as one product form or heat treatment of a heat.

centering is best done by computer. Implications of the lot centering are also straightforward, although a first glance at Eq. (4) can leave one lost in the maze of variables and subscripts.

As pointed out above, different lots are treated as having different intercept values, but all other equation constants are lot-independent. Thus all lots vary in parallel manner with all independent variables, but any two lots will always be separated by a constant increment in log t_r space. This assumption of parallelism may or may not be good in any given case. For the data examined here, the assumption was judged to be appropriate. Adjustments that might be made to the method in the case of lack of parallelism were therefore not attempted.

If any lot is represented by a single datum, all lot-centered variables will be zero and that lot will not contribute to establishment of stress and temperature dependence, although it will contribute to the calculation of average and minimum values as described below. If all data for a given lot occur at a single temperature, all pure temperature variables will be zero and that lot will not contribute to the estimation of temperature dependence. Thus lot-to-lot variation is addressed directly and vulnerability of the method to "bad" data distributions is minimized.

Use of lot-centered models to predict average and minimum behavior is described in detail in the Appendix. Suffice it to say here that the method certainly presents an estimate of the average far superior in reliabilty to what could be obtained from fitting the entire data base as a single population without regard to lot-to-lot variations. In its ability to separate the within-lot and between-lot variances, the method also offers superior possibilities for the estimation of minima.

The selection of the particular model form to use in Eqs. (2–4) can be performed exactly as previously described by Booker.[15–17] Details of the model selection procedure will not be repeated here except to reemphasize the power and flexibility of the techniques involved. Literally tens of thousands of potential models can be explored, then reduced to a handful and finally to one with a minimum of tedium for the analyst. Some judgement is still involved, but that is considered more asset than liability. Any method relying strictly on computerized calculations without the opportunity for appropriate human intervention is dangerous at best.

RESULTS

The data listed in Table 7 were analyzed by using the above T_s normalization and the generalized regression model selection procedure with heat-centered data. After the above plotting of the data and preliminary analysis runs to identify possible outliers and behavior trends, the lot-centered data were run through a computer program that examined and ranked (on the basis of R^2, the coefficient of determination) all models involving from two to six terms, with each term being a subset of those shown in one list of Table 8. Thus, a total of 2948 models were examined. The model forms from terms in list 1 provided generally superior results to those in list 2.

After this run, the ten best models with three or four terms from those in list 1 were selected for further study. Of these 20 models many were rejected because of inherently poor behavior on extrapolation or other undesirable characteristics. (Most fit the actual data approximately equally well, as shown in Table 9.) Models chosen for final study are listed (with statistics) in Table 10. Again, most of these models provide virtually equivalent fits to the data; all also behave well on extrapolation, at least over the range of variables required for the current study. Therefore, one could defend the choice of any of these candidate models.

Examination of data plots, residual plots, model forms, etc. led to the choice of the first model (2,4,5,8) from Table 10 as optimum. Fits to data with rupture lives beyond 10,000 h were given special weight and consideration in making this choice. The best fit equation for this model is

$$\log t_r = C_h - 166.381 \log \sigma + 77.007 (\log \sigma)^2 - 11.297 (\log \sigma)^3 - 0.010352T \log \sigma , \qquad (5)$$

where σ is the stress in MPa, T the temperature in K, and t_r the rupture life in h. Values of the heat (lot) constant, C_h, for the individual heats are given in Table 11. The average heat constant (determined as described in the Appendix) was 139.47.

Table 8. Terms used for generalized model selection[a]

Term	List 1	List 2
1	σ	σ
2	$\log \sigma$	$\log \sigma$
3	$1/\sigma$	$1/\sigma$
4	$(\log \sigma)^2$	$(\log \sigma)^2$
5	$(\log \sigma)^3$	$(\log \sigma)^3$
6	T	$1/T$
7	σT	σ/T
8	T log	$(\log \sigma)/T$
9	T/σ	$(\log \sigma)^2/T$
10	$T (\log \sigma)^2$	$(\log \sigma)^3/T$
11	$T (\log \sigma)^3$	

[a]All models considered were composed of terms from one of these lists.

Table 9. Values of R^2 for the Ten Leading Models with Three or Four Terms

Three terms		Four terms	
Terms[a]	R^2 (%)[b]	Terms[a]	R^2 (%)[b]
1,4,6	96.4	1,5,7,11	97.4
1,5,6	96.4	1,5,8,10	97.5
6,7,11	96.6	1,2,4,10	97.5
1,4,10	96.8	1,4,6,8	97.5
1,2,8	96.8	1,3,5,10	97.5
7,8,11	96.9	1,5,9,10	97.5
7,8,10	97.0	1,2,5,10	97.5
1,5,8	97.2	1,4,5,10	97.5
1,4,8	97.2	1,5,10,11	97.5
1,5,10	97.4	1,5,7,10	97.5

[a]Terms take from Table 8, List 1.
[b]Coefficient of determination.

Table 10. Final Candidate Models Chosen for Detailed Study

Terms[a]	R^2 (%)[b]	V_W[c]	V_B[d]
2,4,5,8[e]	97.1	0.0197	0.1253
2,4,5,6[e]	96.4	0.0245	0.1386
1,5,8	97.2	0.0190	0.1209
1,4,5,10	97.5	0.0173	0.1162
1,2,5,10	97.5	0.0173	0.1162
1,5,7,10	97.5	0.0172	0.1169
1,5,10,11	97.5	0.0173	0.1170
1,2,8	96.8	0.0215	0.1181

[a]Terms as listed in Table 8, list 1.

[b]Coefficient of determination.

[c]Within-lot variance.

[d]Between-lot variance.

[e]Added to list of candidates because of inherently stable extrapolation characteristics.

Table 11. Individual Heat Constants from Lot-Centered Regression Fits of the Chosen Model to Creep Data

Heat	Constant
Average	139.47
Av — 1.65SEE	138.84
C56445	139.72
Y8509	139.74
04A4EY	138.86
04A9EY	139.23
05A3EY	138.87
05A5EY	138.92
52C9EK	139.35
8-232	139.85
9419	139.79
9422	139.65
9457	139.63
9458	139.40
9478	139.79
9497	139.72

Note that the above fitting procedure yields a separate estimate of the within-heat variance (V_W) and the between-heat variance (V_B). A good[15–17] practical method for describing minimum expected creep behavior in general is to substract a multiple of the standard error in log time from the predicted average log time. For these data, that multiple could be chosen as 1.65, consistent with common ASME practice.[23] In this case, for individual heats the standard error is defined as $\sqrt{V_W}$. For prediction of overall minimum behavior among all heats, we defined the standard error as $\sqrt{V_B + V_W}$. Figures 6 through 19 compare predicted behavior with experimental data on an individual heat basis. Figures 20 through 23 make the same comparison on an overall basis for all heats involved. In both cases, the solid lines shown represent average predicted behavior either for the particular heat or for the overall data base, whichever is appropriate for the given comparison. The dashed curves are estimated "minimum" behavior based on the average minus twice the appropriate standard error in log time. In all cases, the description of the data is excellent.

ANALYSIS OF TERTIARY CREEP DATA

Available data for time to tertiary creep (t_{ss}) as determined by the 0.2%-offset method were next analyzed, since the stress to cause onset of tertiary creep is one of the criteria used to determine time-dependent allowable stresses. Data for the creep strain to the onset of tertiary creep (e_{ss}) were also examined because a knowledge of t_{ss} and e_{ss} has been found to be useful in describing creep strain-time behavior.[19,24,25]

Previous work[26–28] found that t_{ss} could be related to t_r by an equation of the form

$$t_{ss} = A t_r^{\beta} \, . \tag{6}$$

Detailed study showed that both A and β remained constant over the range of the data examined, being given by 0.442 and 1.0395, respectively. Figure 24 displays this relationship. Note that since the value of β is

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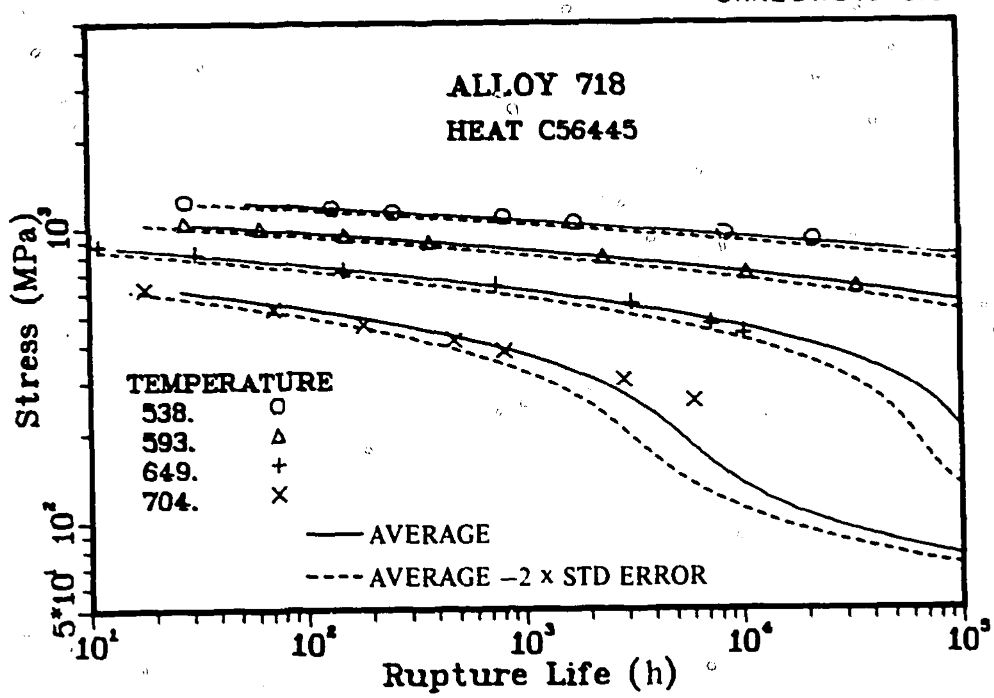

Fig. 6. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat C56445.

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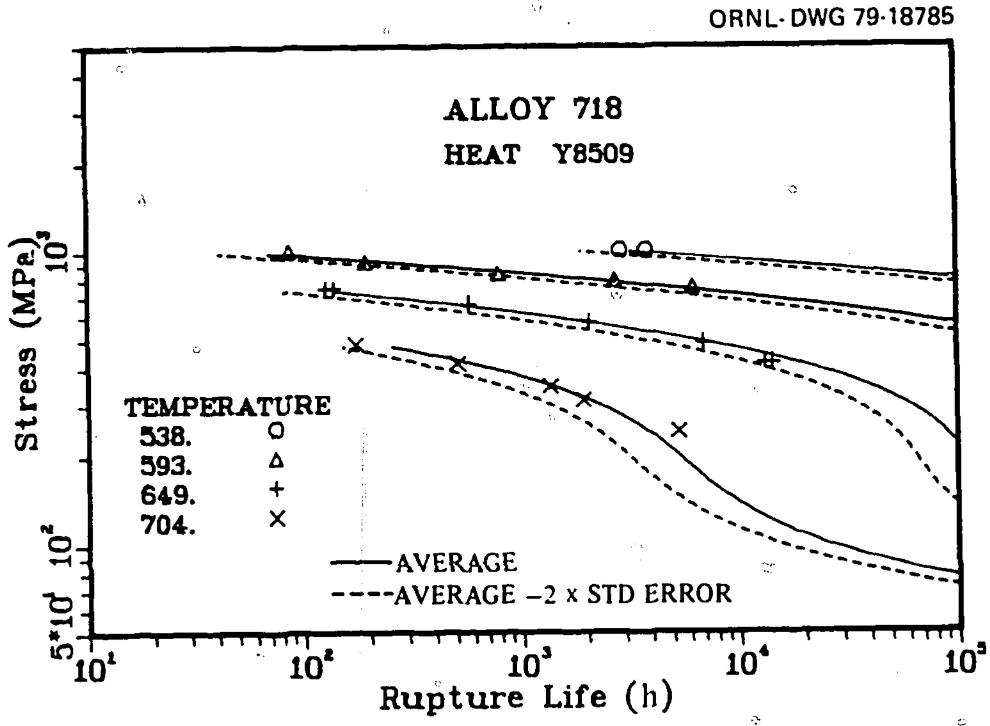

Fig. 7. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat Y8509.

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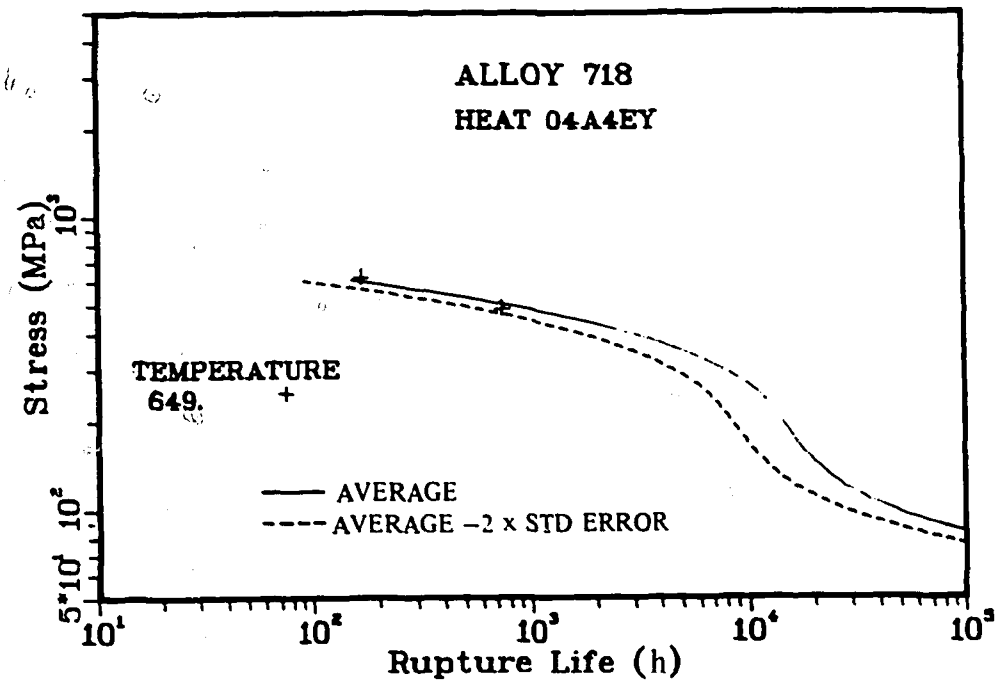

Fig. 8. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy Heat 04A4EY.

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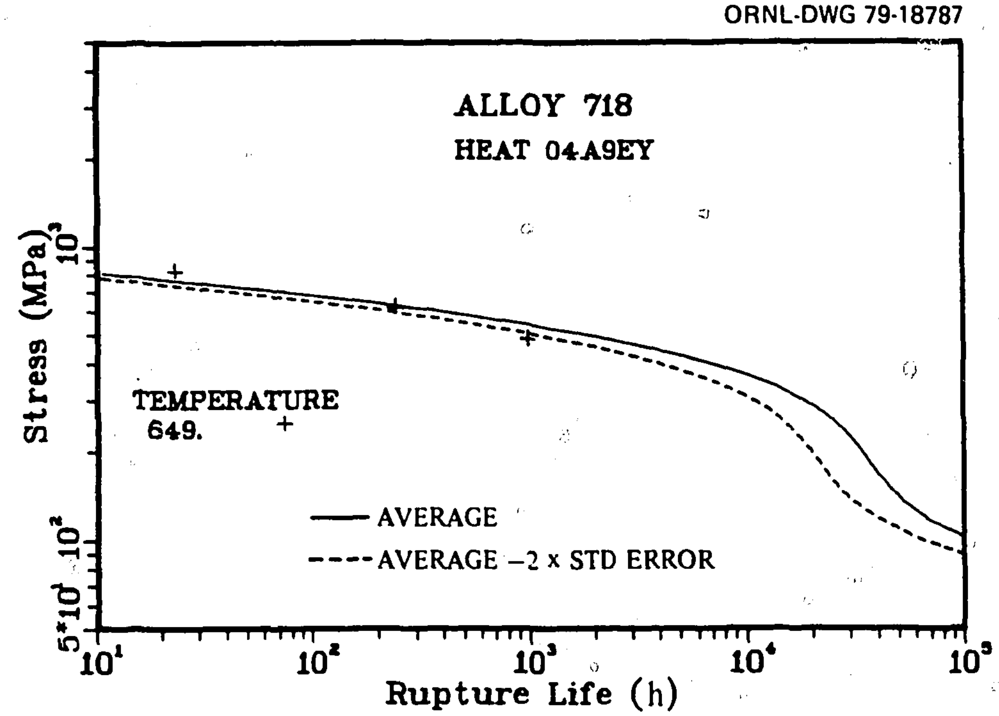

Fig. 9. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 04A9EY.

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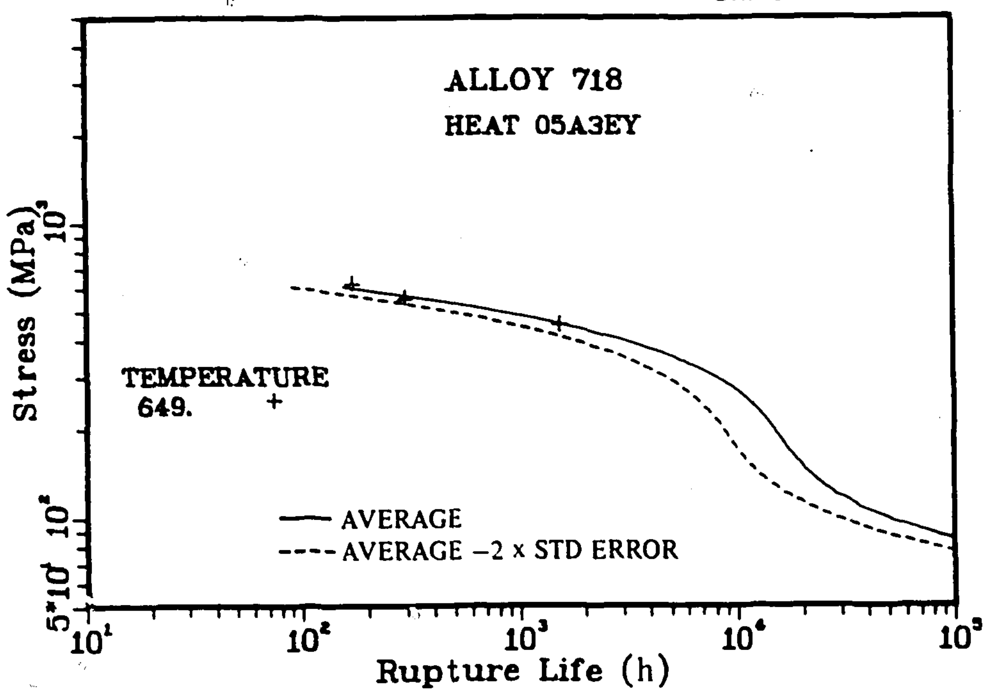

Fig. 10. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 05A3EY.

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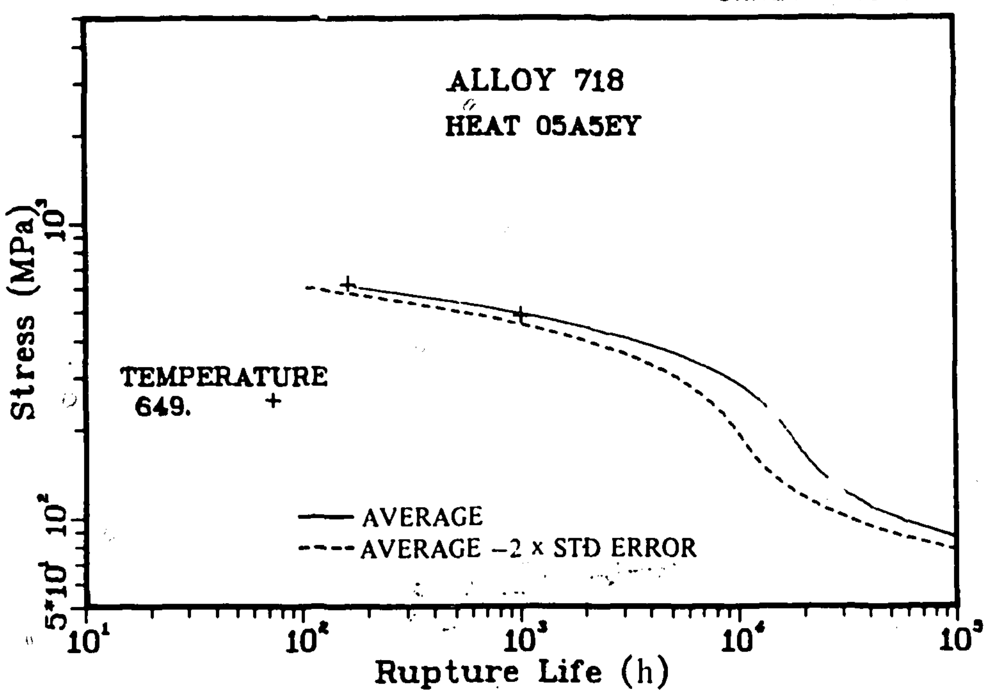

Fig. 11. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 05A5EY.

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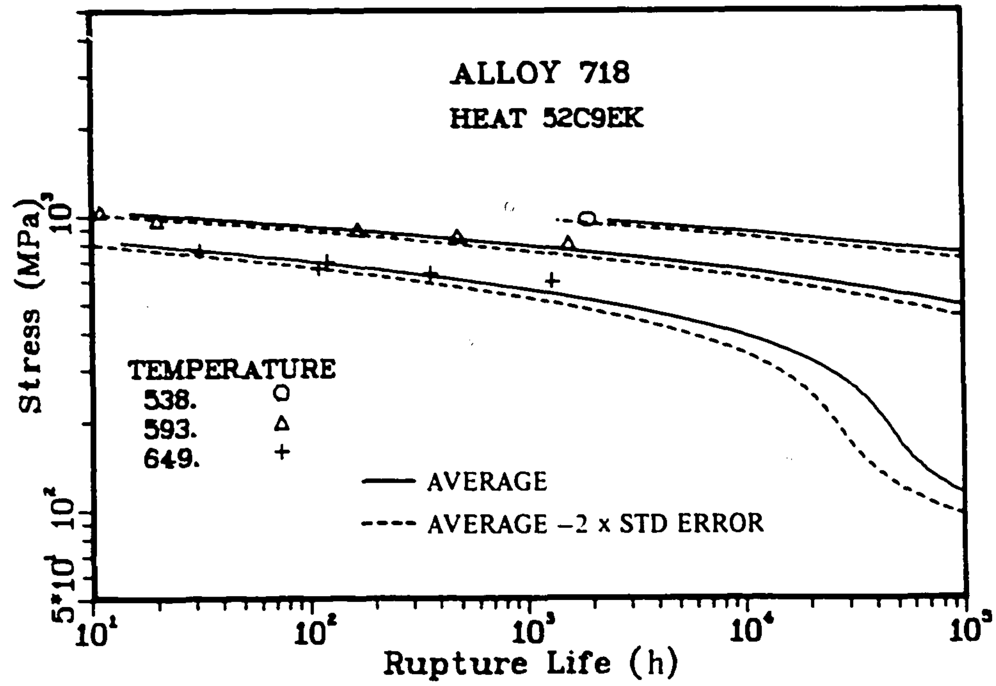

Fig. 12. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 52C9EK.

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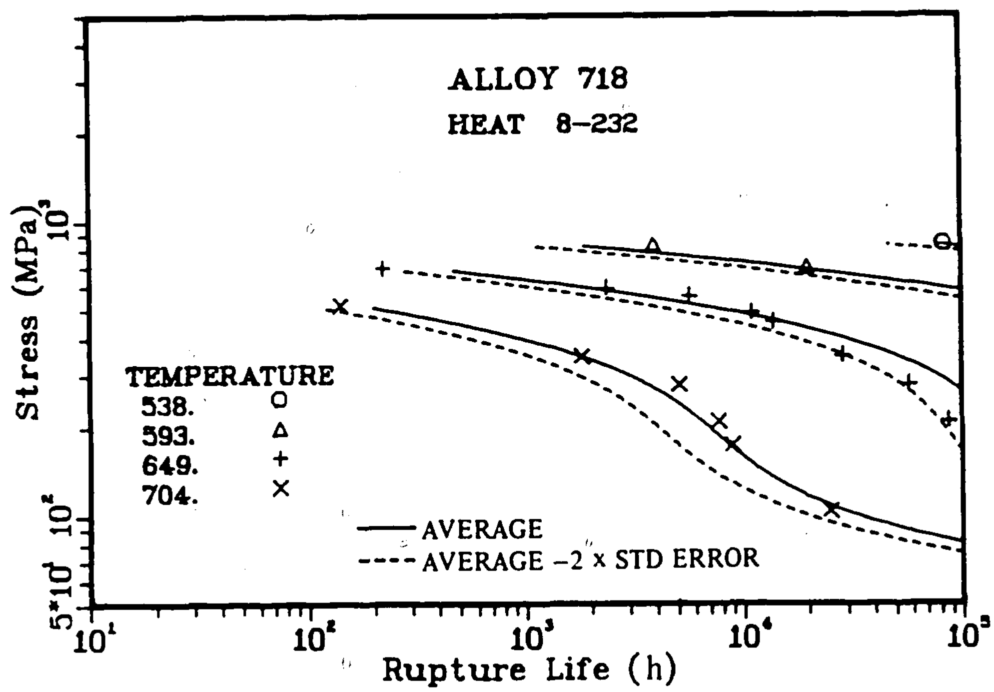

Fig. 13. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 8-232.

ORNL-DWG 79-21012

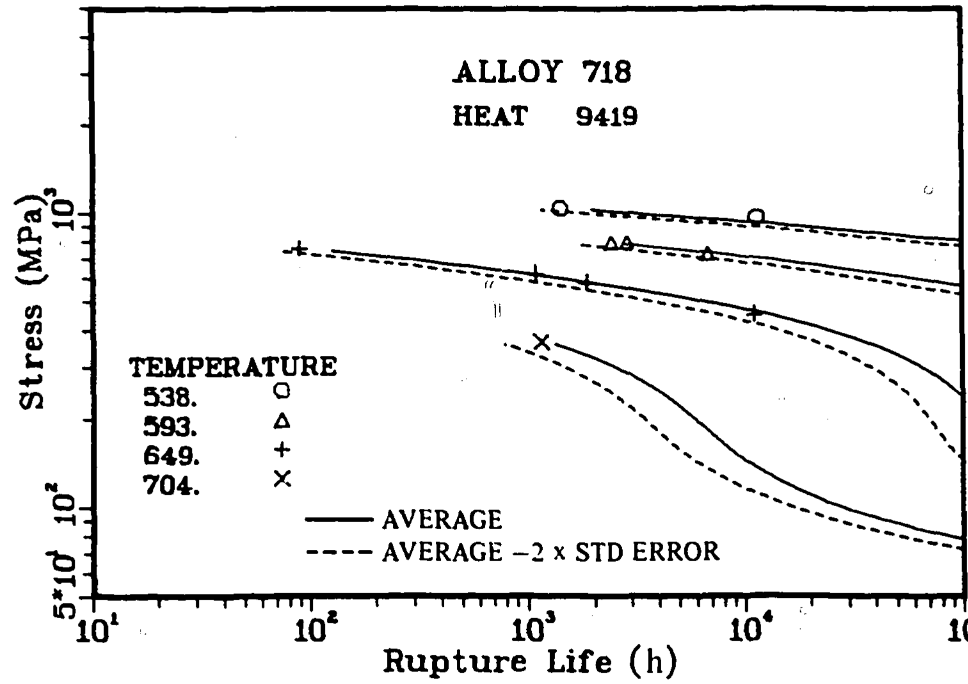

Fig. 14. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9419.

ORNL-DWG 79-21013

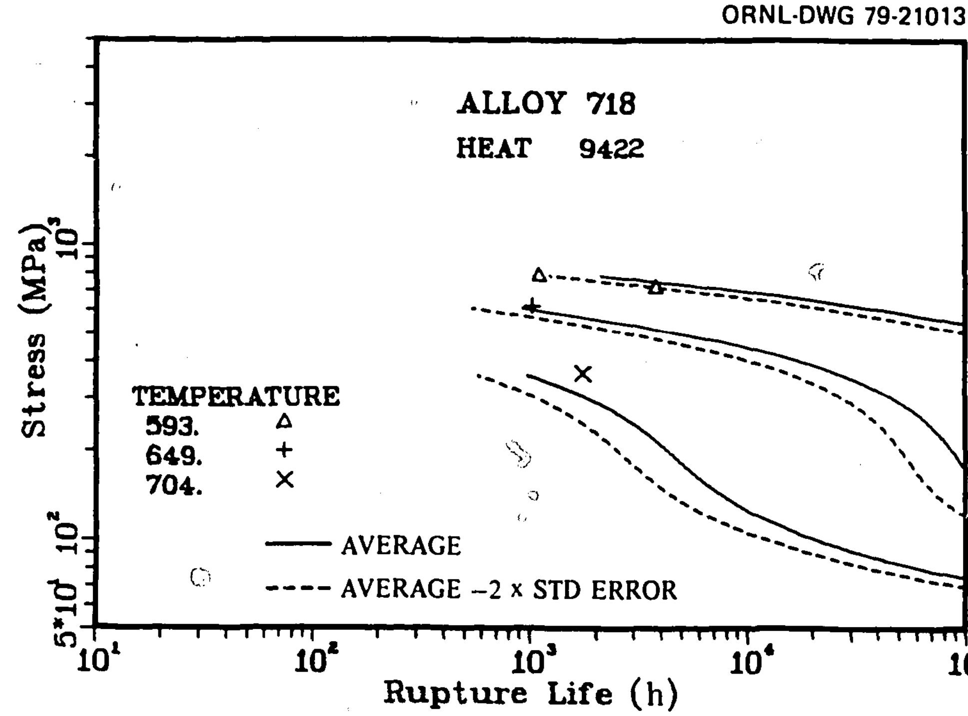

Fig. 15. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9422.

ORNL-DWG 79-21014

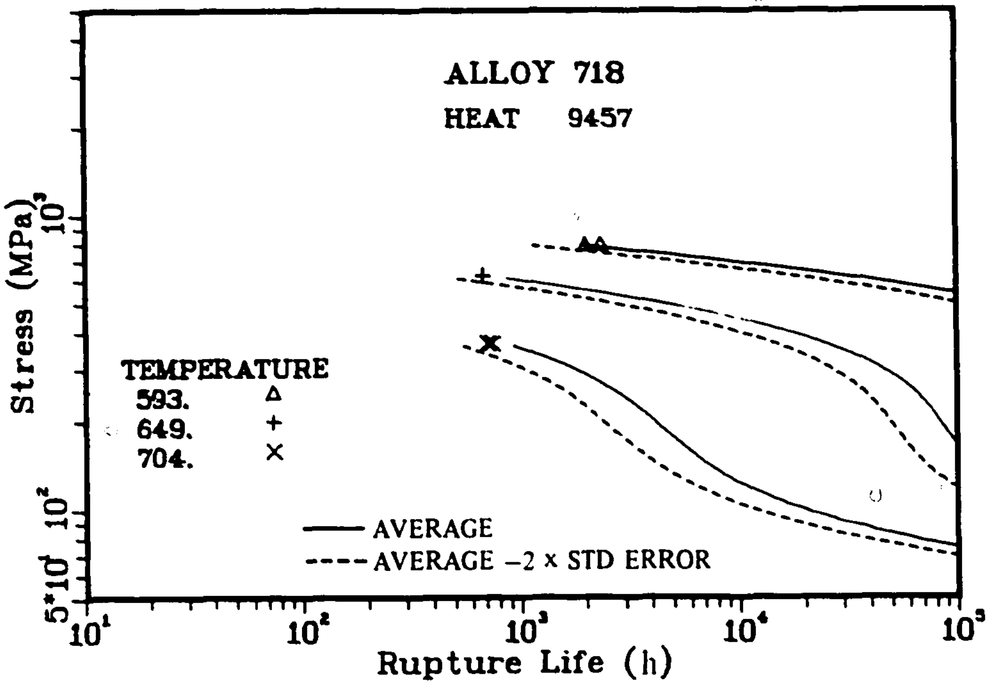

Fig. 16. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9457.

ORNL-DWG 79-21015

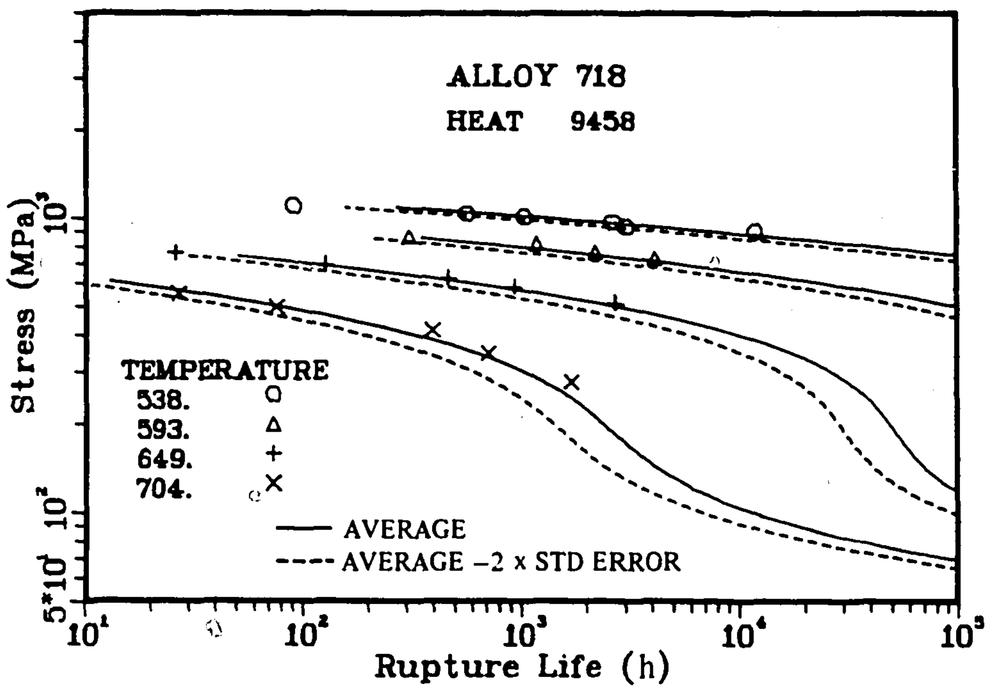

Fig. 17. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9458.

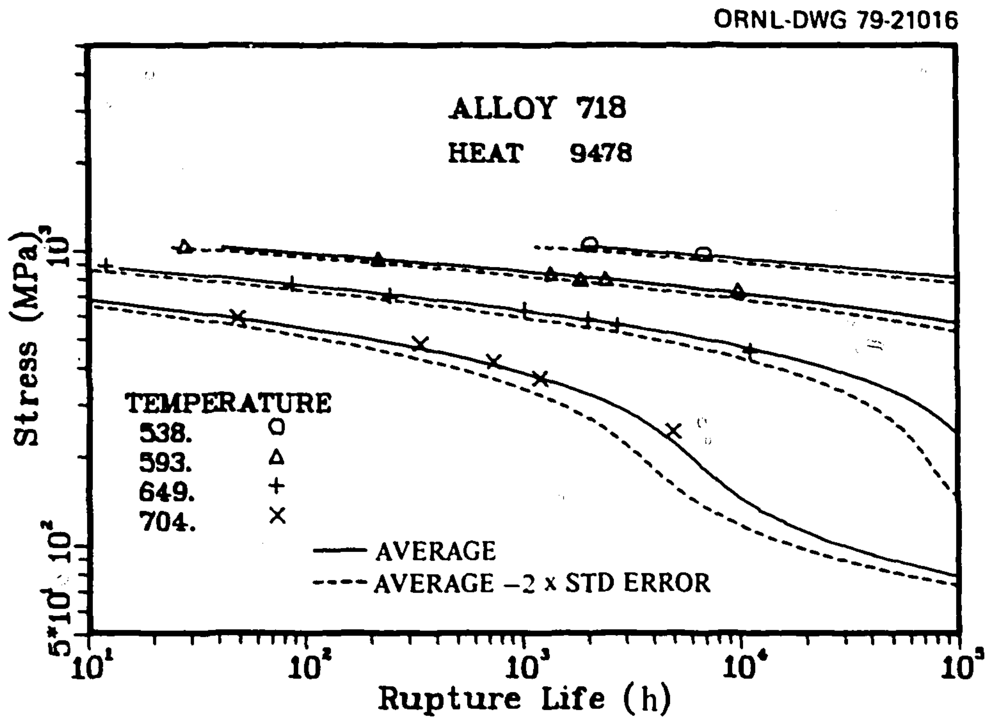

Fig. 18. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9478.

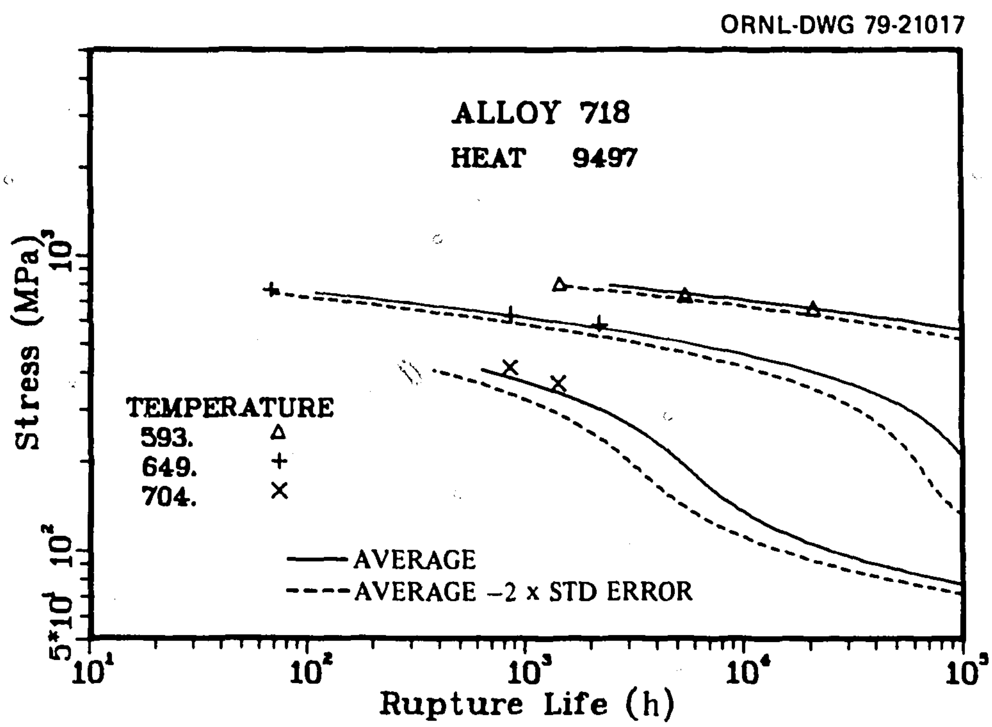

Fig. 19. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Alloy 718 Heat 9497.

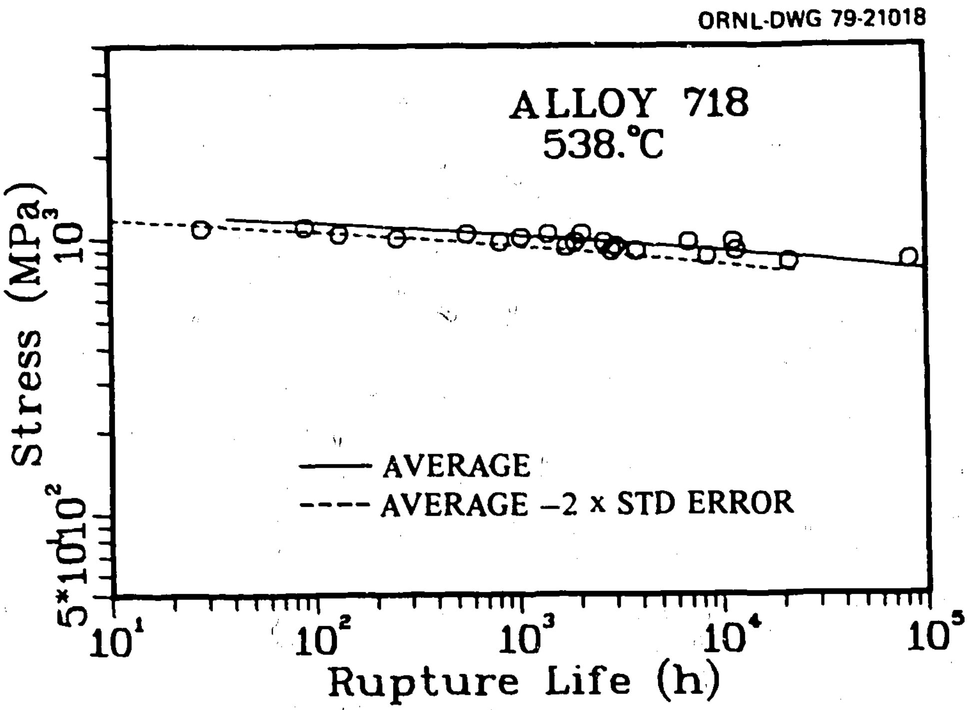

Fig. 20. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Several Heats of Alloy 718 at 538°C (1000°F).

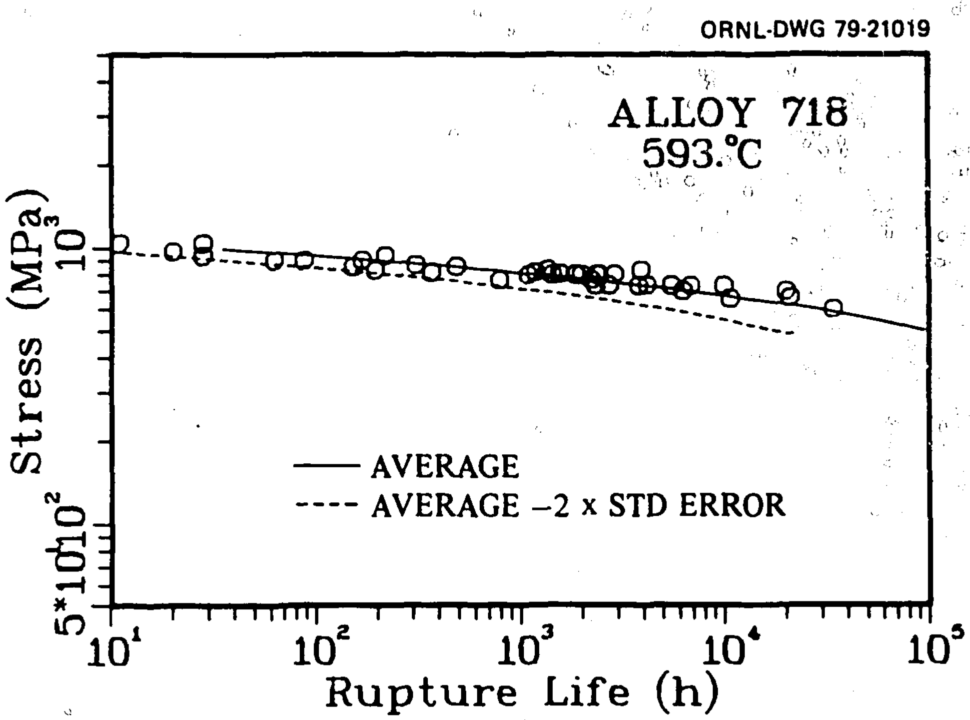

Fig. 21. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Several Heats of Alloy 718 at 593°C (1100°F).

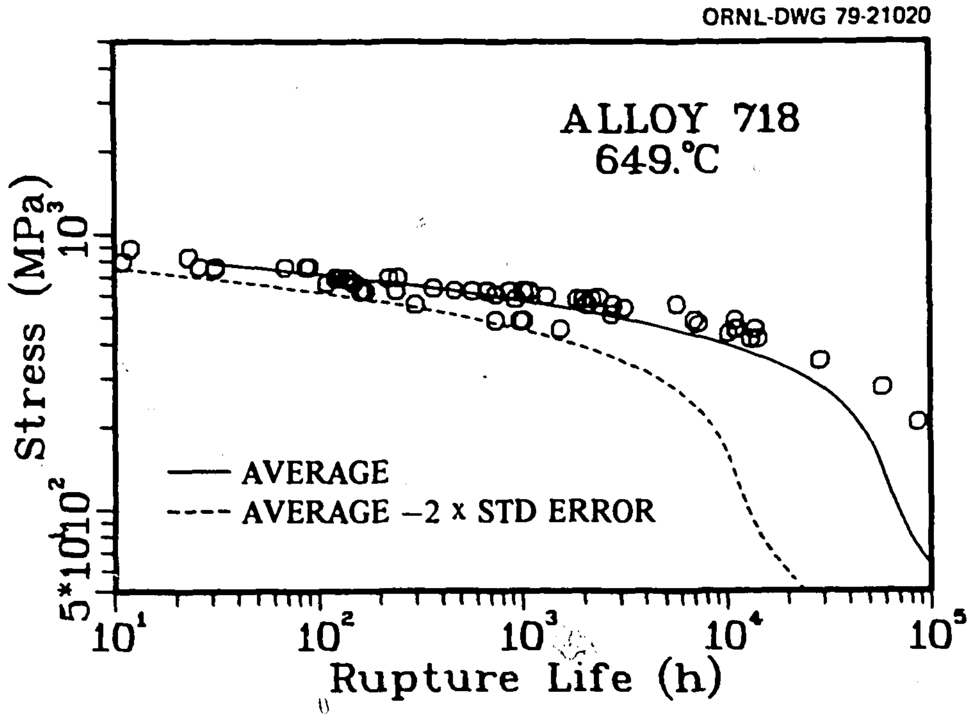

Fig. 22. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Several Heats of Alloy 718 at 649°C (1200°F).

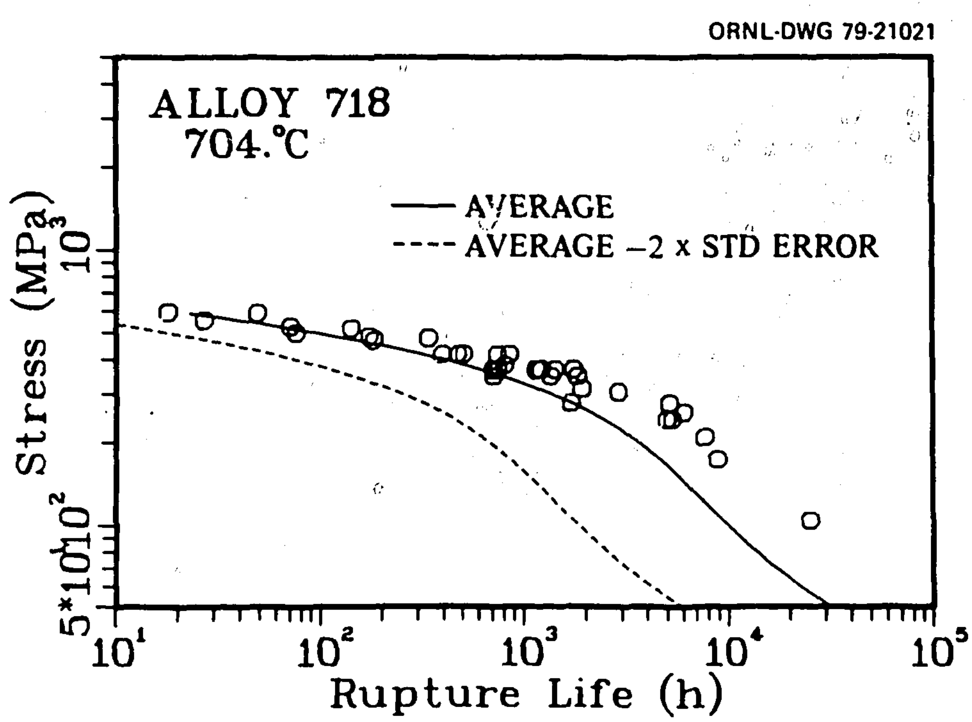

Fig. 23. Comparison Between Predicted and Experimental Creep-Rupture Behavior of Several Heats of Alloy 718 at 704°C (1300°F).

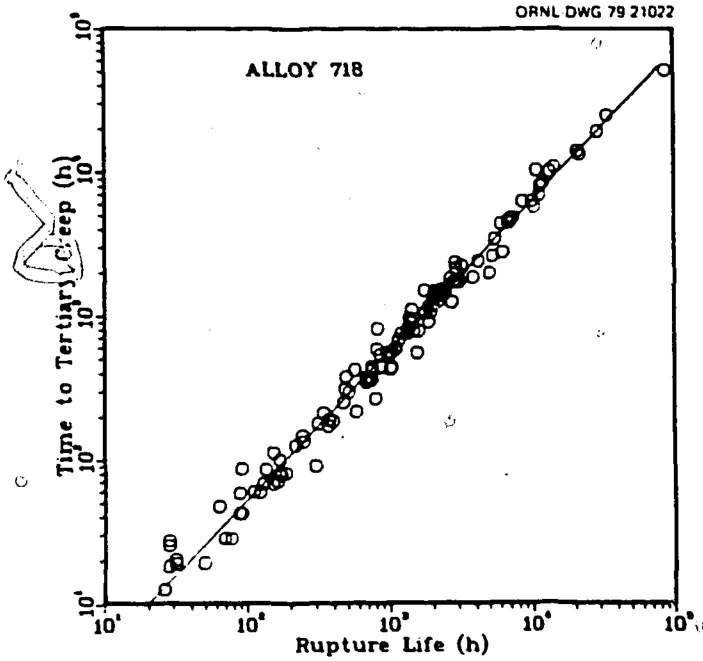

Fig. 24. Relationship Between Rupture Life and Time to the Onset of Tertiary Creep (0.2% Offset) for Alloy 718 (538–704°C).

greater than one, the ratio of t_{ss} to t_r increases with time, and t_{ss} will in fact at some point exceed t_r. This trend obviously becomes unrealistic at some point, but the data indicate that it is accurate up to $t_r = 10^5$ h. At this point $t_{ss}/t_r \approx 0.7$. For this reason, we recommend that the value of t_{ss}/t_r be maintained at 0.7 for longer times. Such an assumption prevents unrealistic predictions and is conservative in the estimation of allowable stresses by the tertiary creep criteria.

Methods for prediction of the strain to tertiary creep, e_{ss}, are discussed elsewhere.[19,24,25,27–29] Briefly, one first defines the average creep rate to the onset of tertiary creep, $\dot{e}_{ss}$, as

$$e_{ss} = (e_{ss} - 0.2)/t_{ss} \ . \tag{7}$$

For the current data a relationship of the form

$$e_{ss} = Bt_r^{-\alpha} \tag{8}$$

described the behavior well. The values of B and α were constant in the temperature range 593 to 704°C, given by 2.142 and 1.151, respectively. However, for the data at 538°C, an adequate fit could be obtained only by using separate B and α values of 34.182 and 1.443, respectively. In the absence of data at other temperatures, we suggest interpolation in log $\dot{e}_{ss}$ vs T space between 538 and 593°C and use of the 538°C constants below 538°C. In general the 538°C curve yields a higher value for $\dot{e}_{ss}$ at a given value of t_r. However at very long times the curves cross over. It might be more reasonable to expect that the curves simply converge. Therefore we recommend that the high-temperature curves be used at all temperatures in such cases (t_r > 11,000 h). Figures 25 and 26 compare the predictions of Eq. (7) with experimental data.

Equations (6) and (7) can be combined to yield predictions for e_{ss}, since $e_{ss} = \dot{e}_{ss} t_{ss}$. Figure 27 compares predicted values for e_{ss} with experimentally observed values. The data show a large amount of scatter, but the predictions do a good job of describing the data trends.

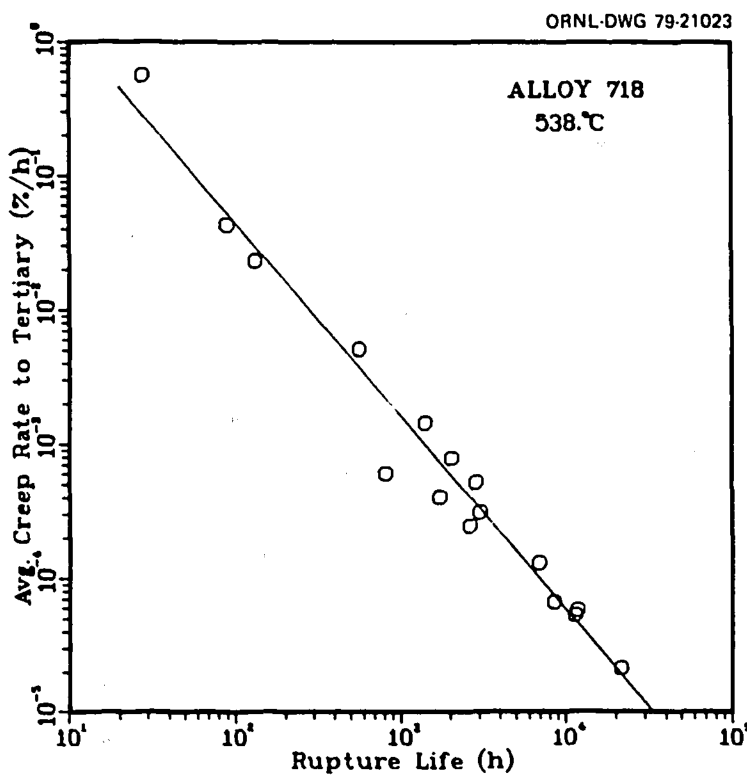

Fig. 25. Relationship Between Rupture Life and Average Creep Rate to the Onset of Tertiary Creep for Alloy 718 at 538°C.

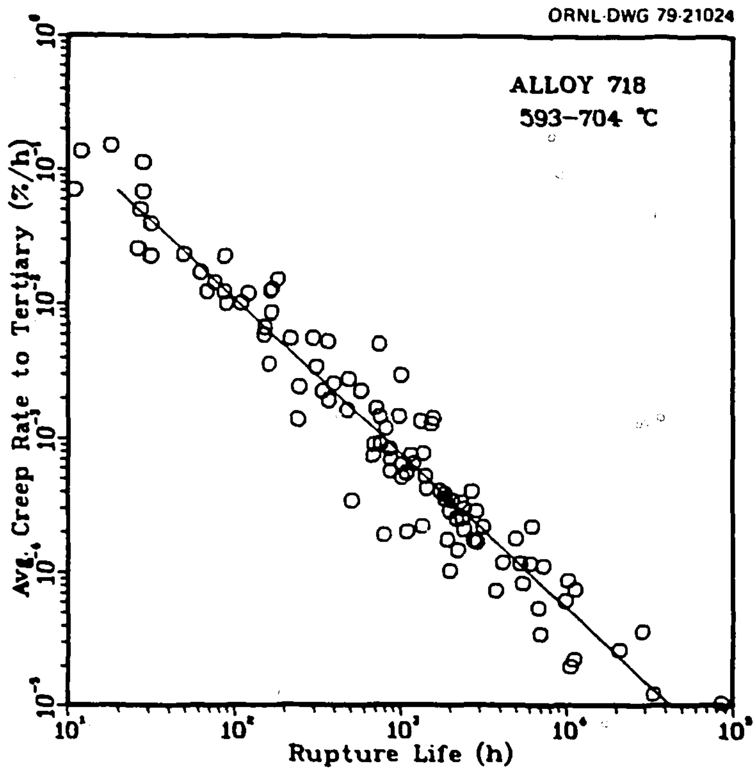

Fig. 26. Relationship Between Rupture Life and Average Creep Rate to the Onset of Tertiary Creep for Alloy 718 at 593 to 704°C.

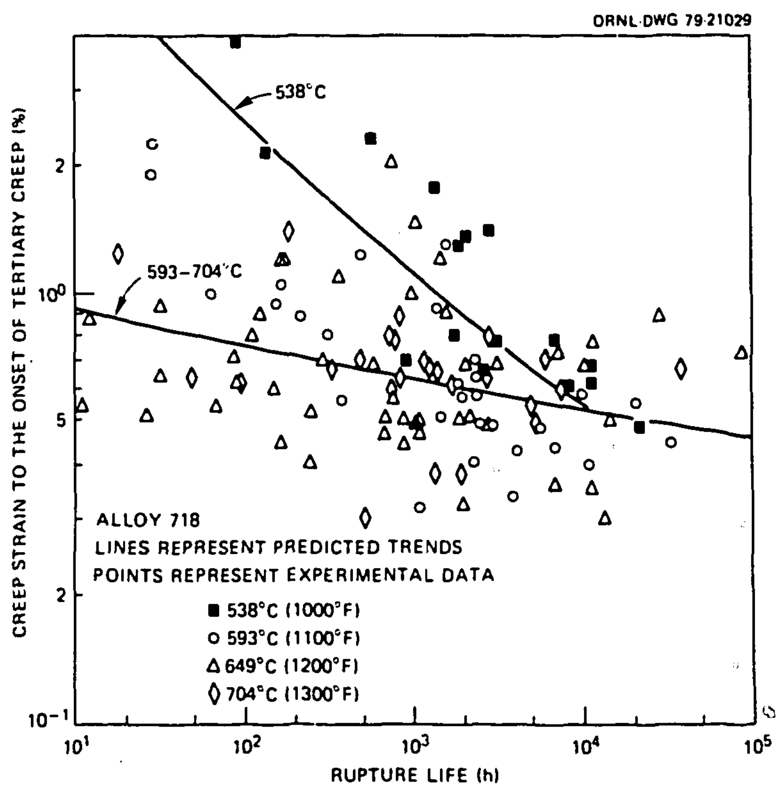

Fig. 27. Comparison of Predicted and Experimental Values of Creep Strain to the Onset of Tertiary Creep for Alloy 718.

CREEP STRAIN-TIME BEHAVIOR

In a previous analysis[24] of the creep strain-time behavior of a single heat of alloy 718, the concept of a "master creep curve" was used to represent the data. As illustrated in Figs. 28 through 30, the curve was constructed by plotting normalized creep strain ($e^* = e/e_{ss}$) versus normalized time ($t^* = t/t_{ss}$). Within normal data scatter, the normalized creep data at all stresses and temperatures appeared to fall on a single "master" curve. Data for three other heats also appeared consistent with this curve. This "master creep curve" was analytically represented as

$$e^* = \exp[1.75(t^* - 1)](t^*)^{0.2} \ . \tag{9}$$

Initial comparison of the current more comprehensive data set with the predictions of Eq. (9) showed good agreement (Figs. 31–33).

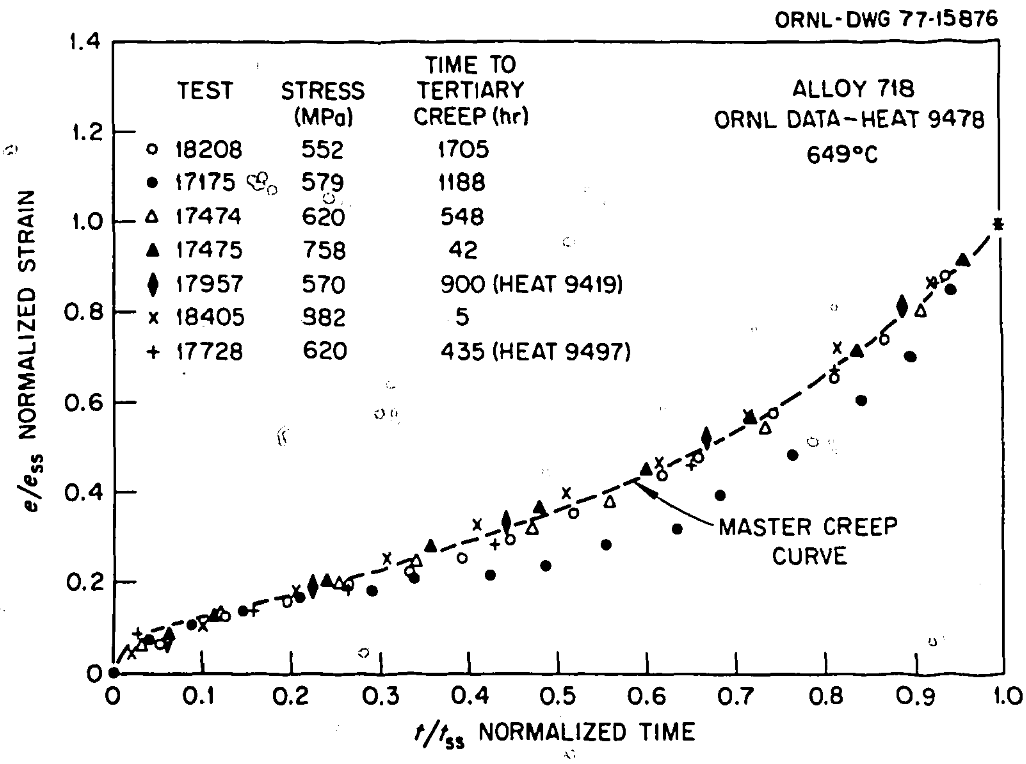

Fig. 28. Normalized Creep Curves for ORNL Data at 593°C.

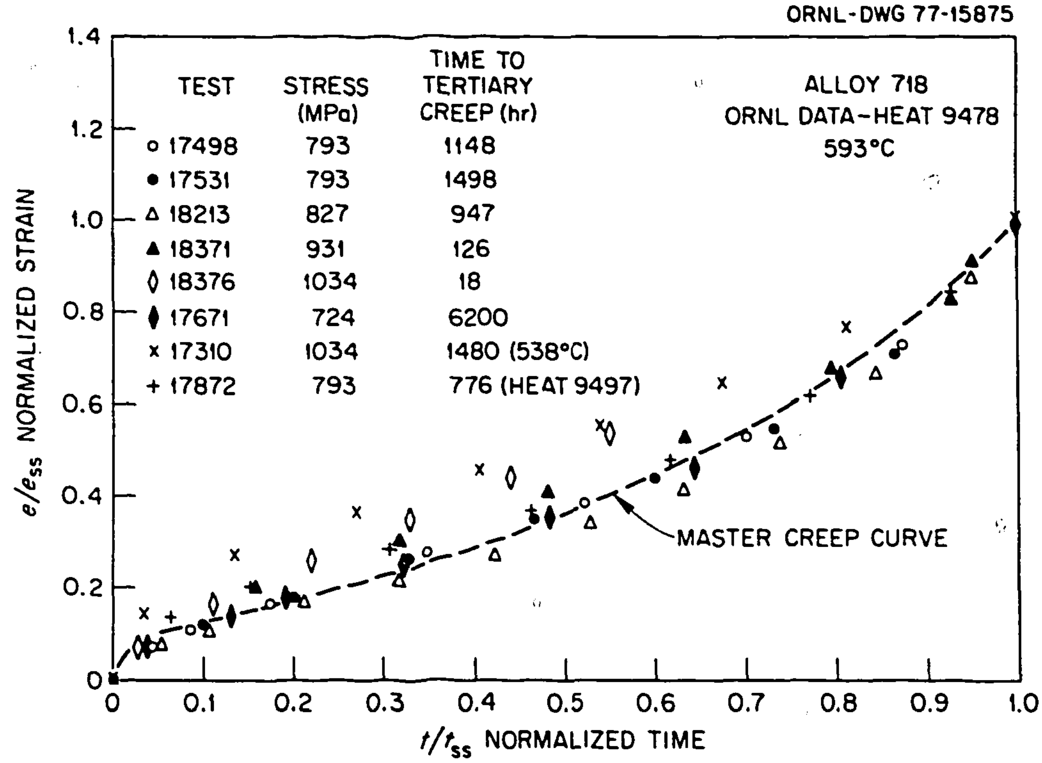

Fig. 29. Normalized Creep Curves for ORNL Data at 649°C.

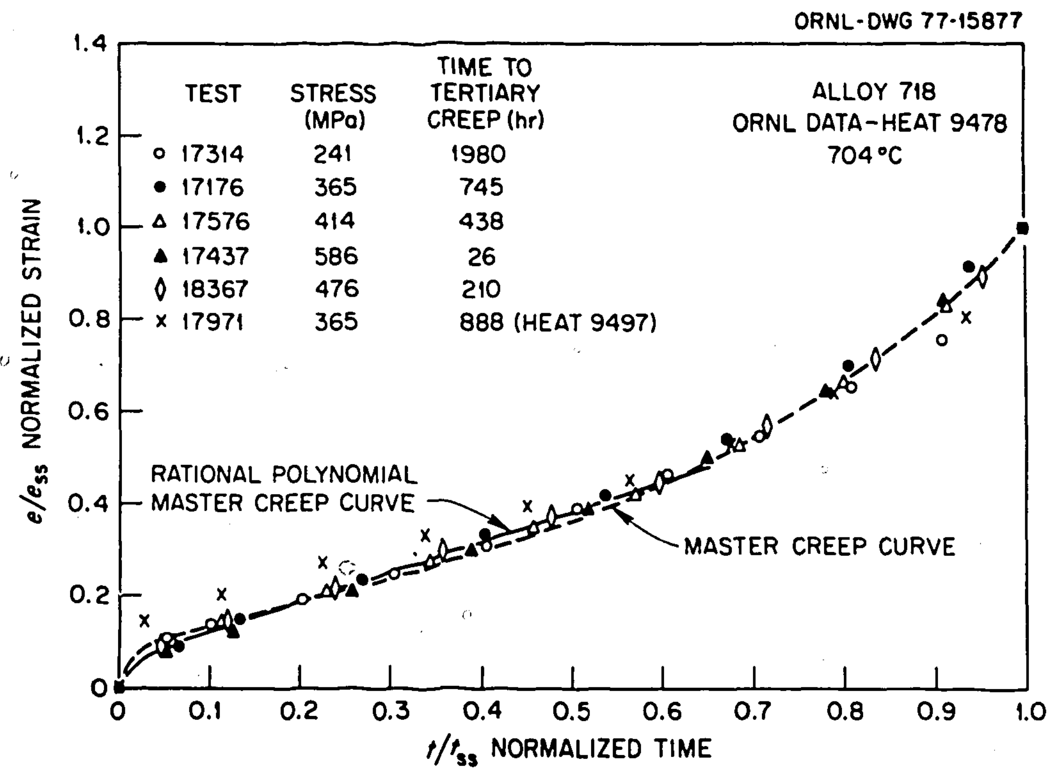

Fig. 30. Normalized Creep Curves for ORNL Data at 704°C.

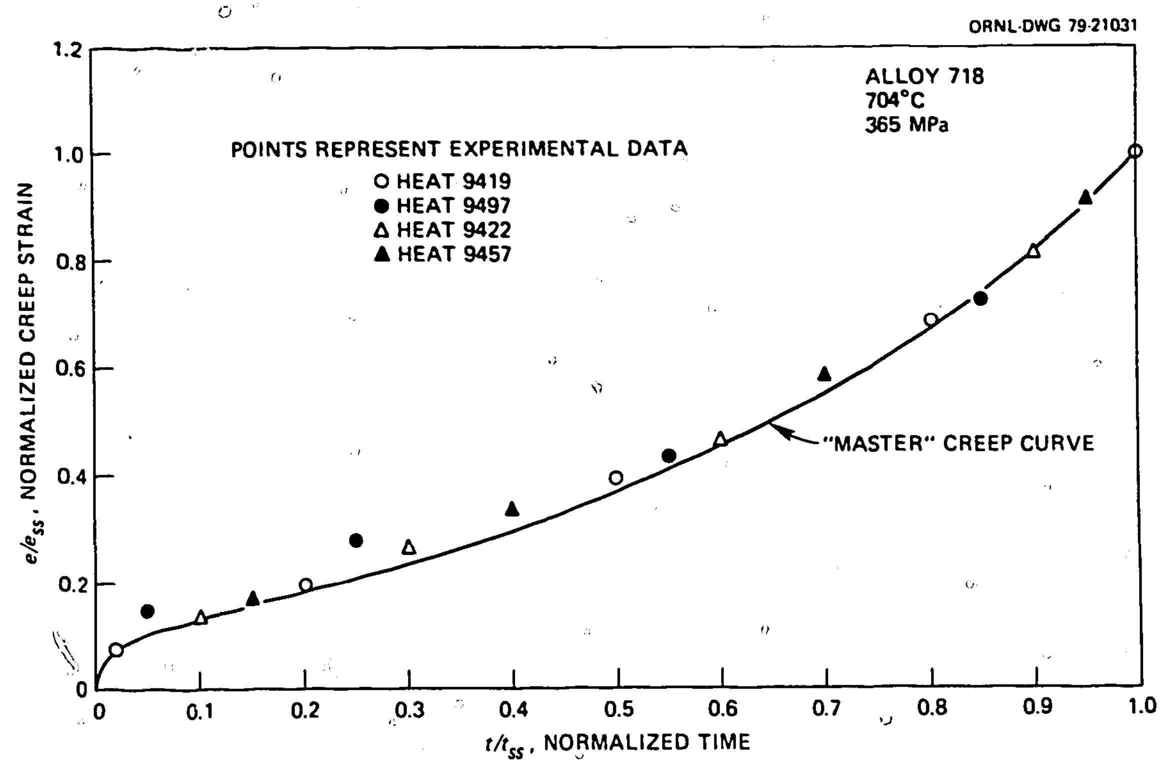

Fig. 31. Normalized Creep Curves for Several Heats of Alloy 718 at 704°C.

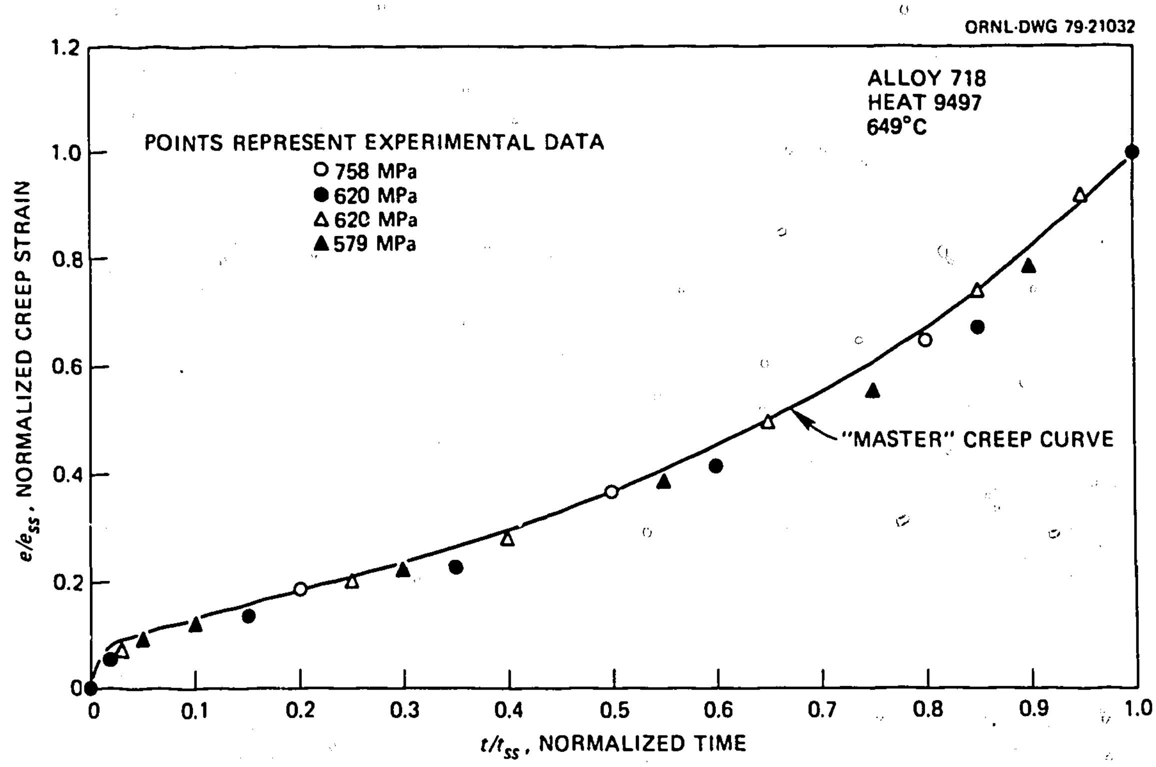

Fig. 32. Normalized Creep Curves for Heat 9497 of Alloy 718 at 649°C.

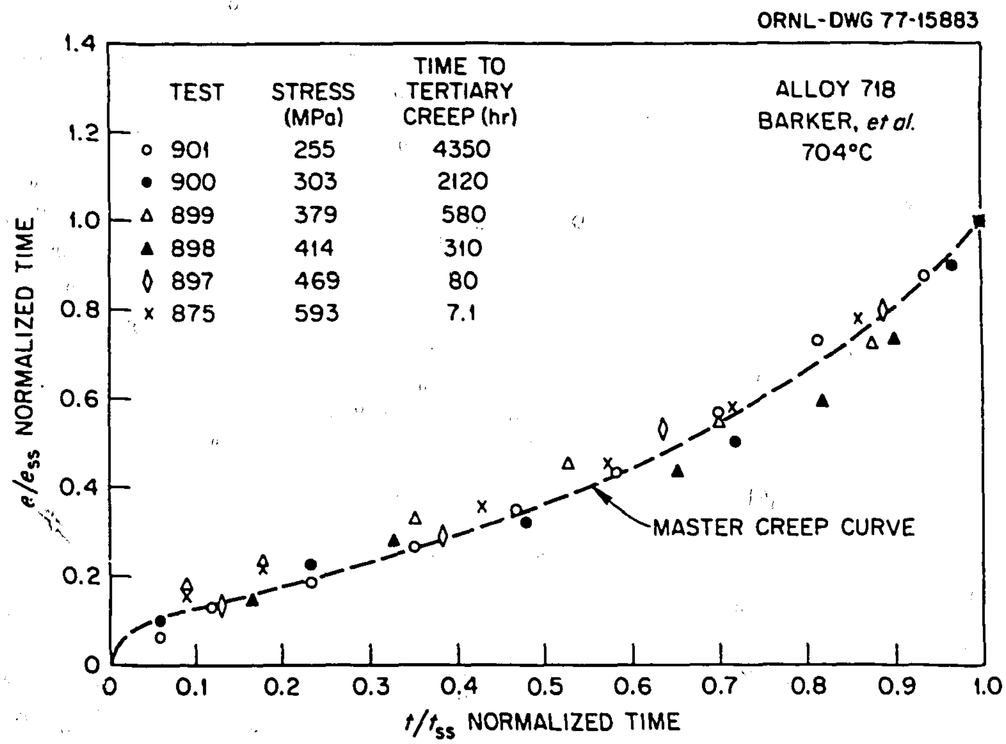

Fig. 33. Normalized Creep curves for Heat C56445 of Alloy 718 at 704°C.

However, it was noted that tests yielding high (>1%) values of e_{ss} tended to produce normalized creep curves falling above the master curve. Tests yielding low (<0.5%) values of e_{ss} tended to produce normalized curves falling below the master curve. The source of this trend can be divined from an examination of the geometric properties of the master curve.

Figure 34 shows the master curve, including delineation of several geometric properties of that curve. The curve does not have a true linear region, but the normalized linear creep rate, $\dot{e}^*_m$ can be approximated by a line through $t^* = 0.05$ and $t^* = 0.4$. This line intersects $t^* = 1$ at a value of e^* denoted as e^*_3. Since we are using a 0.2%-offset value for e_{ss}, e^*_3 is defined as

$$e^* = (e_{ss} - 0.2)/e_{ss} \; . \tag{10}$$

Thus, if e_{ss} changes significantly, the value of e^*_3 will be changed enough to alter the geometric properties of the master curve.

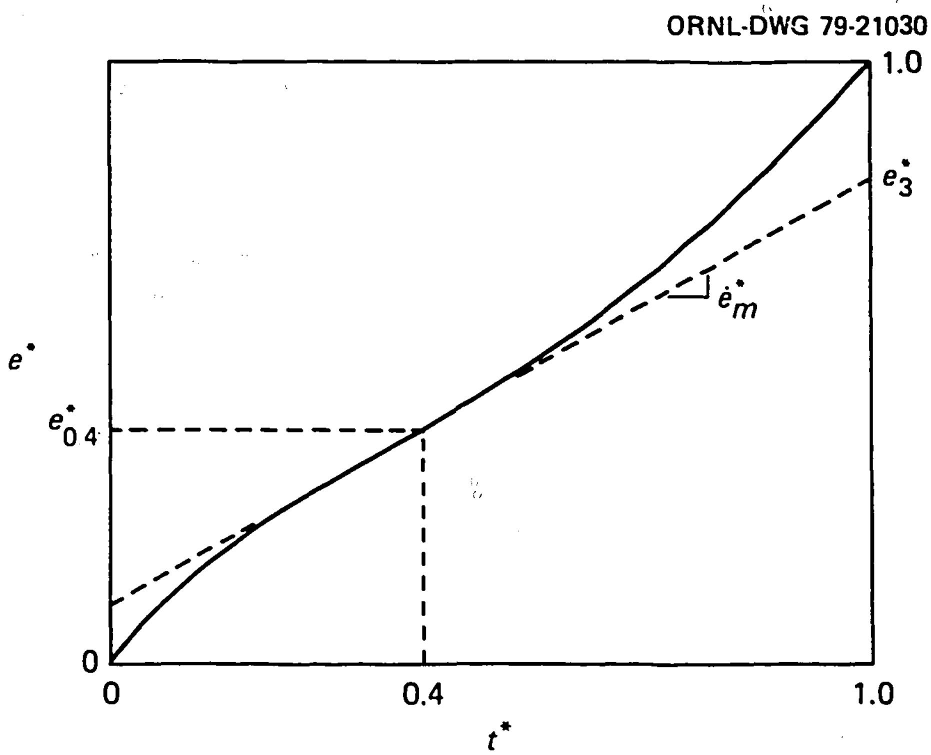

Fig. 34. Schematic Illustration of the Normalized Creep Curve Proposed for Alloy 718.

Figure 27 shows that e_{ss} does not change greatly over substantial time-temperature regions. Still, the master curve will more accurately depict behavior if it is "fine-tuned" to reflect variations in e_{ss}.

We have elected to base modifications in the master curve upon modifications to the predicted value of e^* for $t^* = 0.4$. This point was chosen because it approximately corresponds to the end of the secondary creep region. By definition the normalized strain at this point, $e_{0.4}^*$, is given by

$$e_{0.4}^* = e_3^* - 0.6\dot{e}_m^* \ . \tag{11}$$

Now define $\dot{e}_m^*$ more precisely as the slope of a line* through the t^*, e^* points (0.05, 0.1), (0.4, $e_{0.4}^*$) and (1, e_3^*). Thus $\dot{e}_m^*$ is defined as

---

*Note that this line no longer necessarily passes through the point (0.05, $e_{0.05}^*$), but it is still a good approximation for the linear creep line.

$$e_m^* = (e_3^* - 0.1)/0.95 \ . \qquad (12)$$

Equations 10 through 12 can be used to estimate $e_{0.4}^*$ as a function of e_{ss}. Now generalize Eq. (9) as

$$e^* = \exp[\beta(t^* - 1)](t^*)^{0.2} \ , \qquad (13)$$

where β is determined by the condition that $e^* = e_{0.4}^*$ at $t^* = 0.4$. Thus,

$$\beta = (\ln e_{0.4}^* + 0.1832)/(-0.6) \ . \qquad (14)$$

Equations (10) through (14) can now be used to estimate normalized creep curves as a function of varying e_{ss}. Figures 35 through 38 compare these predicted variable normalized curves with experimental data. The data include a certain amount of inevitable scatter, but the above "fine-tuning" has clearly increased the accuracy of the predictions. These predictions can then be used to estimate creep strain-time behavior. Since the predictions are based on predictions of t_r, the above treatment of heat-to-heat variability in t_r can be used to predict variations in strain-time behavior. Average values of C_h will yield

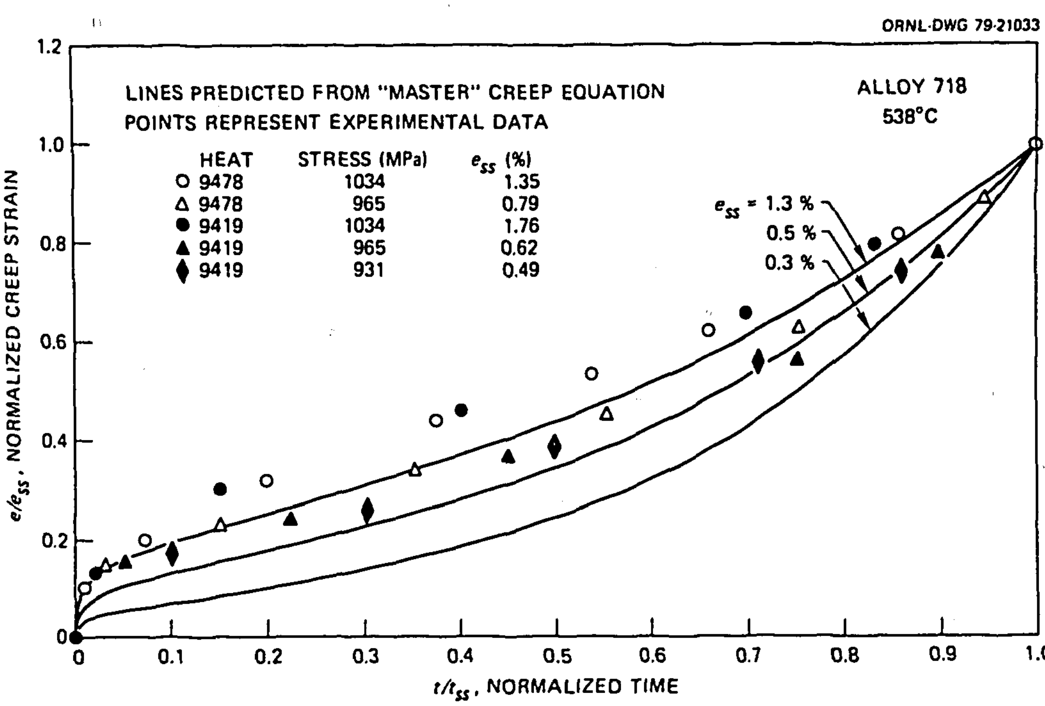

Fig. 35. Variable Normalized Creep Curves Modified for Variations in e_{ss} for Alloy 718 at 538°C.

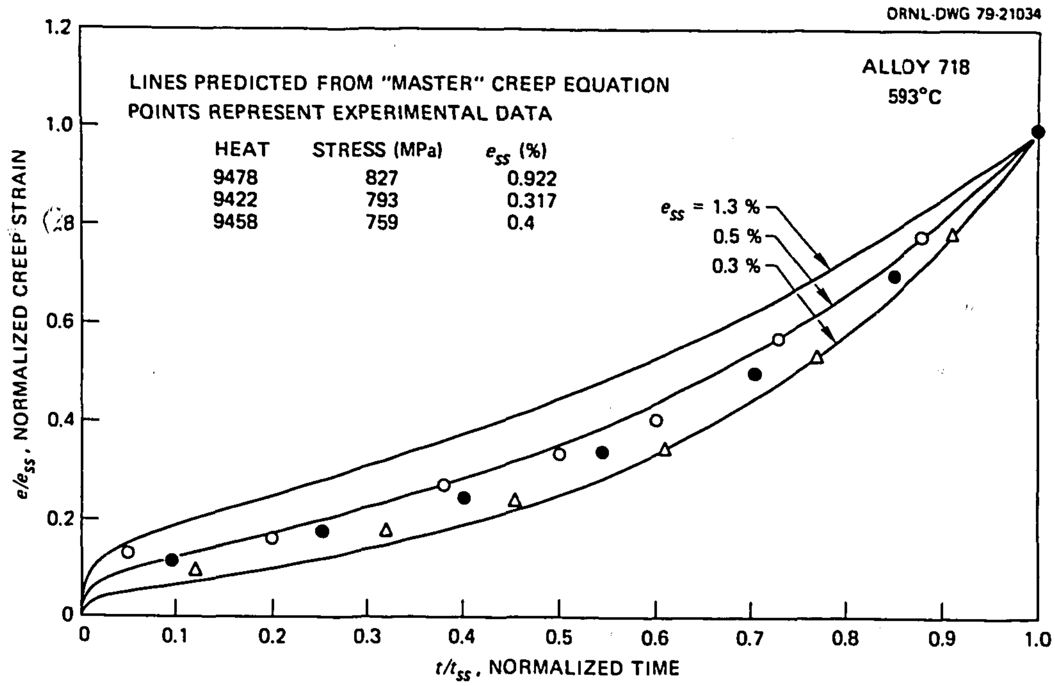

Fig. 36. Variable Normalized Creep Curves Modified for Variations in e_{ss} for Alloy 718 at 593°C.

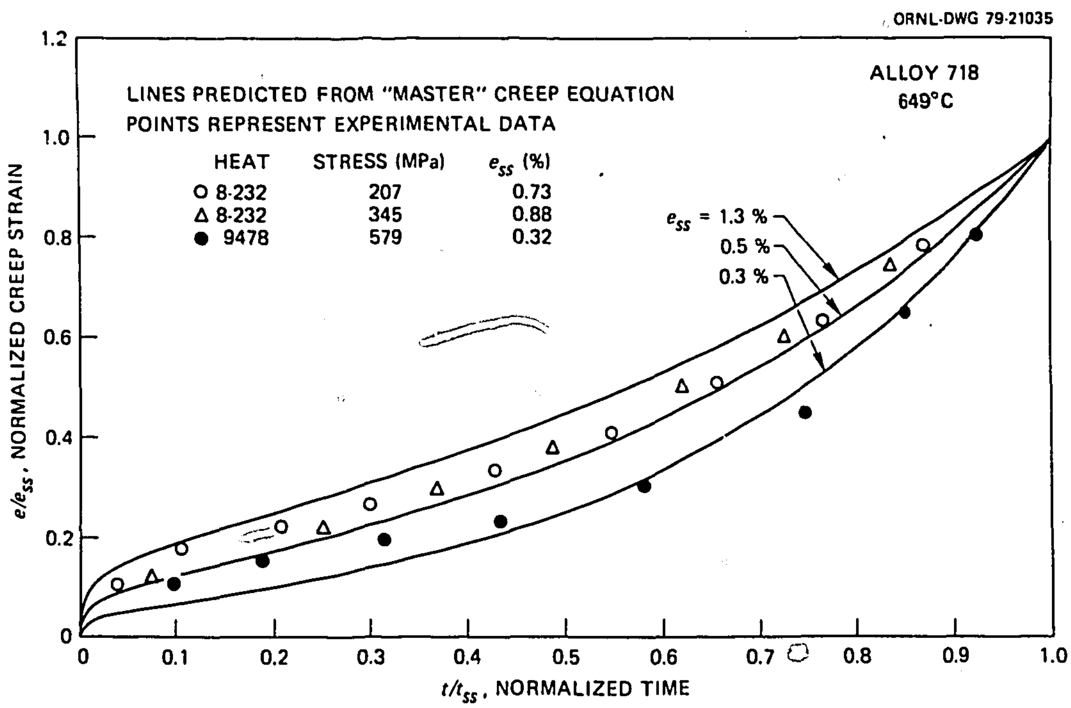

Fig. 37. Variable Normalized Creep Curves Modified for Variations in e_{ss} for Alloy 718 at 649°C.

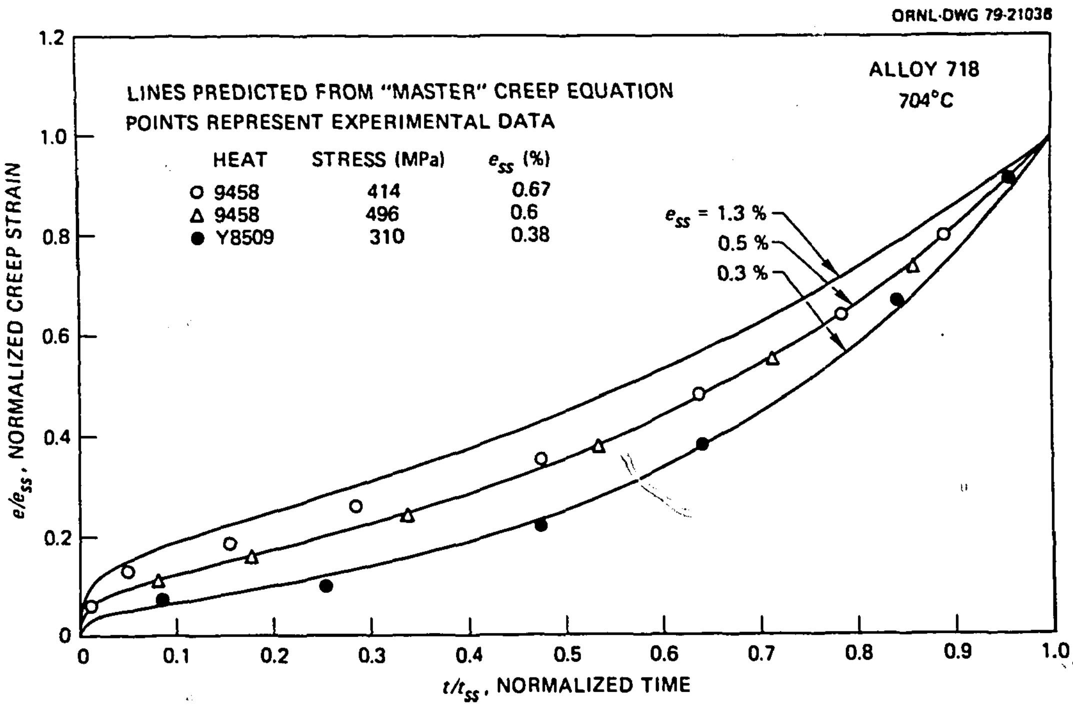

Fig. 38. Variable Normalized Creep Curves Modified for Variations in e_{ss} for Alloy 718 at 704°C.

average t_r and thus average strain-time behavior, and the individual heat values of C_h will yield individual heat predictions for t_r and thus for strain-time behavior.

ALLOWABLE STRESSES

The above analyses can be used to estimate time-dependent stress for alloy 718 with one exception. This 1% strain criterion includes both time-dependent and time-independent strains. An analysis of tensile stress-strain behavior is beyond the scope of this report, so the 1% strain criterion cannot be accurately determined from the results. However, since the onset of tertiary creep generally occurs before this material accumulates 1% strain, the 1% criterion cannot be the controlling factor in the allowable stress except at short times and low temperatures.

Since the time to tertiary creep has been related to the rupture life, the primary problem in establishing allowable stresses is reduced to one of determining the "minimum" creep-rupture behavior. The empirical definition of minimum as average minus 1.65 times the overall standard error in log time as used above appears to provide a good estimate of minimum rupture behavior. By use of this criterion, the minimum rupture life for any stress-temperature combination is given as the average life divided by 4.25. Thus, the criterion provides a known constant safety factor in terms of life.

Historically[23] the ASME Code has defined minimum as 1.65 "standard deviations" below the mean in terms of log stress rather than log time. Since the current regression analyses were necessarily performed with log time as the dependent variable, they yield no estimate of the standard error in terms of log stress. The lot-centered regression results can, however, be used to estimate the stress to rupture for various times for each heat. For a given time, these values can then be plotted against temperature to form a "strength trend curve."[23]

Such curves were constructed for times of 10, 30, 100, 300, 1000, 3000, 10,000, 30,000, 100,000, and 300,000 h, per the tabulations in Code Case N-47. For each heat, stresses were estimated only at temperatures for which data were available. Although log stress is typically[23] related to temperature linearly, we found it necessary to describe log stress as a cubic function of temperature for the above ten strength trend curves. Each of these fits yielded not only an equation for average strength but also an estimate of the standard error in log stress for each time. These standard errors ranged from 0.0164 for 100 h to 0.0506 for 300,000 h. Also, the cubic equations did not yield reasonable results when extrapolated to temperatures below 538°C. (They "turned down.")

Figures 39 through 42 illustrate the variation of rupture strength of alloy 718 with temperature for various rupture times. In particular, Figs. 39 and 42 compare the predictions made by the conventional strength trend curve approach and by the lot-centered regression approach. Note that for a given time the trend curve approach involves a fixed safety factor in terms of log stress. For temperatures around 620°C, where the long-term rupture strength decreases rapidly, this factor corresponds to virtually no safety factor in terms of time. Moreover, the trend curve approach is very vulnerable to inhomogeneous

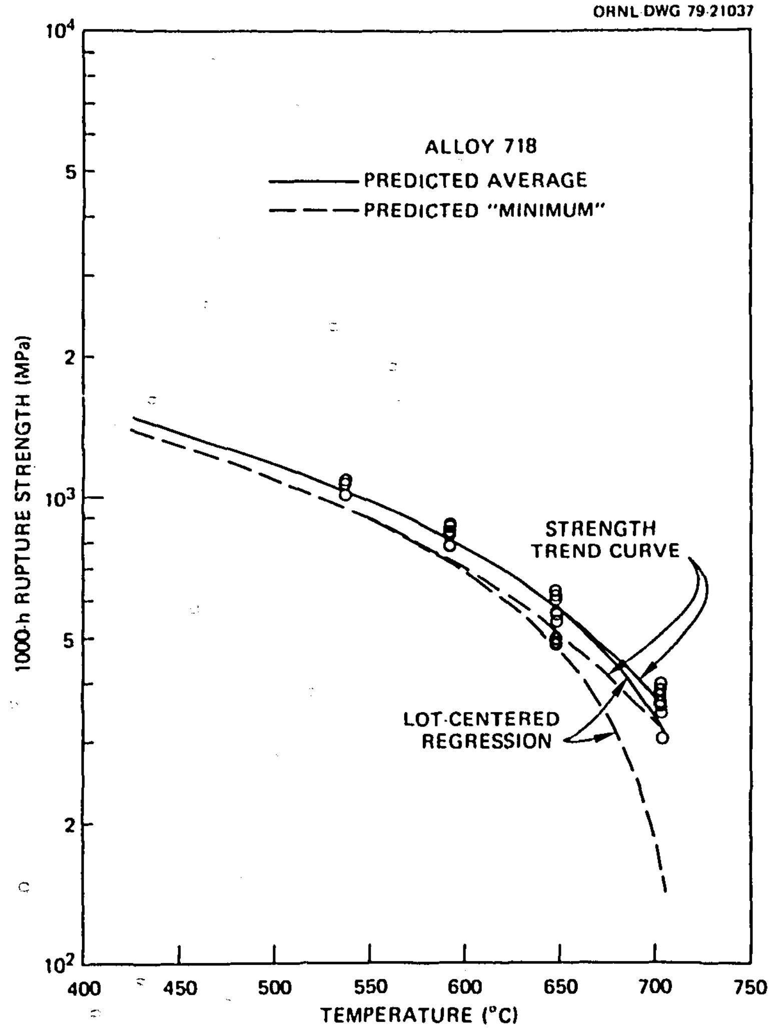

Fig. 39. Estimated Stress for Rupture in 1000 h as a Function of Temperature for Alloy 718.

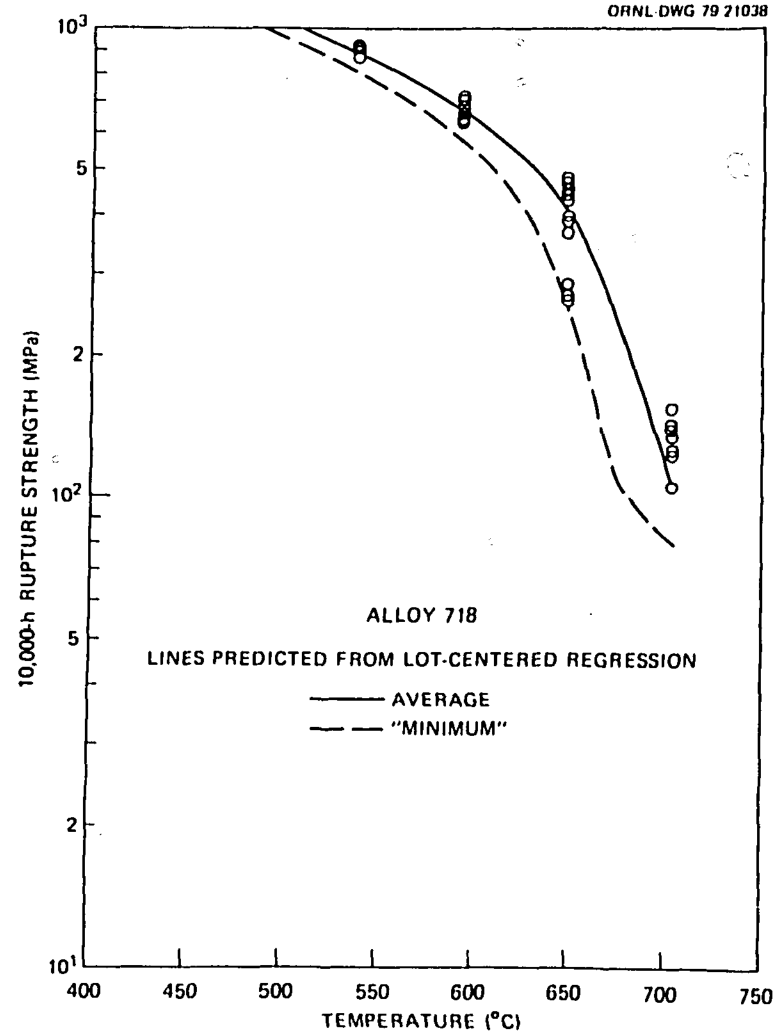

Fig. 40. Estimated Stress for Rupture in 10,000 h as a Function of Temperature for Alloy 718.

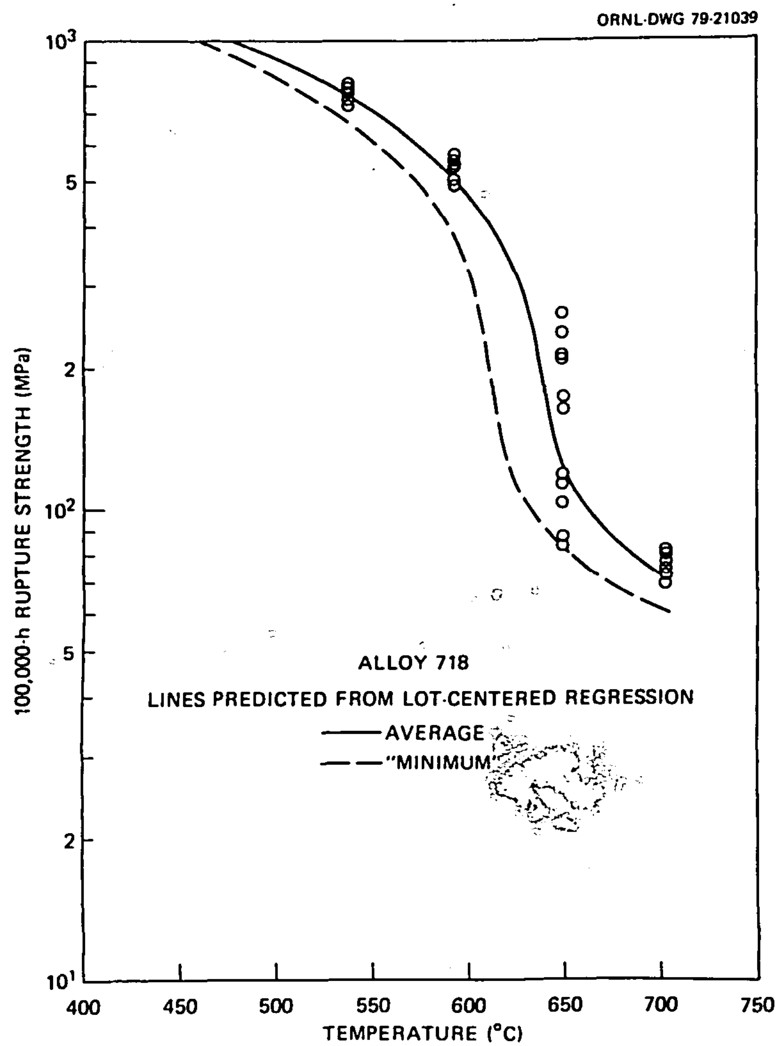

Fig. 41. Estimated Stress for Rupture in 100,000 h as a Function of Temperature for Alloy 718.

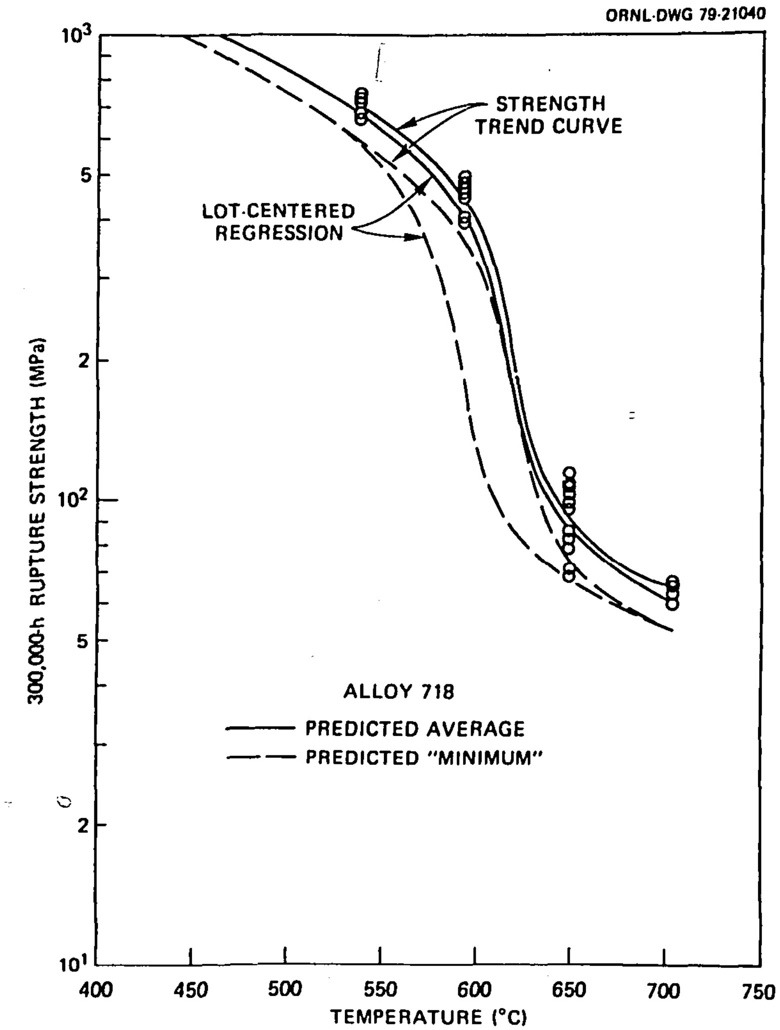

Fig. 42. Estimated Stress for Rupture in 300,000 h as a Function of Temperature for Alloy 718.

data distributions. At any temperature, it will predict an average strength that is the mean of the heats for which data are available at that temperature, even if these heats are all stronger or weaker than true average.

Thus, we decided to use the lot-centered regression results directly to determine allowable stresses for the following reasons.

1. The method yields a constant, well-defined safety factor in terms of service time.

2. The results can be extrapolated to temperatures below 538°C with generally reasonable results, although some low-temperature short-time stresses estimated in this way fall above the minimum expected ultimate tensile strength of this material.

3. The behavior of this material is somewhat different from that of the materials currently in ASME Code Case N-47. Thus, the previous experience with the trend curve approach may not be directly relevant.

4. The lot-centered regression results are not sensitive to inhomogeneous distribution in the data. For example, if all heats for which data are available at a given temperature are strong, the lot-centered regression results will fall somewhat below the mean of the data. Figures 39 through 42 clearly illustrate this point. No data are available at 704°C for five of the six weakest heats in the current data package. As a result the predictions for 704°C fall below the mean of the data shown in the figures at that temperature.

Once the minimum stress to rupture is determined in this fashion, the minimum stress to tertiary creep can immediately be estimated by a similar technique. For example, a t_{ss} of 100,000 h corresponds to a t_r of 1.43×10^5 h by the above relations. Thus, the minimum stress to produce onset of tertiary in 100,000 h is the same as the minimum stress to produce rupture in 1.43×10^5 h.

Table 12 displays calculated values of minimum stress to rupture, while Table 13 displays calculated values of minimum stress to the onset of tertiary creep. Note that if any of these values exceed estimated minimum ultimate tensile strength (UTS) at temperature for this material, then those values should be replaced by that UTS value. Such a situation typically occurs at shorter times in extrapolation of creep

Table 12. Alloy 718, Expected Minimum Stress-to-Rupture Values

Temperature		Expected Minimum Rupture Stress, MPa,[a] for Each Rupture Life									
(°C)	(°F)	10 h	30 h	100 h	300 h	1000 h	3000 h	10,000 h	30,000 h	100,000 h	300,000 h
427	800	1500[b]	1499	1498	1470	1401	1339	1269	1206	1136	1072
454	850	1500[b]	1485	1417	1355	1287	1224	1155	1092	1022	956
482	900	1428	1367	1299	1238	1170	1108	1039	975	903	837
510	950	1312	1251	1184	1134	1055	992	923	858	785	715
538	1000	1198	1138	1071	1010	941	878	807	740	663	587
566	1050	1086	1026	959	897	828	763	689	618	533	443
593	1100	980	920	852	789	718	651	572	492	386	180
621	1150	871	810	741	676	602	528	437	331	123	85
649	1200	763	701	629	560	478	391	254	113	82	69
677	1250	655	589	513	436	334	193	103	81		
704	1300	548	478	391	294	153	101	79			

[a] 1 ksi = 6.895 MPa

[b] Values arbitrarily set at 1500 maximum since they exceed expected ultimate tensile strength (UTS) under some conditions. Values exceeding minimum expected UTS should be set at the minimum UTS values.

Table 13. Alloy 718, Expected Minimum Stress-to-the-Onset-of-Tertiary Creep

Temperature		Expected Minimum Stress to Tertiary, MPa,[a] for Each Time									
(°C)	(°F)	10 h	30 h	100 h	300 h	1000 h	3000 h	10,000 h	30,000 h	100,000 h	300,000 h
427	800	1500[b]	1499	1498	1438	1371	1311	1244	1183	1115	1050
454	850	1500[b]	1448	1382	1232	1257	1197	1130	1069	1001	935
482	900	1389	1330	1265	1206	1140	1080	1013	952	882	815
510	950	1273	1215	1150	1091	1025	965	897	834	762	692
538	1000	1160	1101	1037	977	911	850	781	715	639	561
566	1050	1048	990	925	865	797	734	662	591	506	409
593	1100	942	883	817	756	687	620	541	461	346	118
621	1150	833	773	706	642	568	494	400	275	105	79
649	1200	724	662	592	523	439	346	172	99	77	66
677	1250	614	549	471	391	277	137	92	76		
704	1300	504	432	340	227	120	90	74			

[a] 1 ksi = 6.895 MPa

[b] Values arbitrarily set at 1500 maximum since they exceed expected ultimate tensile strength (UTS) under some conditions. Values exceeding minimum expected UTS should be set at the minimum UTS values.

data to low temperatures. The current investigation did not include an examination of tensile data, so we arbitrarily placed a 1500 MPa upper limit on the stress values. Table 14 displays calculated time-dependent allowable stresses, which are in this case always controlled by the rupture criterion.

Figure 43 compares the estimated minimum stress to rupture in 300,000 h for alloy 718 with those currently listed in Code Case N-47. At the lower temperatures, alloy 718 is far superior tc the others in strength, but at about 570°C it begins to rapidly lose strength with temperature. In the temperature range from about 610 to 704°C alloys 718 and 800H are approximately equal in terms of 300,000-h rupture strength. Note that alloy 800H is a solution-treated high-nickel

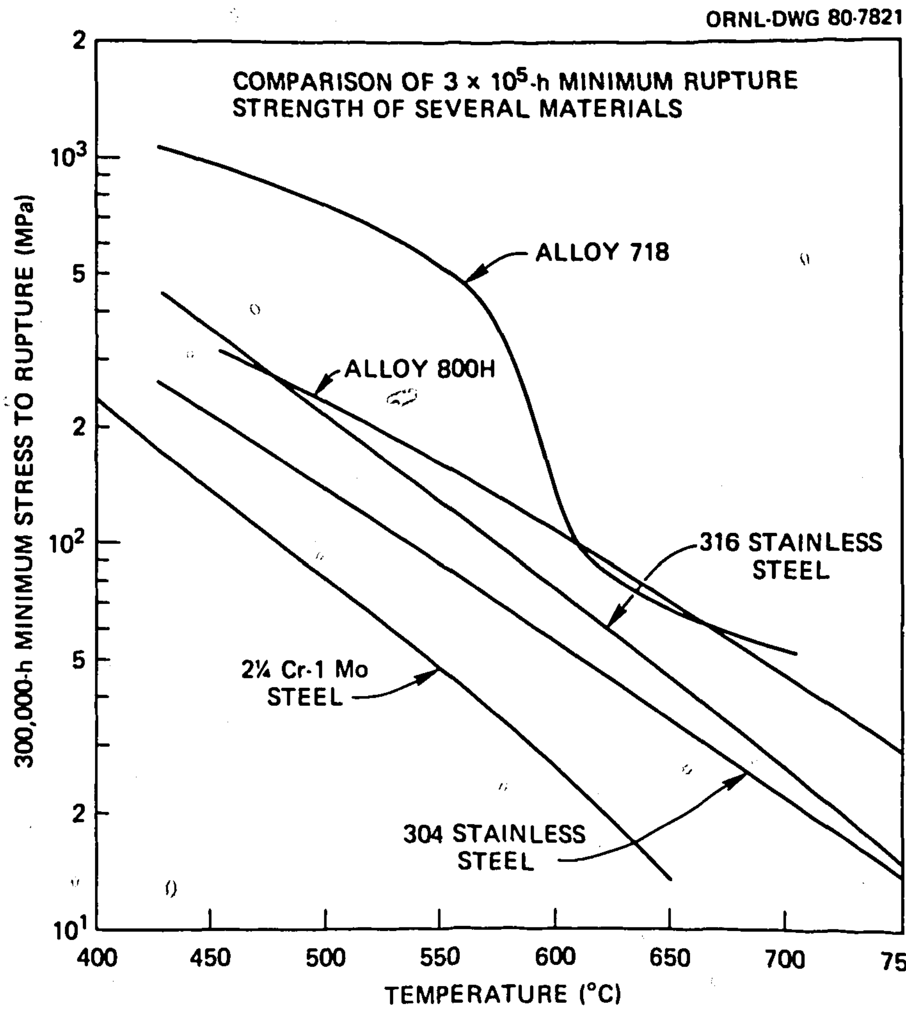

Fig. 43. Comparison of Estimated Minimum Stress for Rupture in 300,000 h for Alloy 718 and Materials Currently in ASME Code Case N-47.

Table 14. Alloy 718 Time-Dependent Allowable Stress,[a] S_t

Temperature		S_t, MPa,[b] for									
(°C)	(°F)	10 h	30 h	100 h	300 h	1000 h	3000 h	10,000 h	30,000 h	100,000 h	300,000 h
427	800	1000	999	999	980	934	893	846	804	757	715
454	850	1000	990	945	903	858	816	770	728	681	637
482	900	952	911	866	825	780	739	693	650	602	558
510	950	875	834	789	749	703	661	615	572	523	477
538	1000	799	759	714	673	627	585	538	493	442	391
566	1050	724	684	639	598	552	509	459	412	355	295
593	1100	653	613	568	526	479	434	381	328	257	120
621	1150	581	540	494	451	401	352	291	221	82.0	56.7
649	1200	509	467	419	373	319	261	169	75.3	54.7	46.0
677	1250	437	393	342	291	223	129	68.7	54.0		
704	1300	365	319	261	196	102	67.3	52.7			

[a]All values obtained from 2/3 times minimum stress to rupture from Table 12. If the above values exceed 2/3 times minimum ultimate tensile strength (UTS), they should be adjusted to a value equal to 2/3 times minimum UTS.

[b]1 ksi = 6.895 MPa

alloy. Thus, the above trend may indicate that alloy 718 loses much of its dispersion strengthening by overaging at high temperatures and long times. Thereafter, the alloy must depend upon solution strengthening for creep resistance.

Figure 44 shows the variation in estimated time-dependent allowable stress with temperature. Note that some time dependence is indicated even at 427°C (800°F). No data are available below 538°C (1000°F). If the assumption of zero time dependence at 427°C (commonly made for austenitic alloys in Code Case N-47) is desired, it is implemented as follows. First, determine the time-independent allowable stress at 427°C. Let this value also be the "time-dependent" allowable at 427°C for all times. Then interpolate linearly between this point and the appropriate 538°C point for the various times shown in Fig. 44 to determine consistent allowable stresses at temperatures between 427 and 538°C.

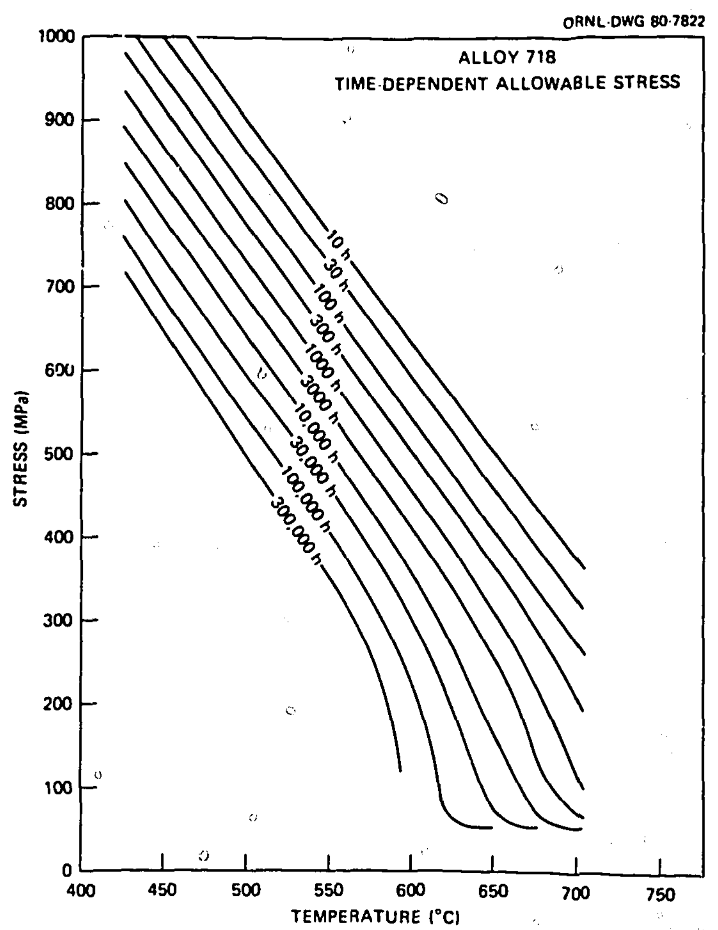

Fig. 44. Time-Dependent Allowable Stress of Alloy 718 as a Function of Temperature.

CONCLUSIONS

1. The creep and creep-rupture behavior of alloy 718 varies consistently with stress and temperature over the temperature range 538 to 704°C (1000–1300°F) for rupture times ranging from 10 to 87,000 h. This behavior can be represented by fairly simple analytical models, using lot-centered regression and generalized model selection.

2. The solution treatment temperature is an important factor in determining the creep strength of alloy 718. The 954°C (1750°F) solution treatment initially yields higher strength than the 982°C (1800°F) treatment. However, this difference decreases with time in test, with the decrease occurring sooner at higher temperatures.

3. Alloy 718 appears to display smaller heat-to-heat variations due to composition than does type 304 stainless steel.

4. Consistent determination of minimum rupture behavior for alloy 718 requires that safety factors be applied to the average in terms of log time, not log stress.

5. The time-dependent allowable stress per ASME Code Case N-47 for alloy 718 is always given by 2/3 times the minimum rupture strength.

6. For temperatures up to about 570°C, the 300,000-h minimum rupture stress for alloy 718 is far above that for materials currently in Code Case N-47. However, the allowable stresses drop off rapidly with temperature. In the range 620 to 704°C alloys 718 and 800H have approximately equal 300,000-h minimum rupture strengths.

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APPENDIX

CALCULATION OF AVERAGE AND MINIMUM STRENGTH BY REGRESSION ON HEAT-CENTERED DATA

As described in the text, fitting a multiheat set of creep or creep-rupture data using heat-centered data can yield results that accurately portray the stress and temperature dependences of the material under consideration. Predictions also include different intercept values to yield different strength levels for different lots or heats of material for which data are available. This appendix illustrates how an average strength level can also be predicted by the analysis. Finally, aspects of the method that lend themselves to accurate determination of minimum values are discussed, although detailed methods of defining minima are beyond the scope of the current investigation. Results are discussed within the framework of rupture data because the models are more general. However, all discussions herein are equally applicable to tensile or any other data treated by this method.

First, return to Eq. (3) of the text,

$$\hat{Y}_{Kh} - \overline{Y}_h = \sum_{i=1}^{N} a_i^{\prime}(X_{iKh} - \overline{X}_{ih}) \ . \tag{A1}$$

Here the barred variables represent sample arithmetic average values for a given lot of index h. The index i refers to the term in the model and K to the particular datum within heat h. Equation (A1) is fit to the data as written, with $Y_{Kh} - \overline{Y}_h$ as the dependent variable, where Y_{Kh} is the experimental values of log t_r. However, since $\overline{Y}_h$ is a known constant for a given heat, all the error in prediction is in the estimation of $\hat{Y}_{Kh}$. Thus, when Eq. (A1) is fit to data by least squares and the $a_i^{\prime}$ are determined, the total "error" in fitting of the model can be described by a residual sum of squares, RSS, given by

$$\text{RSS} = \sum_{h=1}^{H} \sum_{K=1}^{M} (\hat{Y}_{Kh} - Y_{Kh})^2 \ . \tag{A2}$$

If there are n data total, RSS has a number of degrees of freedom, d.f., given by

$$\text{d.f.} = n - N - H \ , \qquad \text{(A3)}$$

where N is the number of terms in the model and H is the number of lots (and thus the number of lot averages involved in the fitting).

By separating different lots through their different lot constants, this method attempts to describe only within-lot variations in behavior. No modeling of between-lot differences has been done at this point. Thus, the variance defined by the fit is an estimate of the pooled within-lot variance, V_W,

$$VW = \text{RSS/d.f.} \ . \qquad \text{(A4)}$$

Now Eq. (A1) can be transformed to Eq. (4) of the text,

$$\hat{Y}_{Kh} = \overline{Y}_h - \sum_{i=1}^{N} a_i^{\prime} X_{ih} + \sum_{i=1}^{N} a_i^{\prime} X_{iKh} \qquad \text{(A5)}$$

or

$$\hat{Y}_{Kh} = C_h + \sum_{i=1}^{N} a_i^{\prime} X_{iKh} \ , \qquad \text{(A6)}$$

where the differences in behavior of different lots are not now explicitly defined in terms of the lot constants, C_h, where

$$C_h = \overline{Y}_h - \sum_{i=1}^{N} a_i^{\prime} \overline{X}_{ih} \ . \qquad \text{(A7)}$$

Since C_h is a single constant for a given lot, estimation of average behavior simply consists of estimating the average lot constant C. Two methods immediately suggest themselves. First, one might choose to simply define C as the arithmetic mean of the C_h. Indeed, if the between-lot variability is much larger than the within-lot variability, such an approach would be justified. However, if there is a significant amount of within-lot variability, the estimates of C_h will contain some error. Lots for which there are more data will have a better estimate of C_h than lots with fewer data. Thus not all lots should be weighted equally.

Perhaps one should weight each lot according to the number of data available for that lot. This approach is correct only if the within-lot variability is much larger than the between-lot variability. If not, this procedure (which weights each *test* equally) is not fair, since no one lot is necessarily more "important" in the collection of lots available, even if it is represented by more data.

A possible solution comes from the work of Mandel and Paule,[1] who studied variations in behavior caused by measurements of chemical variables at different laboratories. After Sjodahl,[2] we simply extrapolate Mandel's lab-to-lab variation results to our lot-to-lot variation data.

Following this approach, we find that the C_h for each lot should be given a weight W_h of

$$W_h = K_h/(\lambda K_h + 1) \ , \tag{A8}$$

where K_h is the number of data for lot h and λ is V_B/V_W, where V_B is the between-lot variance for the lots involved. Knowing the appropriate weights, $\overline{C}$ can be calculated by

$$\overline{C} = \sum_{h=1}^{H} C_h w_h \Big/ \sum_{h=1}^{H} w_h \ . \tag{A9}$$

Unfortunately, the W_h cannot be estimated at this point, since V_B and thus λ are unknown. As a result, we have one equation in two unknowns and a solution can be obtained only by iterative techniques. However, such techniques are easily implemented by computer.

Mandel and Paule[1] present an iterative technique that does indeed result in a solution for both $\overline{C}$ and V_B. Results for our data are given in the text. These results were obtained typically after only three or four iterations. Sjodahl[2] has reported similar quick convergence to a solution. The result is probably the most fairly weighted estimate of average behavior obtainable by any technique proposed to this point.

Note also that by the direct separation of the variability into its two components, V_B and V_W, this method also yields a more reliable estimate of total variability than could be obtained by estimates of error that are a mixture of within-lot and between-lot variability. Since variance estimation is central to the estimation of any statistical limits, regression on lot-centered data thus also opens the way for superior techniques to estimate these limits.

Of course, all these advantages are clear only if the assumptions within the method are met. But what if they aren't? Specifically, what if the log σ vs log t_r isotherms for different lots are not parallel? First, if the lots represent a good sampling of the behavior to be expected within the material, estimates of C_h and the stress and temperature dependence of an average lot should still be good. The lack of fit caused by this nonparallelism will inflate the estimated variance and result in more conservative lower bounds. While these bounds may lose some statistical meaning, they at least move in the right direction, the nonparallelism introducing additional uncertainty. Perhaps even better estimates could be obtained by examination of the slope variations in the spirit of Manson's "heat fingerprinting."[3]

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