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Predicting the Strain to Tertiary Creep for Elevated-Temperature Structural Materials

M. K. Booker
V. K. Sikka

~~APPLIED TECHNOLOGY~~

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METALS AND CERAMICS DIVISION

PREDICTING THE STRAIN TO TERTIARY CREEP FOR ELEVATED-TEMPERATURE STRUCTURAL MATERIALS

M. K. Booker and V. K. Sikka

JULY 1976

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M. K. Booker and V. K. Sikka

ABSTRACT

The creep strain incurred before the onset of tertiary creep can be an important design criterion in the use of elevated-temperature structural materials. Various methods for predicting the amount of this strain are discussed. Application of these methods to data for types 304 and 316 austenitic stainless steels, nickel-base Inconel alloy 718, and ferritic 2 1/4 Cr-1 Mo steel is presented, with generally good results. The behavior of these four materials, including variations among different materials, is discussed in terms of basic material characteristics.

INTRODUCTION

The design of modern elevated-temperature power generation systems requires a careful and thorough consideration of the time-dependent mechanical behavior of the construction materials used. Much experimental and analytical consideration has been given to the treatment of stress-rupture properties as well as to actual strain-time deformation characteristics. However, far less fundamental and practical consideration has been given to the onset of tertiary creep. Penny and Marriott[1] express the view that creep rupture as an instability is more related to the conditions preceding it and causing its onset than to the conditions after its occurrence. Therefore, the onset of tertiary creep, if viewed as the beginning of failure, can have fundamental significance. Grant et al.[2,3] support this view, finding that the onset of tertiary creep (especially in terms of ductility) can be more fundamental than rupture itself.

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[1] R. K. Penny and D. L. Marriott, *Design for Creep*, McGraw-Hill, London, 1971, pp. 173–76.

[2] N. J. Grant and A. G. Bucklin, "On the Extrapolation of Short-Time Stress-Rupture Data," *Trans. Am. Soc. Met.* 42: 720–51 (1950).

[3] N. J. Grant, "Stress Rupture Testing," pp. 41–72 in *High Temperature Properties of Metals*, American Society for Metals, Cleveland, Ohio 1951.

From a design viewpoint, a major consideration is that prevention of tertiary creep can prevent the associated cracking, extensive voidage, and instabilities. Also, the amount of inelastic strain that a component can endure at elevated temperatures without developing plastic instabilities or excessive cracking and voidage can be a useful design limit. Current design rules[4] specify a fixed 1% limit on total inelastic membrane (through thickness) strain for elevated-temperature components. Clearly, though, a strain limit that could be directly related to material ductility under the temperature and loading conditions of interest would be more fundamentally meaningful. For the reasons given above, one indicator of such a limit might be the amount of creep strain that a material can withstand before the onset of tertiary creep.

Finally, currently available expressions for creep strain as a function of time, stress, and temperature[5,6] generally describe only the primary and secondary portions of the creep curve. Therefore, use of these expressions is valid only up to the onset of tertiary creep. Under constant load, isothermal conditions, the most obvious cutoff on the validity of such expressions is the time to the onset of tertiary creep. However, in the more realistic situation of variable load and temperature, the cutoff on the above analytical creep expressions depends upon the particular hardening law which applies. The most commonly recommended[7–9] hardening law is the hypothesis of "strain hardening."[10] Under the assumptions of strain hardening, the instantaneous creep rate ($\dot{e}_c$) is a function only of stress (σ), temperature

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[4] *Interpretations of the ASME Boiler and Pressure Vessel Code, Code Case 1592,* American Society of Mechanical Engineers, New York, 1974.

[5] L. D. Blackburn, "Isochronous Stress-Strain Curves for Austenitic Stainless Steels," *The Generation of Isochronous Stress-Strain Curves,* American Society of Mechanical Engineers, New York, 1972.

[6] M. K. Booker et al., *Mechanical Property Correlations for 2 1/4 Cr-1 Mo Steel in Support of Nuclear Reactor Systems Design,* ORNL/TM-5329 (June 1976).

[7] C. E. Pugh et al., *Currently Recommended Constitutive Equations for Inelastic Design Analysis of FFTF Components,* ORNL-TM-3602 (September 1972).

[8] J. M. Corum et al., *Interim Guidelines for Detailed Inelastic Analysis of High-Temperature Reactor System Components,* ORNL-5014 (December 1974).

[9] C. E. Pugh et al., *Background Information for Interim Methods of Inelastic Analysis for High-Temperature Reactor Components of 2 1/4 Cr-1 Mo Steel,* ORNL/TM-5226 (May 1976).

[10] C. C. Davenport, "Correlation of Creep and Relaxation Properties of Copper," *J. Appl. Mech.* 60: A-55 (1938); cited in *Fatigue, Tensile, and Relaxation Behavior of Stainless Steels,* TID-26135 (1975).

(T), and accumulated creep strain (e_c), regardless of the previous conditions under which the strain was incurred:

$$\dot{e}_c = f(\sigma, T, e_c) \ . \qquad (1)$$

Therefore, at any given stress and temperature state in a series of such states, the onset of tertiary creep will occur not after a particular time, but after an accumulation of a given amount of creep strain. Thus, analytical creep expressions under conditions of variable load and temperature are valid up to the strain to tertiary creep, e_3, in any given stress-temperature combination. Clearly, then, the quantity e_3 can be an important design variable. This paper reports the results of a study of the variations in e_3 with time, stress, and temperature for four important elevated-temperature structural materials.

MATERIALS

Data have been analyzed for types 304 and 316 austenitic stainless steel, ferritic 2 1/4 Cr-1 Mo steel, and nickel-base Inconel alloy 718. Tables 1 and 2 describe the material used, while the Appendix shows the actual data in tabular form, these data sets being the same as those analyzed in ref. 11. No discernable effects of specimen geometry were found, while effects due to heat-to-heat and heat treatment variations will be discussed below. Data for the Garofalo et al.[12] heat of type 316 stainless steel and for Inconel alloy 718 heat Y8509 include total strain (i.e., both instantaneous loading strain and creep strain), since separate measurements of loading strain were not available. For heats 9T2796 and 8043813 of type 304 stainless steel, and both heats of Inconel alloy 718 and 2 1/4 Cr-1 Mo steel, onset of tertiary creep was determined by the 0.2% offset method. For the other heats, onset of tertiary creep was determined by the first deviation from linear secondary creep (see Fig. 1).

These materials are of particular importance in elevated-temperature nuclear power generation systems. Types 304 and 316 stainless steel will be used extensively in the primary and secondary sodium loops in Liquid-Metal Fast Breeder Reactor (LMFBR) systems, while 2 1/4 Cr-1 Mo steel will be used in both the High-Temperature Gas-Cooled Reactor and the LMFBR steam generator units.

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[11] M. K. Booker, C. R. Brinkman, and V. K. Sikka, "Correlation and Extrapolation of Creep Ductility Data for Four Elevated-Temperature Structural Materials," pp. 108–45 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, American Society of Mechanical Engineers, New York, 1975.

[12] F. Garofalo, R. W. Whitmore, and F. Von Gemmingen, "Creep and Creep-Rupture Relationships in an Austenitic Stainless Steel," *Trans. Metall. Soc. AIME* 221: 310–19 (1961).

Table 1. Compositions and Product Forms of Materials Investigated

Heat	Reference	Product Form	Content, wt %[a]												
			C	Mn	P	S	Si	Cr	Ni	Co	Mo	Cu	N	Nb + Ta	Ti
9T2796	b	25.4-mm plate	0.051	1.37	0.041	a	0.4	18.5	9.87	0.1	0.3	0.24	0.031	c	c
9T2796	d	50.8-mm plate	0.047	1.22	0.029	0.012	0.47	18.5	9.58	0.05	0.10	0.10	0.031	c	c
55697	e	7-mm rod	0.052	1.1	0.011	0.01	0.52	18.92	9.52	0.035	0.12	0.10	0.052	c	c
8043813	f	25.2-mm plate	0.062	1.87	0.04	0.0043	0.48	17.8	8.95	0.20	0.32	0.20	0.033	c	c
ASTM A240, 479		Plate, rod	0.08[g]	2.0[g]	0.045[g]	0.03[g]	1.0[g]	17–19	8–10						
332990	e	7-mm rod	0.052	1.72	0.012	0.02	0.38	17.8	13.55	0.14	2.33	0.20	0.041	c	c
Garofalo et al.	h	12.7-mm bar	0.07	1.94	0.01	0.021	0.38	18.0	11.4	b	2.15	c	0.043	c	c
ASTM A240, 479		Plate, rod	0.08[g]	2.0[g]	0.045[g]	0.03[g]	1.0[g]	16–18	10–14		2–3				
C56445	i, j	25.2-mm pancake	0.05	0.21		0.006	0.05	18.18	52.16	0.06	3.03	c		5.31	0.76
GE Spec C50T79			0.010[g]	0.35[g]		0.03[g]	0.4[g]	17.0–21.0	50.0–55.0	0.75[g]	2.80–3.30			5.0–5.5	0.65–1.15

[a] All analyses include balance iron. No analysis available on Inconel alloy 718 heat Y8509 (ref. 34), 2 1/4 Cr-1 Mo data used included bar and pipe forms conforming to the following specifications: 2.00–2.50% Cr; 0.9–1.1% Mo; room temperature 0.2% offset yield strength ≥207 MPa (30 ksi); room-temperature ultimate tensile strength ≥414 MPa (60 ksi). Data from ref. 6.

[b] Ref. 20.

[c] Not reported.

[d] From R. W. Swindeman, "Creep-Rupture Correlations for Type 304 Stainless Steel (Heat 9T2796)," to be presented at Symposium on Structural Materials for Elevated-Temperature Nuclear Power Generation Service, ASME Winter Meeting, Houston, Texas, Nov. 30–Dec. 4, 1975.

[e] From L. D. Blackburn, Hanford Engineering Development Laboratory, private communication, November 1973.

[f] R. W. Swindeman and C. E. Pugh, *Creep Studies on Type 304 Stainless Steel (Heat 8043813) Under Constant and Varying Loads*, ORNL-TM-4427 (June 1974).

[g] Maximum allowed.

[h] From ref. 12.

[i] From G. E. Korth, Aerojet Nuclear Company, private communication, January 1975.

[j] From J. R. Barker, E. W. Ross, and J. F. Radavich, "Long-Time Stability of Inconel 718," *J. Met.* 20(1): 31–41 (January 1970).

Table 2. Heat Treatments and Specimen Gage Lengths of Materials Studied

Heat, Description	Initial Gage Length (mm)	Treatment	Time (hr)	Temperature (°C)	Cooling Method
		Type 304 Stainless Steel			
9T2796, 25-mm plate	57.2[a]	Anneal	0.5	1093	Air cool
9T2796, 51-mm plate	57.2	Anneal	0.5	1093	Air cool
8043813	57.2[a]	Anneal	0.5	1065	Air cool
55697	31.8	Anneal	1.0	1066	Rapid air cool
		Type 316 Stainless Steel			
332990	31.8	Anneal	1.0	1066	Rapid air cool
Garofalo et al.	38.1	Anneal	0.5	1093	Water quench
		2 1/4 Cr-1 Mo Steel			
Annealed[b]	50.8[c]	Austenitize	1	927	Furnace cool 28°C/hr to 450°C Air cool to room temperature
Isothermally annealed[b]	50.8[c]	Austenitize	1	927	Furnace cool 83°C/hr to 704°C
		Hold	2	704	Furnace cool 333°C/hr to room temperature
		Inconel Alloy 718			
C56445	50.8	Anneal	2.0	982	Air cool
		Age	8.0	718	Furnace cool 55°C/hr to 621°C
		Age	8.0	621	Air cool
Y8509	Unknown	Anneal	1.0	982	Water quench
		Age	8.0	718	Furnace cool 11–56°C/hr to 621°C, air cool

[a] Some high-stress and/or low-temperature tests were run on 31.8-mm-gage-length specimens.

[b] Typical heat treatment.

[c] Some tests were run on 76.2-mm-gage-length specimens.

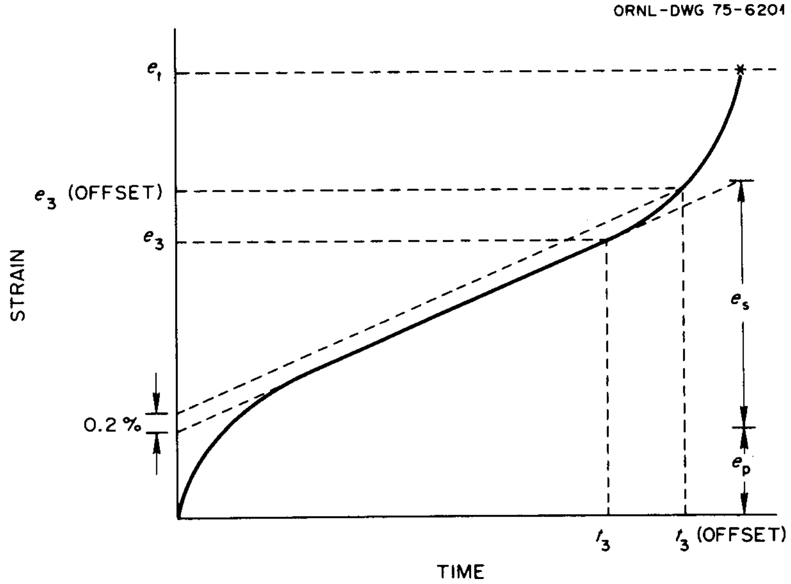

Fig. 1. Definitions of Creep Quantities Examined.

Inconel alloy 718, because of its high-temperature inherent strength and fatigue resistance, will be used as an LMFBR bolting material as well as for some structural applications in the core internals.

METHODS OF ANALYSIS

Creep ductility data are difficult to analyze quantitatively because of their inherent large amount of scatter. Heat-to-heat variations can be large, and even within a given heat, ductility data generally show more scatter than, say, stress-rupture data. Also, data for the strain to tertiary creep, e_3, are often scarce. Reference 11 presents a parametric method for predicting various creep ductility quantities (including e_3) as functions of stress and temperature, with generally good results.

Alternatively, given an equation for creep strain such as those reported in refs. 5 and 6, one can calculate e_3 as follows. First, determine the time to tertiary creep as a function of stress and temperature, t_3 (σ,t), for instance by the methods given in ref. 13. Then, knowing the creep strain as a function of time, stress, and temperature, one simply has to insert t_3 (σ,t) as the time to calculate e_3 at a given stress and temperature. A similar procedure can be used

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[13] M. K. Booker and V. K. Sikka, "Interrelationships Between Creep Life Criteria for Four Nuclear Structural Materials," presented at 1975 Annual Meeting, American Nuclear Society, New Orleans (June 1975); to be published in *Nuclear Teachnology*; also ORNL-TM-4997 (August 1975).

to calculate e_3 from sets of isochronous stress-strain curves calculated by parametric or other means.[14] For a given time, calculation of the stress to cause onset of tertiary creep allows determination of e_3 from the isochronous curve for that time at the temperature of interest. Such a procedure is mentioned in ref. 15.

The above three methods (hereafter referred to as the parametric, creep equation, and isochronous curve methods) all have merit. However, the parametric approach suffers from a lack of availability of data for e_3. In this approach, the time, t_3, and the average creep rate to tertiary creep, $\dot{e}_3 = e_3/t_3$, are separately analyzed by standard parametric techniques, then combined for a prediction of $e_3 = \dot{e}_3 t_3$. Thus, one must directly have data for both e_3 and t_3, which are often difficult to obtain. Furthermore, it has been found[11] that the parametric method yields optimum results when individual heats of material are treated separately.

The creep equation and isochronous curve methods are quite similar, and therefore have similar weaknesses. First, it is difficult to account for heat-to-heat variations by these techniques. Also, by attempting to describe the entire creep strain–time behavior of a material, one might sacrifice accuracy in the prediction of a single point, that is, the onset of tertiary creep. Finally, both methods require extensive and difficult analyses and rely on the availability of a large number of strain-time curves at various stresses and temperatures.

An approach which alleviates most of the objections to the above procedures involves use of the so-called "plasticity resource,"[16,17]

$$e_s = \dot{e}_m t_r \ , \qquad (2)$$

where $\dot{e}_m$ is the minimum creep rate. As discussed in earlier Russian work,[16,17] e_s has been suggested as a possible estimate of e_3. Since data for $\dot{e}_m$ and t_r are both widely available, e_s can be predicted by

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[14] A. O. Schaefer, ed., *The Generation of Isochronous Stress-Strain Curves*, American Society of Mechanical Engineers, New York, 1972.

[15] J. E. Bynum and B. W. Roberts, "Creep Behavior of a Formed Plate of Type 304 Stainless Steel," pp. 49–64 in *Elevated-Temperature Properties of Austenitic Stainless Steels*, American Society of Mechanical Engineers, New York, 1974.

[16] V. S. Ivanova, "Creep Ductility Criterion for Metals," pp. 212–16 in *Zavodskaya Laboratoria*, vol. 21, No. 2, 1955, Brutcher Translation No. 4210.

[17] I. A. Oding and V. S. Ivanova, "Analysis and Application of Certain Creep Criteria," pp. 62–66 in *Vestnik Mashinostroeniya*, vol. 35, No. 5, 1955, Brutcher Translation No. 4211.

the parametric method of ref. 11. Alternatively, Monkman and Grant[18] found that t_r and $\dot{e}_m$ were related by

$$\dot{e}_m = F{t_r}^{-\lambda} , \tag{3}$$

where λ is about equal to unity, and F is a material constant. Then e_s is given by

$$e_s = F{t_r}^{1-\lambda} . \tag{4}$$

The obvious weakness of the plasticity resource approach is that it does not yield a direct prediction of e_3. Based upon empirical relationships similar to those previously reported,[13,18] a simple generalization of the plasticity resource approach could be obtained with either of the following equations:

$$\dot{e}_3 = B{\dot{e}_m}^{\alpha} , \tag{5}$$

$$\dot{e}_3 = D{t_r}^{-\gamma} , \tag{6}$$

where the parameters B, α, D, and γ may be functions of temperature and material. In ref. 13, a relationship between t_3 and t_r was proposed of the form

$$t_3 = A{t_r}^{\beta} , \tag{7}$$

where A and β are material constants relatively independent of temperature. Thus, since $\dot{e}_3 = e_3 t_3$, e_3 may be given by

$$e_3 = AB{t_r}^{\beta}{\dot{e}_m}^{\alpha} , \tag{8}$$

or

$$e_3 = AD{t_r}^{\beta-\gamma} . \tag{9}$$

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[18] F. C. Monkman and N. J. Grant, "An Empirical Relationship Between Rupture Life and Minimum Creep Rate in Creep-Rupture Tests," *Proc., Am. Soc. Test. Mater.* 56: 593–605 (1956).

A combination of Eqs. (3) and (8) yields

$$e_3 = ABF^{\alpha} t_r^{\beta-\alpha\lambda} \ , \tag{10}$$

which shows that Eqs. (8) and (9) are really equivalent in form. Thus, values of e_3 can be predicted from data for t_r and $\dot{e}_m$.

RESULTS

The results of the parametric predictions of ref. 11 are discussed fully there and will not be repeated in detail here. Figures 2 and 3 illustrate predictions obtained using the creep equations developed for types 304 and 316 stainless steel.[19] From these figures it appears that the creep equation approach is less accurate than the parametric and empirical approaches, although the two heats of material for which data are shown are the same heats used in ref. 19 to develop the creep equations. Moreover, heat-to-heat variations in the creep properties of these materials can be large,[20] those in type 304 being especially great.[21] Since no measure of heat-to-heat variation was built into the creep equations in ref. 19, these results cannot account for heat-to-heat variations in e_3. Reference 22 presents some discussion of possible effects of heat-to-heat variation on the creep equation developed for 2 1/4 Cr-1 Mo steel in ref. 23, but these effects are difficult to quantify. For these reasons, the remaining discussion will center on the empirical approach given in Eqs. (5) through (9).

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[19] L. D. Blackburn, "Isochronous Stress-Strain Curves for Austenitic Stainless Steels," *The Generation of Isochronous Stress-Strain Curves*, American Society of Mechanical Engineers, New York, 1972.

[20] V. K. Sikka et al., "Heat-to-Heat Variation in Creep Properties of Types 304 and 316 Stainless Steels," *J. Pressure Vessel Technol., Trans. ASME* 97(4): 243–51 (November 1975).

[21] V. K. Sikka, M. K. Booker, and T. L. Hebble, *Assessment of Tensile and Creep Data for Types 304 and 316 Austenitic Stainless Steels*, report in preparation.

[22] M. K. Booker et al., *Creep Strain–Time Characteristics of Annealed and Isothermally Annealed 2 1/4 Cr-1 Mo Steel*, report in preparation.

[23] M. K. Booker et al., *Mechanical Property Correlations for 2 1/4 Cr-1 Mo Steel in Support of Nuclear Reactor Systems Design*, ORNL/TM-5329 (June 1976).

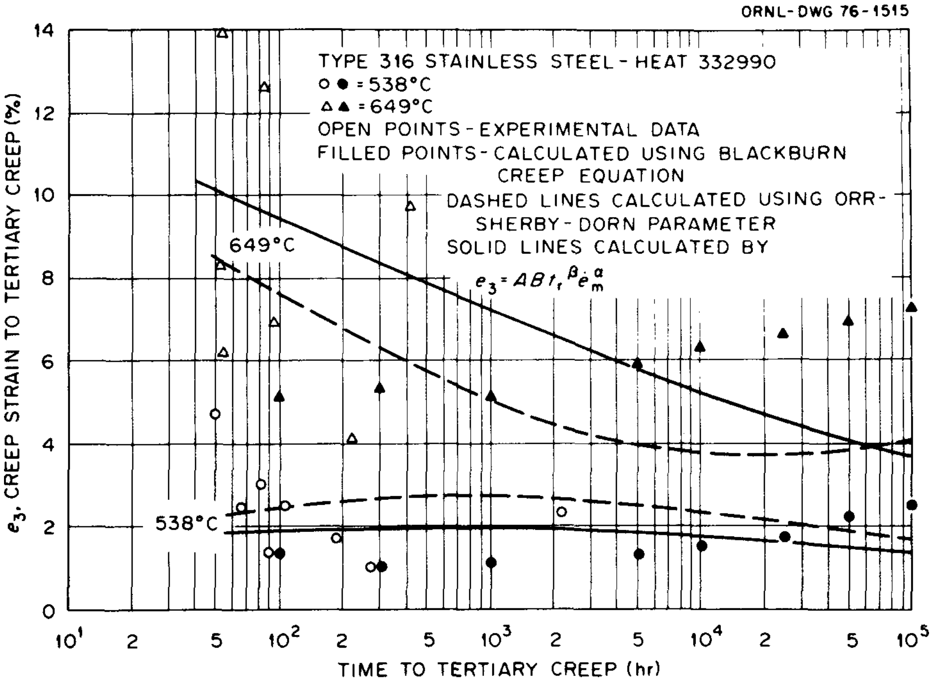

Fig. 2. Variation of Strain to Tertiary Creep with Rupture Life for Heat 332990 of Type 316 Stainless Steel.

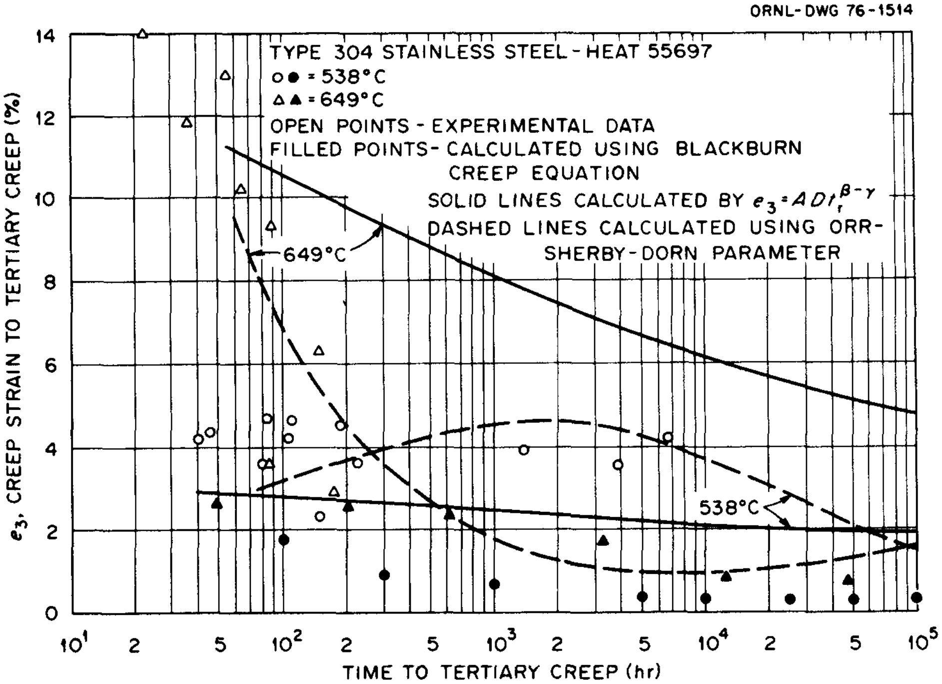

Fig. 3. Variation of Strain to Tertiary Creep with Rupture Life for Heat 55697 of Type 304 Stainless Steel.

Unlike the parametric method presented in ref. 24, Eqs. (5) through (7) were found to be simultaneously applicable to material from various heats with various heat treatments. For Inconel alloy 718 and type 316 stainless steel, only Eq. (7) was applied to more than one heat simultaneously, while all three equations were applied to several heats of 2 1/4 Cr-1 Mo steel. Equations (5) and (6) were applied to four data sets (three heats) of type 304 stainless steel, but Eq. (7) was determined in ref. 13 from many heats. Of the present heats, both 9T2796 and 55697 are relatively weak, while 8043813 is unusually strong.[20] Thus, over a range of strengths in this material, Eqs. (5) through (7) seem to apply simultaneously. More work needs to be done to establish heat-to-heat invariance in these equations, but such invariances would not be surprising, since the current approach is really a normalization procedure (e_3 for a given heat is determined from data for $\dot{e}_m$ and t_r for that same heat). In fact, it was even found to be possible in applying Eqs. (5) and (6) to simultaneously treat data determined by the two different definitions of onset of tertiary creep (the offset method yields both a higher time and a higher strain; thus the average rate is not significantly different from that of the deviation method). However, while the constants in Eqs. (5) through (9) may be determined from several heats of a given material, e_3 for a given heat in a given material condition must be predicted from the appropriate rupture life and minimum creep rate data for that heat in that condition. The same general comments apply to Eq. (3), which was determined simultaneously for each material from all the data listed in the appendix.

Tables 3 and 4 display the results obtained by analyzing the current data according to Eqs. (5) and (6), while Table 5 shows the results obtained in ref. 13 from Eq. (7). Again it should be noted that A, β, B, and α are considered in these tables to be temperature independent, while D and γ are functions of temperature. Figures 4 and 5 illustrate the fit of Eqs. (5) and (6); the fit of Eq. (7) is discussed in ref. 13.

In Table 4, the constant D appears to vary significantly with temperature, while the variations in γ are somewhat minor. To obtain a clearer view of the constant D as a function of temperature, a standard γ value could be obtained for each data set from data at all temperatures, and the D values recalculated at each temperature with γ fixed at this standard value. Also, the proximity of the values of α, β, and γ to unity suggests that these parameters might all be replaced by values of 1 to simplify the models. However, it must be remembered that the values given here were all obtained by techniques of least-squares regression. The values of the various regression constants all represent only estimates of the true values of these constants. Different sets of data for the same materials might yield different estimates.

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[24] M. K. Booker, C. R. Brinkman, and V. K. Sikka, "Correlation and Extrapolation of Creep Ductility Data for Four Elevated-Temperature Structural Materials," pp. 108–45 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, American Society of Mechanical Engineers, New York, 1975.

Table 3. Results of Correlation Between Minimum Creep Rate and Average Creep Rate to Tertiary Creep[a]

Data Set	Number of Points	B	α	RMS[b]	R^2[c]	Temperature Range of Data (°C)
304 Stainless	138	1.110	0.974	0.050	99.3	482–816
316 Stainless G[d]	120	1.602	0.995	0.269	95.6	593–816
316 Stainless H[e]	38	1.092	0.991	0.0235	99.6	538–760
Inconel 718 T[f]	18	0.684	0.86	0.254	92.2	538–760
Inconel 718 C[g]	26	1.40	0.985	0.322	96.2	538–704
2 1/4 Cr-1 Mo	117	0.637	0.854	0.241	90.2	482–677

[a] Minimum creep rate, $\dot{e}_m$, and average creep rate to tertiary creep, $\dot{e}_3$, have been related by $\dot{e}_3 = B\dot{e}_m^{\alpha}$.

[b] RMS = $\Sigma Y^2/(n - \nu)$, where n = number of data points and ν = number of coefficients in the model (here $\nu = 2$); ΣY^2 = sum of squared residuals, $\Sigma Y^2 = \Sigma(\ln \dot{e}_{3_{\mathrm{pred}}} - \ln \dot{e}_{3_{\mathrm{exp}}})^2$, where $\ln \dot{e}_{3_{\mathrm{pred}}}$ = ln [predicted rate (%/hr)], and $\ln \dot{e}_{3_{\mathrm{eff}}}$ = ln [experimentally observed rate (%/hr)].

[c] R^2 = coefficient of determination; R^2 describes how well a regression model describes variations in the data. $R^2 = 100$ signifies complete description, $R^2 = 0.0$ signifies no description. $\sqrt{R^2/100} = R$, the linear correlation coefficient.

[d] Data for total strain, from ref. 29.

[e] Data for creep strain only, from ref. 27.

[f] Data for total strain, from ref. 33.

[g] Data for creep strain only, from ref. 34.

Table 4. Results of Correlation Between Rupture Life and Average Creep Rate to Tertiary Creep[a]

Data Set	Temperature (°C)	Number of Points	D	γ	RMS[b]	R^2[c]
304 Stainless	538	24	4.899	1.030	0.174	94.4
	593	37	22.571	1.198	0.202	96.2
	649	44	25.091	1.089	0.172	97.3
	704	14	33.882	1.099	0.124	98.5
	760	11	33.115	1.034	0.048	99.3
316 Stainless G[d]	593	36	30.265	1.078	0.020	99.6
	704	48	49.383	1.081	0.030	99.6
	816	36	42.921	1.103	0.023	99.6
316 Stainless H[e]	538	7	7.131	1.154	0.174	93.5
	593	12	12.783	1.038	0.171	96.5
	649	12	23.220	1.005	0.027	99.6
	760	7	31.690	1.004	0.014	99.6
Inconel 718 T[f]	593	4	2.044	1.048	0.339	94.4
	649	6	27.859	1.442	0.121	97.4
	704	4	0.081	0.710	0.00406	99.5
	760	3	2.545	1.125	0.0566	97.0
Inconel 718 C[g]	538	6	32.394	1.429	0.491	97.0
	593	6	3.968	1.218	0.0636	99.3
	649	8	1.212	1.020	0.0259	99.7
	704	6	6.640	1.232	0.103	98.8
2 1/4 Cr-1 Mo	538	23	3.531	0.903	0.422	73.1
	593	41	51.761	1.280	0.699	77.2
	649	26	18.168	1.185	0.411	83.8

[a] Rupture life, t_r, and average creep rate to tertiary creep, $\dot{e}_3$, are related by $\dot{e}_3 = Dt_r^{-\gamma}$.

[b] RMS = $\Sigma Y^2/(n - \nu)$, where n = number of data points and ν = number of coefficients in the model (here $\nu = 2$); ΣY^2 = sum of squared residuals, $\Sigma Y^2 = \Sigma(\ln \dot{e}_{3\text{pred}} - \ln \dot{e}_{3\text{exp}})^2$ where $\ln \dot{e}_{3\text{pred}}$ = ln [predicted rate (%/hr)] and $\ln \dot{e}_{3\text{eff}}$ = ln [experimentally observed rate (%/hr)].

[c] R^2 = coefficient of determination; R^2 describes how well a regression model describes variations in the data. $R^2 = 100$ signifies complete description, $R^2 = 0.0$ signifies no description. $\sqrt{R^2/100} = R$, the linear correlation coefficient.

[d] Data for total strain, from ref. 29.

[e] Data for creep strain only, from ref. 27.

[f] Data for total strain, from ref. 33.

[g] Data for creep strain only, from ref. 34.

Table 5. Results of Correlation Between Rupture Life and Time to Tertiary Creep[a]

Data Set	Number of Points	A	β	RMS[b]	R^2[c]	Temperature Range of Data (°C)
304 Stainless, t_{ss}	277	0.752	0.977	0.090	96.6	482–816
304 Stainless, t_2	233	0.685	0.968	0.117	93.6	538–649
316 Stainless, t_2	183	0.526	1.004	0.071	93.5	538–816
2 1/4 Cr-1 Mo, t_{ss}	126	0.334	1.046	0.067	96.1	482–677
Inconel 718, t_{ss}	63	0.424	1.045	0.080	98.2	538–704
Inconel 718, t_2	52	0.285	1.049	0.142	94.3	538–704

[a] Time to tertiary creep, t_3, and rupture life, t_r, have been related by $t_3 = At_r^{\beta}$; t_3 may be t_{ss} (0.2% offset time to tertiary creep) or t_2 (time to first deviation from linear secondary creep).

[b] RMS = $\Sigma Y^2/(n - \nu)$ where n = number of data points and ν = number of coefficients in the model (here ν = 2); ΣY^2 is as in Table 3 but refers to ln (t_3).

[c] R^2 is defined in Table 3.

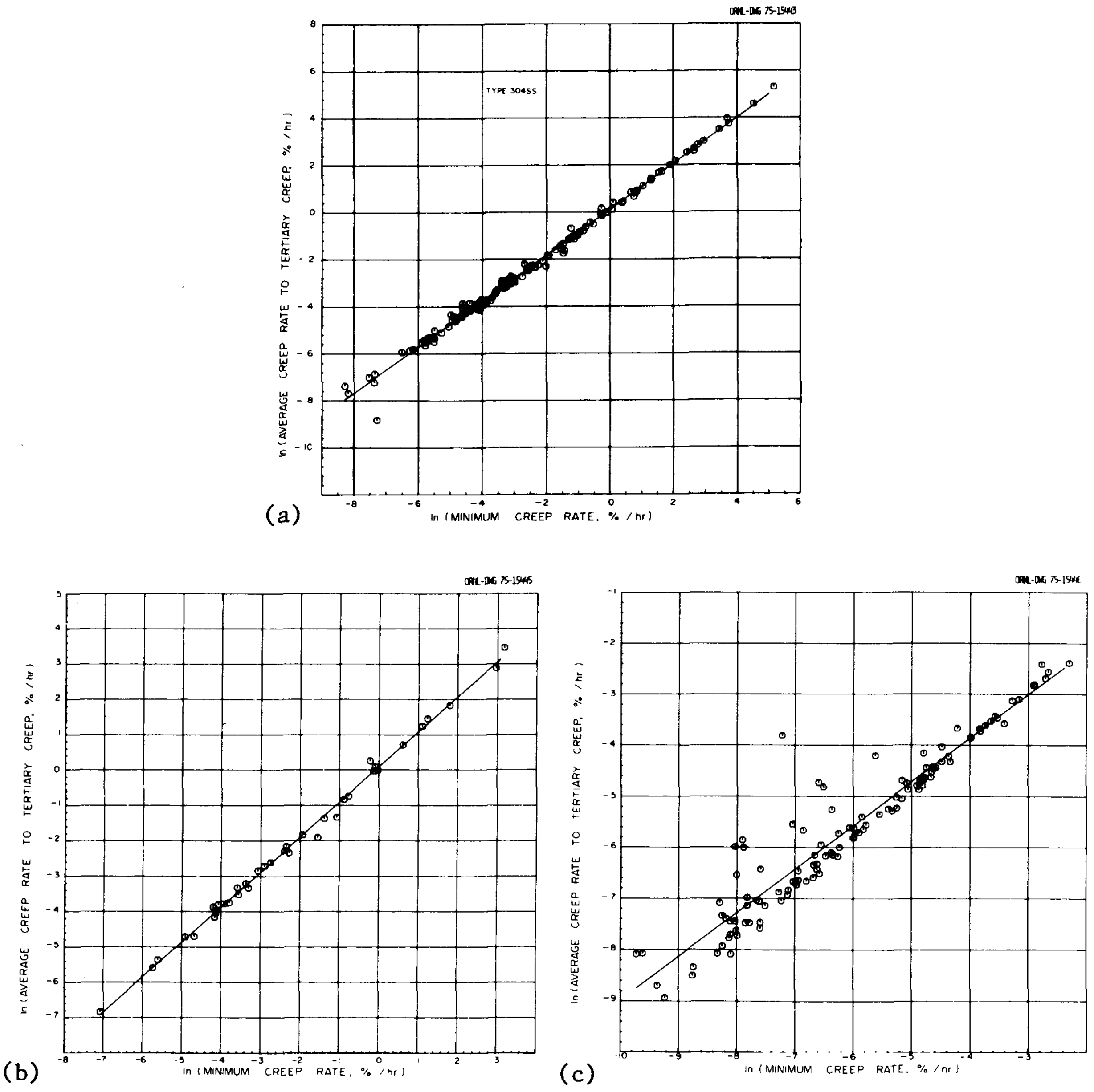

Fig. 4. Relationship Between Minimum Creep Rate and Average Creep Rate to Tertiary Creep for (a) Type 304 Stainless Steel, (b) Type 316 Stainless Steel Heat 332990, and (c) 2 1/4 Cr-1 Mo Steel.

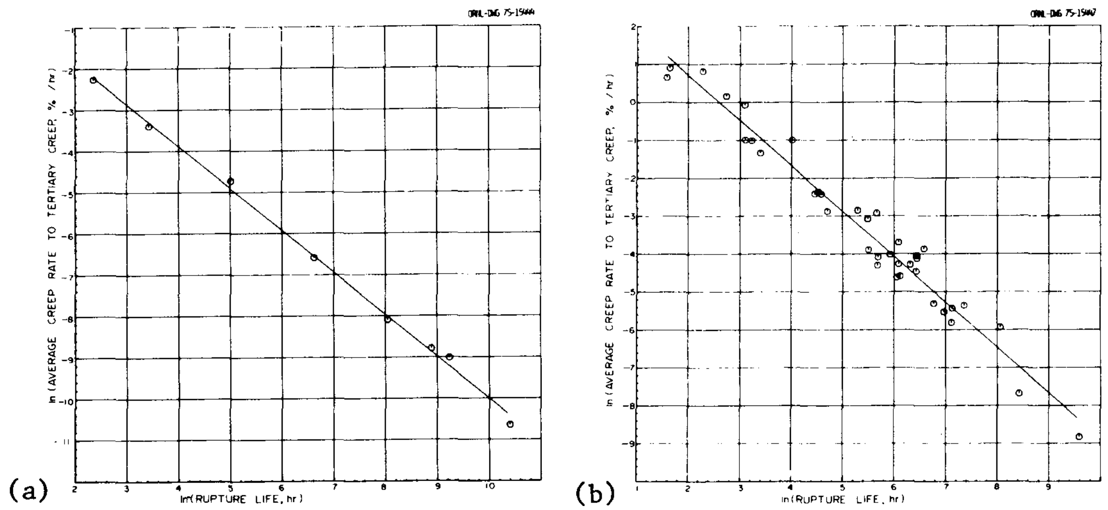

Fig. 5. Relationship Between Rupture Life and Average Creep Rate to Tertiary Creep for (a) Inconel Alloy 718 Heat Y8509 and (b) Type 304 Stainless Steel.

Still, based on the data used here, the values in Tables 3 through 5 are the best available estimates, and these values are used in the following calculations. The use of any other values for the constants (such as unity for α, β, γ) introduces an unnecessary bias. If desired, the uncertainty in the values of these constants can be analyzed by standard statistical techniques. Such techniques are described elsewhere.[25]

Since D (and perhaps γ) from Eq. (9) is a function of temperature, that equation indicates, at a given value for t_r, that e_3 is a function of temperature. All constants in Eq. (8), however, are presumed independent of temperature. Thus, while Eq. (10) shows that Eqs. (8) and (9) are equivalent in form, they appear to yield different implications unless F (and perhaps λ) is a function of temperature. In fact, the results given in Table 6 from analysis by Eq. (3) show that F does indeed vary with temperature, while λ is again near unity. Thus, Eqs. (8) and (9) are consistent. These temperature-dependent results are consistent with

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[25] M. K. Booker and V. K. Sikka, *Empirical Relationships Among Creep Properties of Four Elevated-Temperature Structural Materials*, ORNL/TM-5399 (in press).

Table 6. Results of Correlation Between Rupture Life and Minimum Creep Rate

Data Set	Temperature (°C)	Number of Points	F	λ	RMS	R^2
Type 304 stainless steel	538	24	8.604	1.115	0.237	94.0
	593	41	15.991	1.180	0.214	96.4
	649	45	24.522	1.119	0.160	97.7
	704	14	28.633	1.086	0.140	98.2
	760	11	31.416	1.042	0.0339	99.5
Type 316 stainless steel	538	8	10.452	1.232	0.159	94.6
	593	48	6.410	0.982	0.0949	97.8
	649	12	21.574	1.000	0.0591	99.2
	704	48	32.259	1.038	0.0476	99.3
	760	7	29.207	1.003	0.0183	99.5
	816	36	35.696	1.082	0.0318	99.4
Inconel 718	538	8	13.296	1.378	0.162	98.5
	593	11	2.791	1.211	0.897	90.9
	649	13	1.393	1.142	0.362	95.5
	704	11	2.405	1.165	1.022	81.4
2 1/4 Cr-1 Mo	538	26	7.030	1.075	0.795	65.4
	593	45	97.820	1.414	0.751	81.5
	649	28	36.122	1.316	0.536	84.0

those given in refs. 26 and 27. Also, the implied temperature dependence of e_g is in agreement with the results of ref. 24. Figure 6 illustrates the fit of Eq. (3) to the data.

Predictions from Eqs. (8) and (9) can be compared with experimental data in several ways. Figure 7 illustrates comparisons between experimentally measured values for e_3 and values of e_3 calculated by the above equations for type 304 stainless steel. Considering the large amount of scatter inherent in the data, the agreement in this figure is good.

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[26] R. F. Gill and R. M. Goldhoff, "The Analysis of Long-Time Creep Data for Determining Long-Term Creep Strength," *Met. Eng. Q.* 10: 30–39 (1970).

[27] R. L. Klueh, *The Relationship Between Rupture Life and Creep Properties of 2 1/4 Cr–1 Mo Steel,* ORNL-TM-4522 (May 1974).

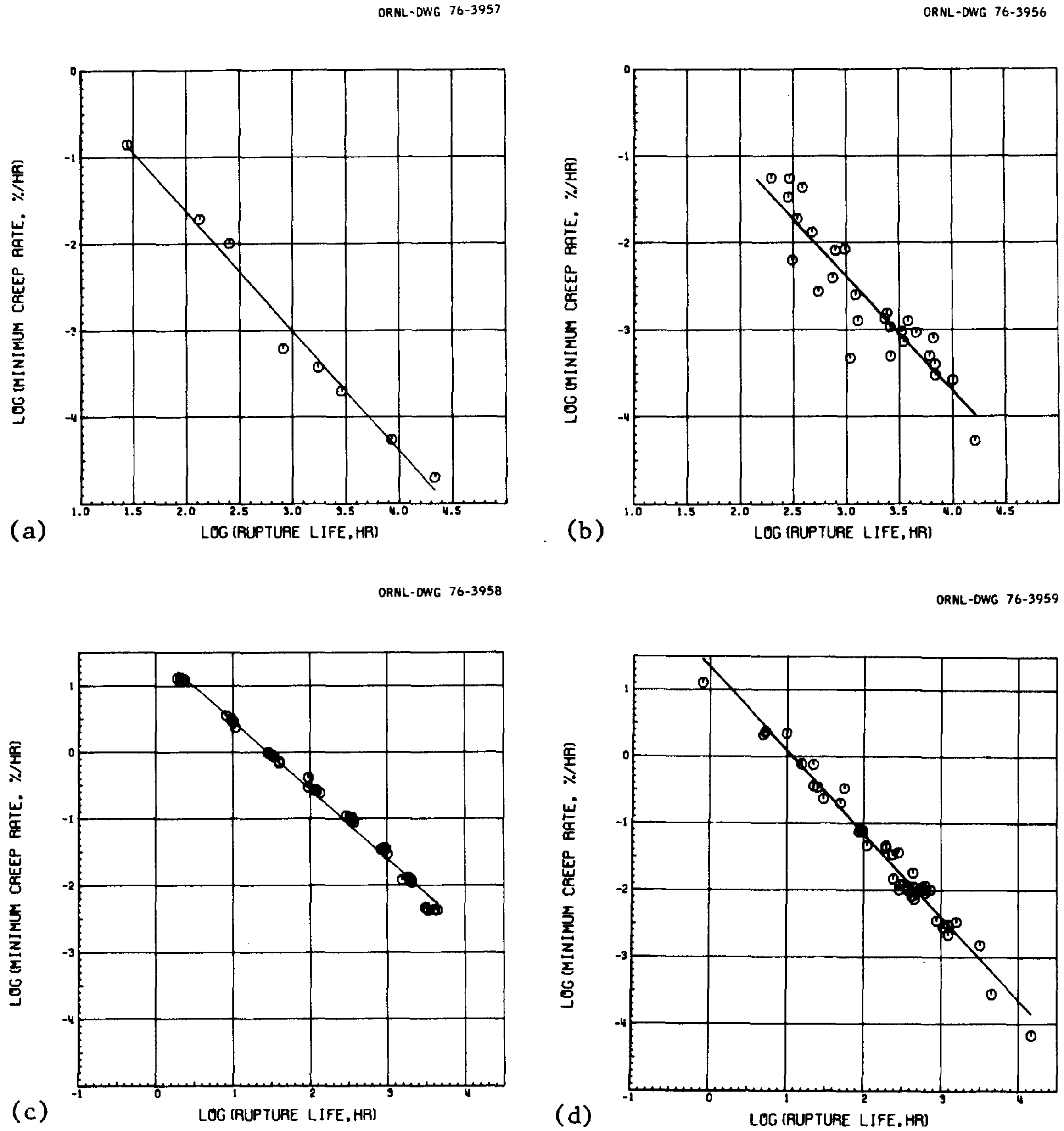

Fig. 6. Isothermal Relationship Between Rupture Life and Minimum Creep Rate for (a) Inconel Alloy 718; (b) 2 1/4 Cr-1 Mo Steel; (c) Type 316 Stainless Steel; and (d) Type 304 Stainless Steel.

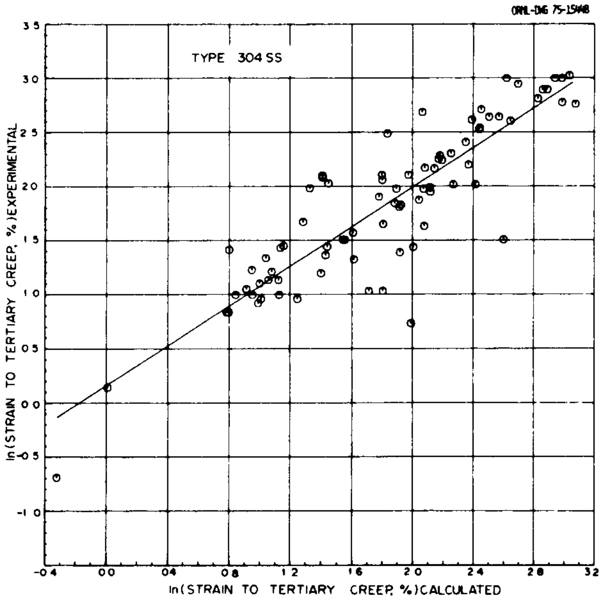

Fig. 7. Comparison of Experimentally Measured Strain to Tertiary Creep with Calculations from Eq. (5) for Type 304 Stainless Steel.

To assess the trends in the data and in the calculated values with time, stress, and temperature, several approaches can be taken. For a plot of e_3 vs t_r (as in Fig. 8), Eqs. (9) and (10) can be evaluated by simply substituting in them a series of values for t_r. These equations will yield average predictions for a material, with no measure of variations due to heat differences, heat treatment, etc. However, that the equations appear applicable to multiple heats indicates that such variations are relatively small. To evaluate Eq. (8), one must have a means for choosing the appropriate value of $\dot{e}_m$ for a given value of t_r. If this choice is made by means of Eq. (3), then Eq. (10) results. For a given heat of material, however, more accurate results might be obtained as follows (if enough data are available). First, fit both the rupture life and minimum creep rate data by some mathematical model, such as a time-temperature parameter,[28] yielding equations of the form

$$t_r = F(\sigma,T) \ , \tag{11}$$

$$\dot{e}_m = G(\sigma,T) \ , \tag{12}$$

where

σ = stress,
T = temperature, and
F and G = functions.

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[28] J. B. Conway, *Stress-Rupture Parameters, Origin, Calculation, and Use*, Gordon and Breach, New York, 1969.

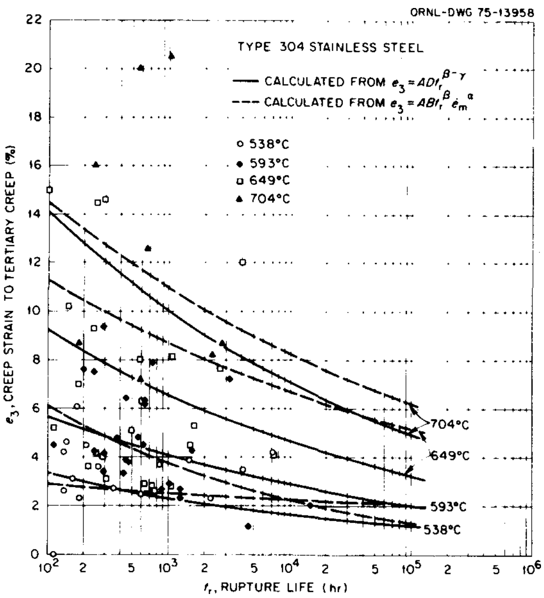

Fig. 8. Variation of Strain to Tertiary Creep with Stress for Type 304 Stainless Steel. Lines calculated by Eqs. (8) and (9).

At the chosen values for T and t_r, Eq. (11) can be solved for σ; substituting these values for T and σ into Eq. (12) yields a value for $\dot{e}_m$. (This procedure is, of course, identical to the parametric prediction of e_s in ref. 24.) The dashed lines in Fig. 8 were calculated by this method, using the Orr-Sherby-Dorn[29] parametric results from ref. 24 from a simultaneous fit to all four data sets of type 304 stainless steel. As discussed in ref. 24, it might be more meaningful to plot e_3 vs σ at various temperatures. Figures 2, 3, and 9–11 illustrate results obtained from such plots for individual heats of material. The abscissa in these plots is the σ value obtained in solving Eq. (11) for the calculated values. The results agree reasonably well with the data and indicate general trends fairly well. Also, as shown in Figs. 2, 3, 9, and 11, the results are quite comparable to the parametric results from ref. 24. It should be noted that, although Eqs. (9) and (10) do not yield different predictions for different heats for e_3 as a function of t_r, they can yield different predictions in terms of stress, since different heats can have different rupture strengths.[20,21] Tables 7 and 8 display results obtained by calculating e_3 at various time levels for the current data sets.

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[29] R. L. Orr, O. D. Sherby, and J. E. Dorn, "Correlations of Rupture Data for Metals at Elevated Temperatures," *Trans. Am. Soc. Met.* 46: 113–28 (1954).

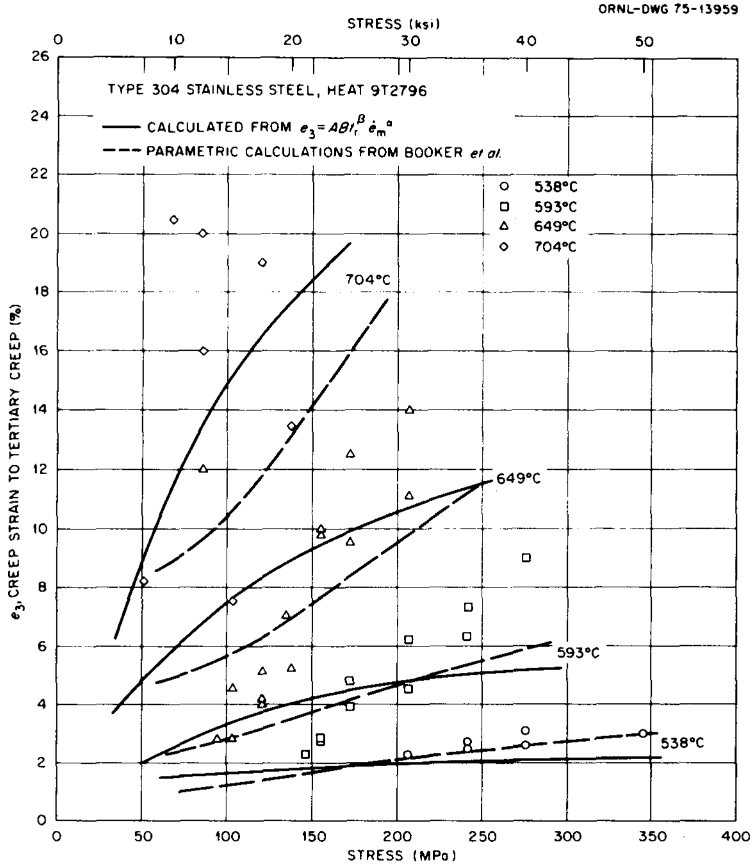

Fig. 9. Variation of Strain to Tertiary Creep with Stress for Heat 9T2796 (25-mm Plate) of Type 304 Stainless Steel. Solid lines were calculated by Eq. (8); dashed lines from ref. 11.

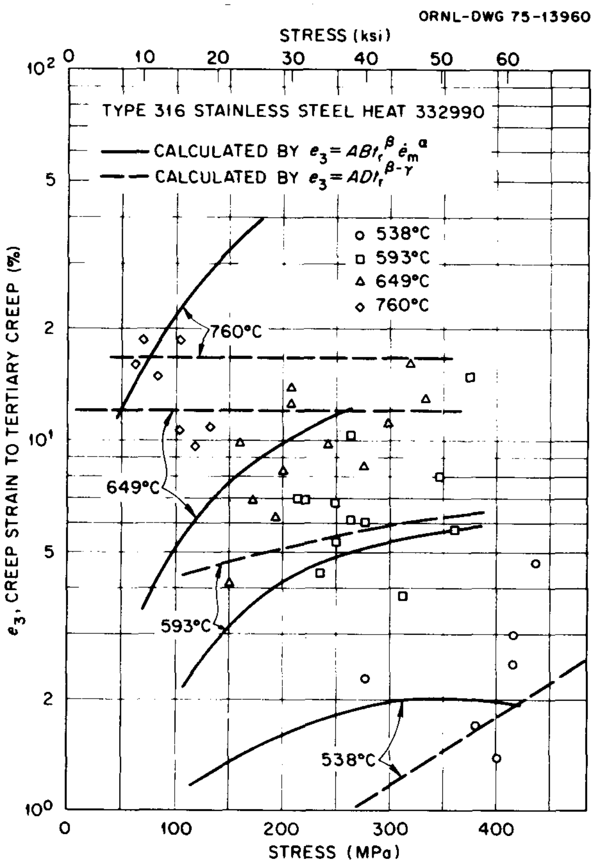

Fig. 10. Variation of Strain to Tertiary Creep with Stress for Heat 332990 of Type 316 Stainless Steel. Lines calculated by Eqs. (8) and (9).

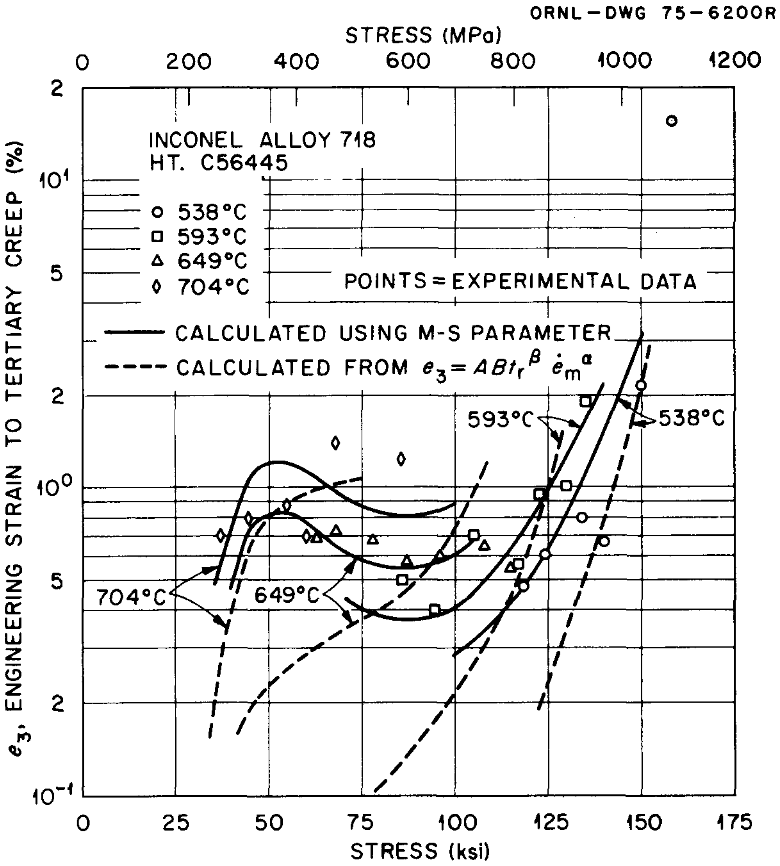

Fig. 11. Variation of Strain to Tertiary Creep with Stress for Heat C56445 of Inconel Alloy 718. Solid lines from ref. 24; dashed lines calculated by Eq. (8).

For the austenitic stainless steels, at a given stress, e_3 generally increases with temperature from 538 to 704°C (1000 to 1299°F). Also, these materials tend to exhibit a decrease in e_3 at constant temperature as the stress is decreased (or rupture life is increased). Trends in the data for Inconel alloy 718 are less clear, although again there is a general tendency for e_3 to increase with either stress or temperature as the other remains constant. As in ref. 24, no clear trends were apparent in the data for 2 1/4 Cr-1 Mo steel, presumably due largely to heat-to-heat and heat treatment variations among the data used, although this material displays variations in the shapes of the creep curves.[30,31]

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[30] M. K. Booker et al., *Mechanical Property Correlations for 2 1/4 Cr-1 Mo Steel in Support of Nuclear Reactor Systems Design*, ORNL/TM-5329 (June 1976).

[31] R. L. Klueh, *The Creep and Rupture Behavior of Annealed 2 1/4 Cr-1 Mo Steel*, report in preparation.

Table 7. Predicted Values for Creep Strain to Tertiary Creep from Eq. (8)

Temperature		Predicted Strain, %, for Rupture Time[a]			
(°C)	(°F)	10^2 hr	10^3 hr	10^4 hr	10^5 hr
Heat 9T2796 25-mm Plate 304 Stainless					
538	1000	2.13(0.83)	2.03(0.79)	1.85(0.72)	1.61(0.63)
593	1100	4.75(1.85)	4.25(1.66)	3.60(1.40)	2.85(1.11)
649	1200	9.01(3.51)	7.47(2.91)	5.81(2.26)	4.30(1.68)
704	1300	14.46(5.64)	11.16(4.35)	8.22(3.20)	5.98(2.33)
Heat 9T2796 51-mm Plate 304 Stainless					
538	1000	1.24(0.48)	1.25(0.49)	1.07(0.42)	0.80(0.31)
593	1100	3.82(1.49)	3.02(1.18)	2.14(0.83)	1.56(0.61)
649	1200	7.64(2.98)	5.36(2.09)	4.18(1.63)	3.99(1.56)
704	1300	12.60(4.91)	10.26(4.00)	10.28(4.01)	12.37(4.82)
Heat 55697 7.0-mm Rod 304 Stainless					
538	1000	2.88(1.12)	2.06(0.80)	1.68(0.66)	1.39(0.54)
593	1100	5.53(2.16)	4.61(1.80)	3.70(1.44)	2.10(0.82)
649	1200	11.60(4.52)	8.94(3.49)	4.47(1.74)	0.91(0.35)
Heat 8043813 25-mm Plate 304 Stainless					
538	1000	7.08(2.76)	5.20(2.03)	3.64(1.42)	2.41(0.94)
593	1100	9.92(3.87)	6.54(2.55)	4.08(1.59)	2.47(0.96)
649	1200	11.00(4.29)	6.66(2.60)	4.06(1.58)	2.67(1.04)
704	1300	10.88(4.24)	6.90(2.69)	4.88(1.90)	3.94(1.54)
Heat 332990 7.0-mm Rod 316 Stainless					
538	1000	1.96(0.88)	2.02(0.91)	1.86(0.84)	1.56(0.70)
593	1100	5.25(2.36)	4.56(2.05)	3.64(1.64)	2.69(1.21)
649	1200	10.20(4.59)	7.88(3.55)	5.70(2.57)	3.96(1.78)
760	1400	15.95(7.18)	11.39(5.13)	7.93(3.57)	
Garofalo et al. 12.7-mm Bar 316 Stainless					
593	1100	6.68(1.60)	8.62(2.07)	10.32(2.48)	10.81(2.59)
649	1200	13.28(3.19)	15.35(3.68)	15.05(3.61)	11.22(2.69)
704	1300	21.26(5.10)	20.10(4.82)	14.26(3.42)	7.87(1.89)
2 1/4 Cr-1 Mo Various Heats					
482	900	0.44(0.10)	1.72(0.41)	4.43(1.06)	8.35(2.00)
538	1000	1.19(0.28)	2.69(0.64)	4.56(1.09)	6.14(1.47)
593	1100	1.56(0.37)	2.52(0.60)	3.26(0.78)	3.63(0.87)
649	1200	1.42(0.34)	1.82(0.44)	2.01(0.48)	
Inconel Alloy 718 Heat C56445 25.4-mm Pancake					
538	1000	2.34(0.40)	0.65(0.11)	0.20(0.03)	0.08(0.01)
593	1100	1.00(0.17)	0.36(0.06)	0.17(0.03)	0.10(0.02)
649	1200	0.76(0.13)	0.42(0.07)	0.31(0.05)	0.16(0.03)
704	1300	1.09(0.18)	0.86(0.15)	0.15(0.02)	0.00(0.00)
Inconel Alloy 718 Heat Y8509 15.9-mm Bar					
538	1000	2.12(0.36)	0.65(0.11)	0.21(0.04)	0.07(0.01)
593	1100	1.02(0.17)	0.34(0.06)	0.12(0.02)	0.05(0.01)
649	1200	0.60(0.10)	0.22(0.04)	0.10(0.02)	0.06(0.01)
704	1300	0.45(0.08)	0.23(0.04)	0.13(0.02)	0.03(0.01)

[a] Values in parentheses are lower limits.

Table 8. Predicted Values for Creep Strain to Tertiary Creep from Eq. (9)

Temperature		Predicted Strain, %, for Rupture Time[a]			
(°C)	(°F)	10^2 hr	10^3 hr	10^4 hr	10^5 hr
		Type 304 Stainless Steel			
538	1000	2.88(0.69)	2.55(0.61)	2.26(0.54)	2.00(0.48)
593	1100	6.13(1.41)	3.69(0.85)	2.22(0.51)	1.33(0.30)
649	1200	11.26(2.82)	8.70(2.18)	6.72(1.68)	5.20(1.30)
704	1300	14.25(3.42)	10.97(2.63)	8.28(1.99)	6.25(1.50)
760	1400	19.15(6.13)	16.80	14.73(5.38)	12.92(4.13)
		Type 316 Stainless Steel — G			
593	1100	11.32(5.21)	9.55(4.39)	8.05(3.70)	6.79(3.12)
704	1300	18.22(8.02)	15.26(6.71)	12.78(5.62)	10.70(4.71)
816	1500	14.31(6.44)	11.39(5.12)	9.07(4.08)	7.22(3.25)
		Type 316 Stainless Steel — H			
538	1000	1.88(0.28)	1.33(0.20)	0.94(0.14)	0.67(0.10)
593	1100	5.75(1.15)	5.32(1.06)	4.92(0.98)	4.54(0.91)
649	1200	12.16(4.86)	12.13(4.85)	12.10(4.84)	12.07(4.83)
760	1400	16.67(7.00)	16.67(7.00)	16.67(7.00)	16.67(7.00)
		Inconel 718 — T			
593	1100	0.85(0.02)	0.85(0.02)	0.84(0.02)	0.84(0.02)
649	1200	1.90(0.30)	0.76(0.12)	0.30(0.05)	0.12(0.02)
704	1300	0.16(0.06)	0.35(0.14)	0.75(0.31)	1.62(0.66)
760	1400	0.75(0.06)	0.62(0.05)	0.52(0.04)	0.43(0.03)
		Inconel 718 — C			
538	1000	2.34(0.09)	0.97(0.04)	0.40(0.02)	0.16(0.01)
593	1100	0.76(0.17)	0.51(0.12)	0.34(0.08)	0.23(0.05)
649	1200	0.58(0.20)	0.61(0.21)	0.65(0.23)	0.68(0.24)
704	1300	1.19(0.20)	0.77(0.13)	0.50(0.08)	0.33(0.06)
		2 1/4 Cr-1 Mo Steel			
538	1000	2.28(0.32)	3.17(0.44)	4.40(0.62)	6.12(0.86)
593	1100	5.88(0.65)	3.43(0.38)	2.00(0.22)	1.17(0.13)
649	1200	3.20(0.35)	2.32(0.26)	1.69(0.18)	1.22(0.13)

[a] Values in parentheses are lower limits.

Figure 12 illustrates predictions for e_s determined from Eq. (4) in comparison with raw data and the results from ref. 24. Table 9 shows the predicted values for e_s analogous to those of Tables 7 and 8 for e_3. Trends in e_s and e_3 appear similar, indicating that e_s may indeed provide a measure of e_3. Figure 13 illustrates a comparison between values of e_s and e_3 at 593°C (1099°F) for the 25-mm (1-in.) plate of heat 9T2796 of type 304 stainless steel, which in this case shows excellent agreement. In fact, as can be seen from the data in the appendix, the agreement is, in general, good, especially considering the scatter involved.

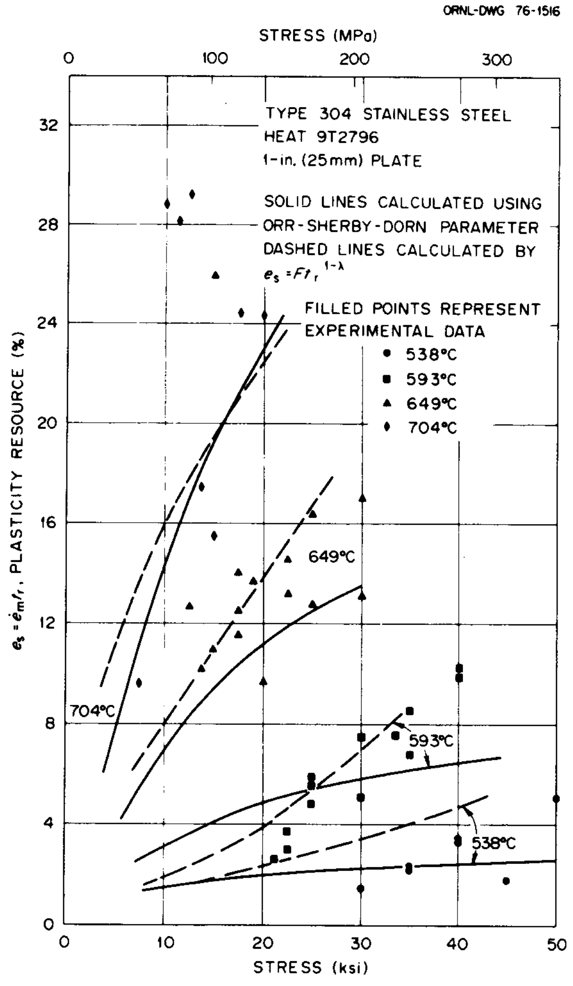

Fig. 12. Variation of Plasticity Resource, $e_s = \dot{e}_m t_r$, with Stress and Temperature for Type 304 Stainless Steel Heat 9T2796 (1-in. Plate).

Table 9. Predicted Values for Plasticity Resource from Eq. (4)

Temperature		Predicted Strain, %, for Rupture Time			
(°C)	(°F)	10^2 hr	10^3 hr	10^4 hr	10^5 hr
		Type 304 Stainless Steel			
538	1000	5.07(1.72)	3.89(1.32)	2.98(1.01)	2.29(0.78)
593	1100	6.98(2.72)	4.61(1.80)	3.05(1.19)	2.01(0.78)
649	1200	14.18(6.24)	10.78(4.74)	8.20(3.61)	6.23(2.74)
704	1300	19.27(7.52)	15.81(6.16)	12.97(5.06)	10.64(4.15)
760	1400	25.89(16.31)	23.50(14.80)	21.34(13.44)	19.37(12.20)
		Type 316 Stainless Steel			
538	1000	3.59(1.04)	2.10(0.61)	1.23(0.36)	0.72(0.21)
593	1100	6.96(3.76)	7.26(3.92)	7.56(4.08)	7.89(4.26)
649	1200	21.57(11.22)	21.57(11.22)	21.57(11.22)	21.57(11.22)
704	1300	27.08(17.33)	24.81(15.88)	22.73(14.55)	20.83(13.33)
760	1400	28.81(18.15)	28.61(18.02)	28.41(17.90)	28.22(17.78)
816	1500	24.47(16.88)	20.26(13.98)	16.77(11.57)	13.89(9.58)
		Inconel Alloy 718			
538	1000	2.33(0.65)	0.98(0.27)	0.41(0.11)	0.17(0.05)
593	1100	1.06(0.11)	0.65(0.06)	0.40(0.04)	0.25(0.02)
649	1200	0.72(0.15)	0.52(0.11)	0.38(0.08)	0.27(0.06)
704	1300	1.12(0.09)	0.77(0.06)	0.53(0.04)	0.36(0.03)
		2 1/4 Cr-1 Mo Steel			
538	1000	4.98(0.70)	4.19(0.59)	3.52(0.49)	2.96(0.41)
593	1100	14.54(2.47)	5.60(0.95)	2.16(0.37)	0.83(0.14)
649	1200	8.43(1.69)	4.07(0.81)	1.97(0.39)	0.95(0.19)

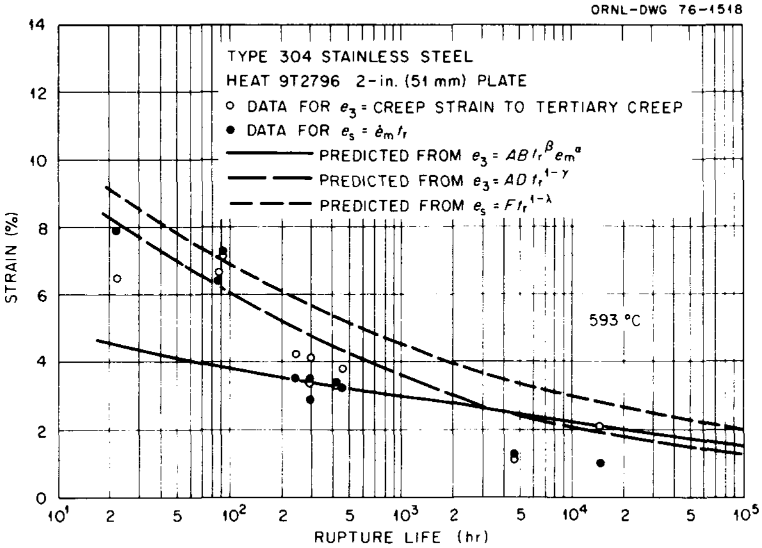

Fig. 13. Comparison of Plasticity Resource and Creep Strain to Tertiary Creep for Type 304 Stainless Steel Heat 9T2796 (2-in. Plate).

LIMITS

Equations (4), (8), (9), and (10) yield the creep strain to tertiary creep, e_3, and the plasticity resource, e_s, as functions of rupture life or rupture life and minimum creep rate. These equations are based on the applicability of Eqs. (3), (5), (6), and (7), which has been directly demonstrated only within the range of experimental data. The discussion in ref. 32 indicates that Eq. (7) is indeed extrapolable to times beyond the range of experimental data, at least over a limited range. Extrapolation of creep data is a common but difficult problem in any case, so more work with Eqs. (3), (5), and (6) probably needs to be done before their extrapolability is verified. However, limited extrapolation is felt to be justified, say, to rupture lives of 10^5 hr and the corresponding values of minimum creep rate.

Due to uncertainty in the predicted values of e_3 (or e_s), especially in the extrapolated regime, it is of interest to calculate lower-limit values of e_3 and e_s. Unfortunately, this calculation cannot be done with confidence by ordinary direct statistical means because of the large scatter and nonnormality in the distribution of the data about the predicted values. Thus the recommended procedure is to calculate lower

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[32] M. K. Booker and V. K. Sikka, "Interrelationships Between Creep Life Criteria for Four Nuclear Structural Materials," presented at 1975 Annual Meeting, American Nuclear Society, New Orleans (June 1975); to be published in *Nuclear Technology*; also ORNL-TM-4997 (August 1975).

limits on t_3 and $\dot{e}_3$ (say t_3' and $\dot{e}_3'$) separately. Then the lower limit on $e_3(e_3')$ can be found by

$$e_3' = \dot{e}_3' t_3' \ . \tag{13}$$

In the present case, $\dot{e}_3$ and t_3' have been calculated logarithmically by

$$\ln \dot{e}_3' = \ln \dot{e}_3 - C_1 S_1 \ , \tag{14}$$

$$\ln t_3 = \ln t_3 - C_2 S_2 \ , \tag{15}$$

where S_1 and S_2 are the standard errors of estimate of ln $\dot{e}_3$ and ln t_3, respectively, and C_1 and C_2 are constants chosen from tolerance tables[33] such that, at a confidence level of 95%, 90% of the values of ln $\dot{e}_3$ and ln t_3 are expected to fall above the lower limits. Thus

$$\ln e_3' = \ln e_3 - C_1 S_1 - C_2 S_2 \ , \tag{16}$$

or

$$e_3' = e^{-C_1 S_1} \ e^{-C_2 S_2} \ e_3 \ , \tag{17}$$

where $e^{-C_1 S_1}$ and $e^{-C_2 S_2}$ are so-called "safety factors" on $\dot{e}_3$ and t_3, tabulated for the equations used in Table 10. The parenthesized values in Tables 7–9 are calculated lower-limit values.

The lower-limit values shown in the tables on the surface often appear quite conservative, but such conservatism is due mainly to uncertainty in the data and is not felt to be unrealistic. As shown in Fig. 14, data for e_s from a large number of heats of type 304 stainless steel taken from the literature[34] show the lower limits to be reasonable estimates.

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[33] W. H. Beyer, ed., *Handbook of Tables for Probability and Statistics*, Chemical Rubber Co., Cleveland, Ohio, 1966, p. 34.

[34] W. F. Simmons and J. A. Van Echo, *Report on the Elevated-Temperature Properties of Stainless Steels, ASTM Data Ser. Publ. DS 5-S1*, American Society for Testing and Materials, Philadelphia, 1965.

Table 10. Safety Factors for Calculation of Minimum Values[a]

Data Set	Temperature (°C)	Safety Factors on Dependent Variable in					
		Eq. (5)	Eq. (6)	Eq. (7)	Eq. (8)[b]	Eq. (9)[c]	Eqs. (3), (4)
304 Stainless	538	0.66	0.40	0.59	0.39	0.24	0.34
	593	0.66	0.39	0.59	0.39	0.23	0.39
	649	0.66	0.43	0.59	0.39	0.25	0.44
	704	0.66	0.41	0.59	0.39	0.24	0.39
	760	0.66	0.55	0.59	0.39	0.32	0.63
316 Stainless — G	593	0.38	0.74	0.62	0.24	0.46	0.54
	704	0.38	0.71	0.62	0.24	0.44	0.64
	816	0.38	0.73	0.62	0.24	0.45	0.69
316 Stainless — H	538	0.73	0.24	0.62	0.45	0.15	0.29
	593	0.73	0.33	0.62	0.45	0.20	0.54
	649	0.73	0.65	0.62	0.45	0.40	0.52
	760	0.73	0.67	0.62	0.45	0.42	0.63
Inconel 718 — T	593	0.30	0.04	0.58	0.17	0.02	0.10
	649	0.30	0.27	0.58	0.17	0.16	0.21
	704	0.30	0.71	0.58	0.17	0.41	0.08
	760	0.30	0.14	0.58	0.17	0.08	
Inconel 718 — C	538	0.29	0.07	0.58	0.17	0.04	0.28
	593	0.29	0.39	0.58	0.17	0.23	0.10
	649	0.29	0.60	0.58	0.17	0.35	0.21
	704	0.29	0.30	0.58	0.17	0.17	0.08
2 1/4 Cr-1 Mo	538	0.40	0.23	0.62	0.25	0.14	0.14
	593	0.40	0.18	0.62	0.25	0.11	0.17
	649	0.40	0.24	0.62	0.25	0.15	0.20

[a] Minimum value of e_3, $\dot{e}_3$, or t_3 is given by the product of the expected value and the safety factor.

[b] Safety factor on Eq. (8) is the product of the factors from Eqs. (5) and (7). This factor does not include a measure of the uncertainty in the value of $\dot{e}_m$ for a given t_r, but is felt to be adequately conservative.

[c] Safety factor on Eq. (9) is the product of the factors from Eqs. (6) and (7).

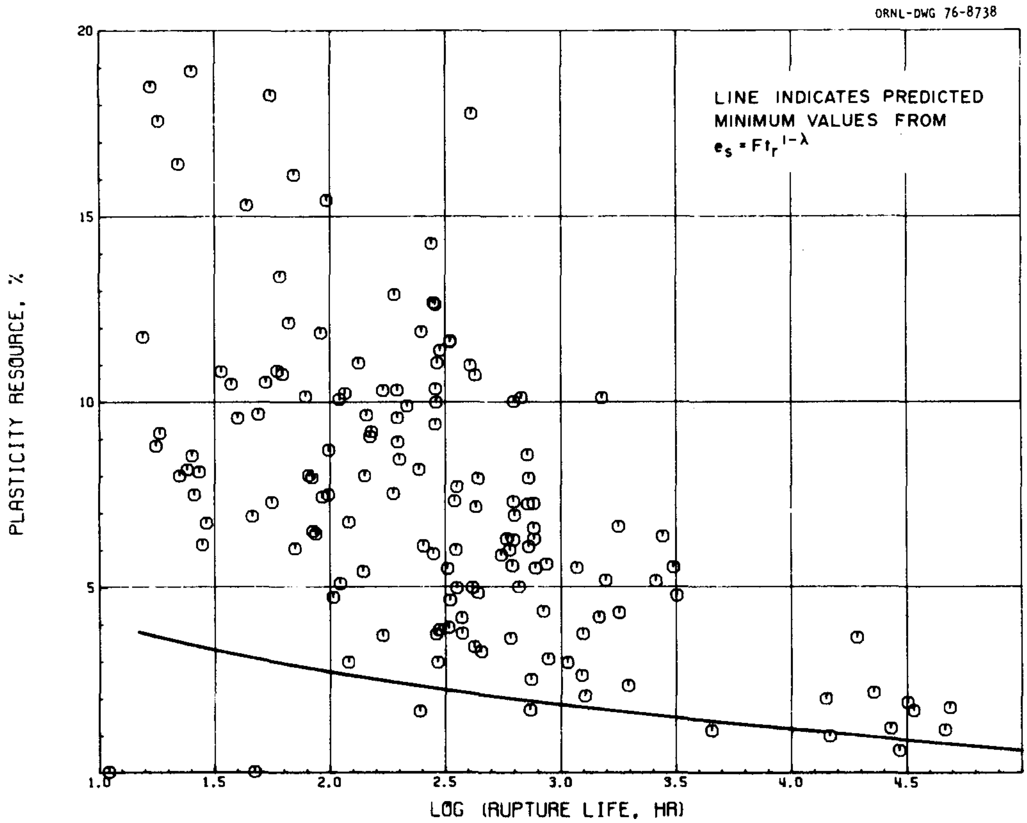

Fig. 14. Comparison of Data for Plasticity Resource of Type 304 Stainless Steel from the Literature with the Current Minimum Predictions.

MODELING OF TEMPERATURE DEPENDENCE

Variations in the above relationships [Eqs. (3) and (5)] can be examined by explicit modeling of the form

$$\dot{e}_m = f_1(t_r,T) \ , \tag{18}$$

$$\dot{e}_3 = f_2(t_r,T) \ . \tag{19}$$

No extensive investigations of this type have been attempted, but all data have been examined using simple expressions of the form

$$\dot{e}_m = F_0 e^{-Q/RT} t_r^{-\lambda_0} \ , \tag{20}$$

$$\dot{e}_3 = D_0 e^{-Q'/RT} t_r^{-\gamma_0} \ , \tag{21}$$

where F_0, D_0, λ_0, γ_0, Q, and Q' are temperature-independent material constants, R is the gas constant (R = 1.99 cal deg^{-1} mole^{-1}), and T is the temperature in kelvins.

Results of correlations using Eqs. (20) and (21) are summarized in Tables 11 and 12. As illustrated in Figs. 15 and 16, the correlation again is quite good except for the 2 1/4 Cr-1 Mo steel.

Equations (20) and (21) immediately yield corresponding expressions for e_s and e_3 of the form

$$e_s = F_0 e^{-Q/RT} t_r^{1-\lambda_0} \ , \tag{22}$$

$$e_3 = AD_0 e^{-Q'/RT} t_r^{\beta-\gamma_0} \ . \tag{23}$$

Note that in Tables 11 and 12 a negative Q value indicates a decrease in ductility with temperature, while a positive Q value indicates that ductility increases with temperature. Similarly, $\lambda_0 > 1$ indicates a decrease in e_s with time, and $\gamma_0 > \beta$ indicates a decrease in e_3 with time.

Table 11. Results of Correlation Among Minimum Creep Rate, Rupture Life, and Temperature[a]

Data Set	Number of Points	F_0	Q	λ_0	RMS[b]	R^2[c]	Temperature Range of Data (°C)
304 Stainless	144	56552	14524	1.133	0.0424	97.3	482–816
316 Stainless G	159	15999	12998	1.020	0.0344	97.0	538–760
Inconel 718	46	0.324	−3965.7	1.215	0.119	91.5	538–760
2 1/4 Cr-1 Mo	128	0.229	−8349	1.280	0.179	73.1	454–677

[a] Minimum creep rate, $\dot{e}_m$, has been expressed as a function of rupture life, t_r, and temperature (°C), T, by $\dot{e}_m = F_0 e^{-Q/RT} t_r^{-\lambda_0}$, where R is the gas constant, R = 2 cal deg^{-1} mole^{-1}.

[b] RMS expressed in terms of ln ($\dot{e}_m$).

[c] Coefficient of determination.

Table 12. Results of Correlation Among Average Creep Rate to Tertiary Creep, Rupture Life, and Temperature[a]

Data Set	Number of Points	D_0	Q	γ_0	RMS[b]	R^2 (%)	Temperature Range of Data (°C)
304 Stainless	139	41725	14042	1.088	0.0380	97.3	482–816
316 Stainless G	120	132.7	2405	1.072	0.00996	99.1	593–816
316 Stainless H	38	205447	16816	1.064	0.0341	97.1	538–760
Inconel 718 T	18	0.157	−6462	1.226	0.0394	94.0	538–760
Inconel 718 C	26	2.99	−177.85	1.150	0.0378	97.6	538–704
2 1/4 Cr-1 Mo	115	0.07	−10134	1.196	0.132	71.9	482–677

[a] Average creep rate to tertiary creep, $\dot{e}_3$, has been expressed as a function of rupture life, t_r, and temperature (°C), T, by $\dot{e}_3 = D_0 e^{-Q/RT} t_r^{-\gamma_0}$, where R is the gas constant, $R = 2$ cal deg^{-1} mole^{-1}.

[b] RMS expressed in terms of ln ($\dot{e}_3$).

[c] Coefficient of determination.

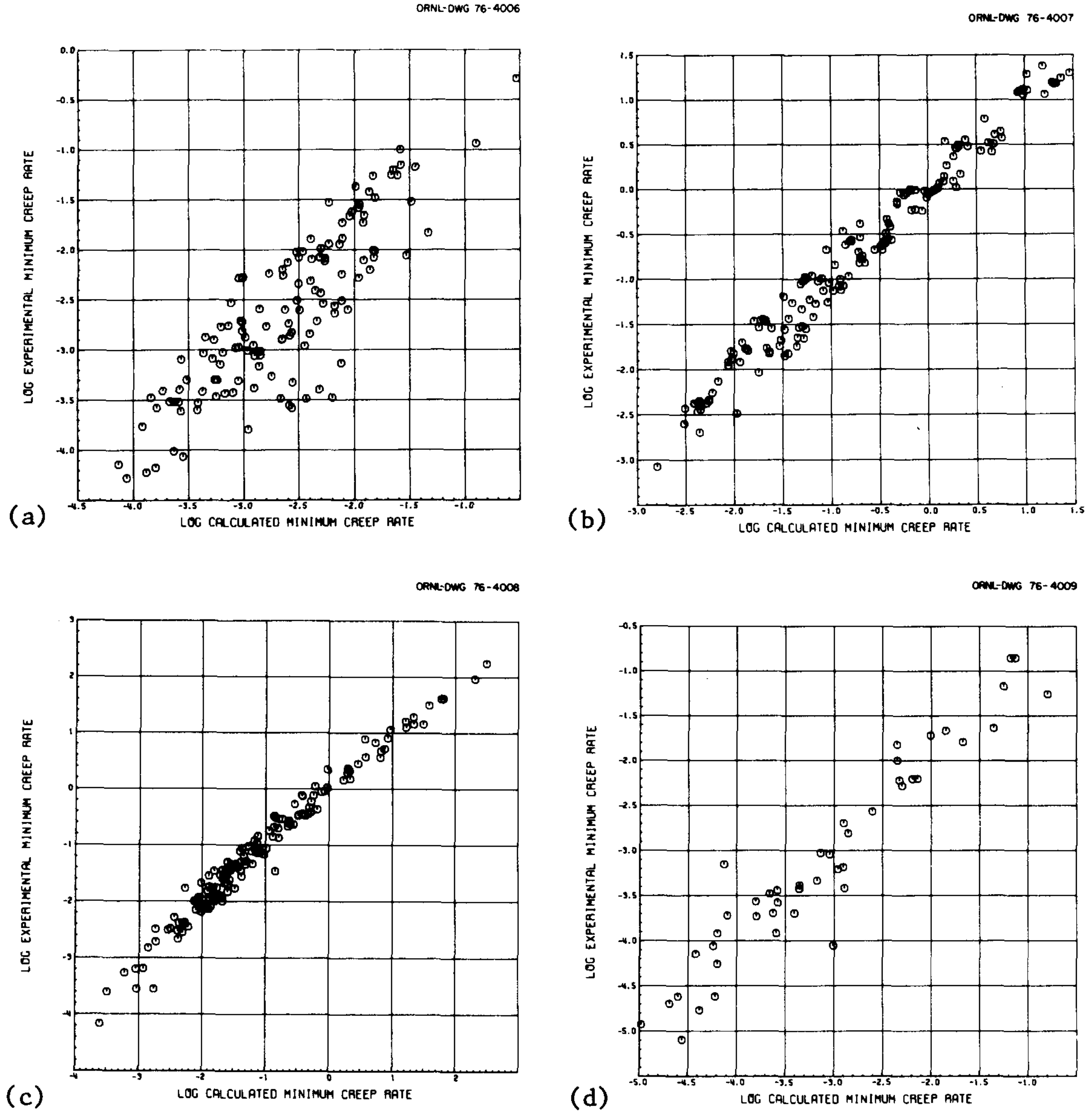

Fig. 15. Comparison of Predicted Values of Minimum Creep Rate with Experiment Values. Predicted $\dot{e}_m = F_0 e^{-Q/RT} t_r^{-\lambda_0}$. (a) 2 1/4 Cr-1 Mo steel. (b) Type 316 stainless steel. (c) Type 304 stainless steel. (d) Inconel alloy 718.

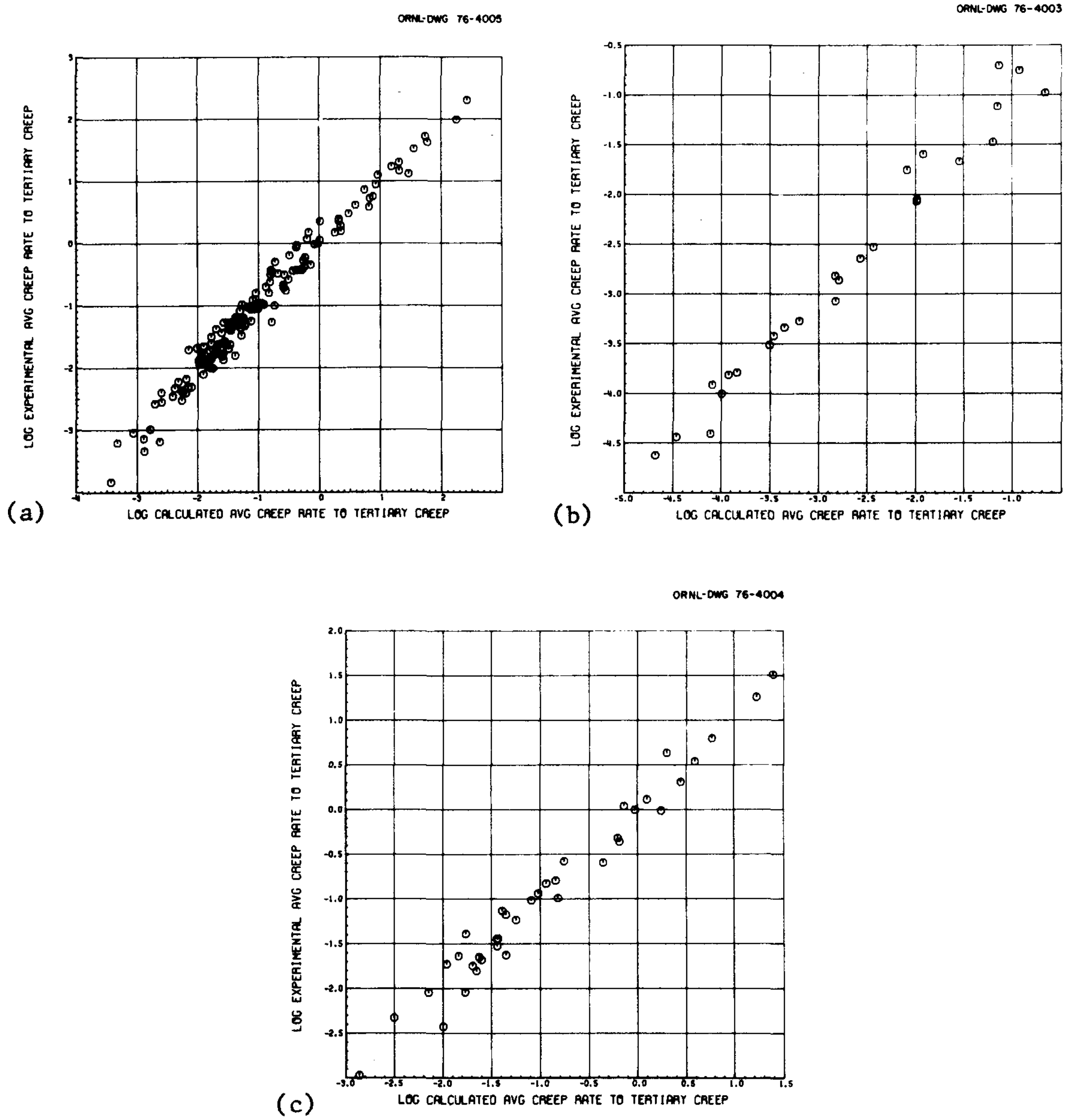

Fig. 16. Comparison of Predicted Values of Average Creep Rate to Tertiary Creep with Experimental Values. Predicted $\dot{e}_3 = D_0 e^{-Q'/RT} t_r^{-\gamma_0}$. (a) Type 304 stainless steel. (b) Inconel alloy 718 — heat C56445. (c) Type 316 stainless steel — heat 332990.

Figures 17 and 18 show the predicted trends in the behavior of the four materials considered here. The predictions compare well with those in Tables 7 through 9, although Eqs. (22) and (23) will not actually fit the particular data used quite as well as Eqs. (4), (8), and (9), due to the added uncertainty in the temperature term. However, by stipulating a consistent mathematical model, it is easier to discern and analyze trends.

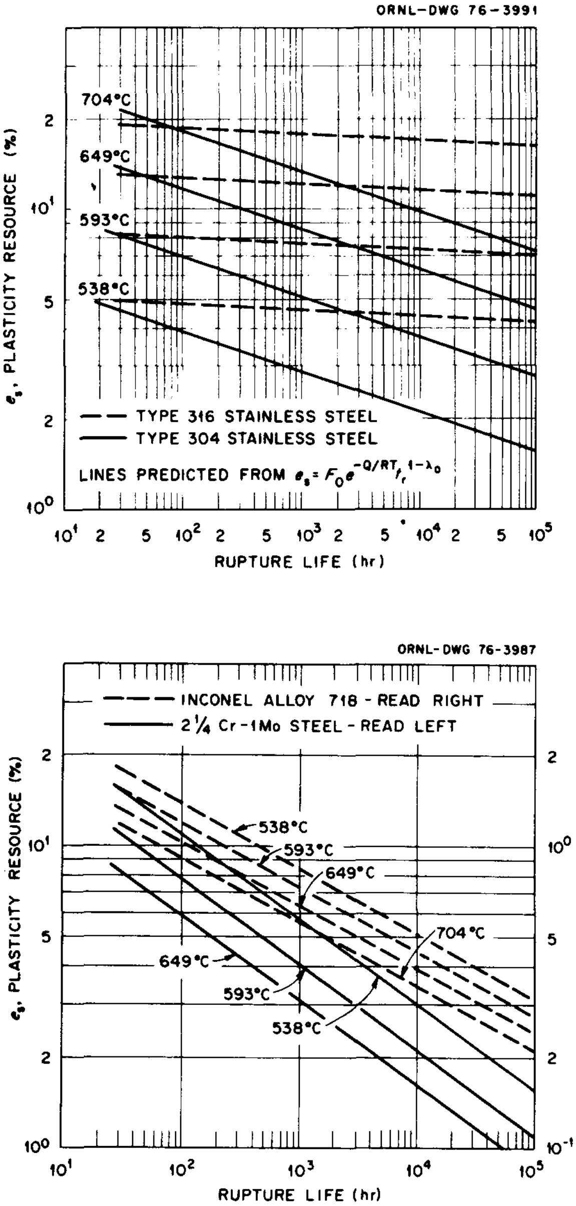

Fig. 17. Predicted Trends in Plasticity Resource from Eq. (20).

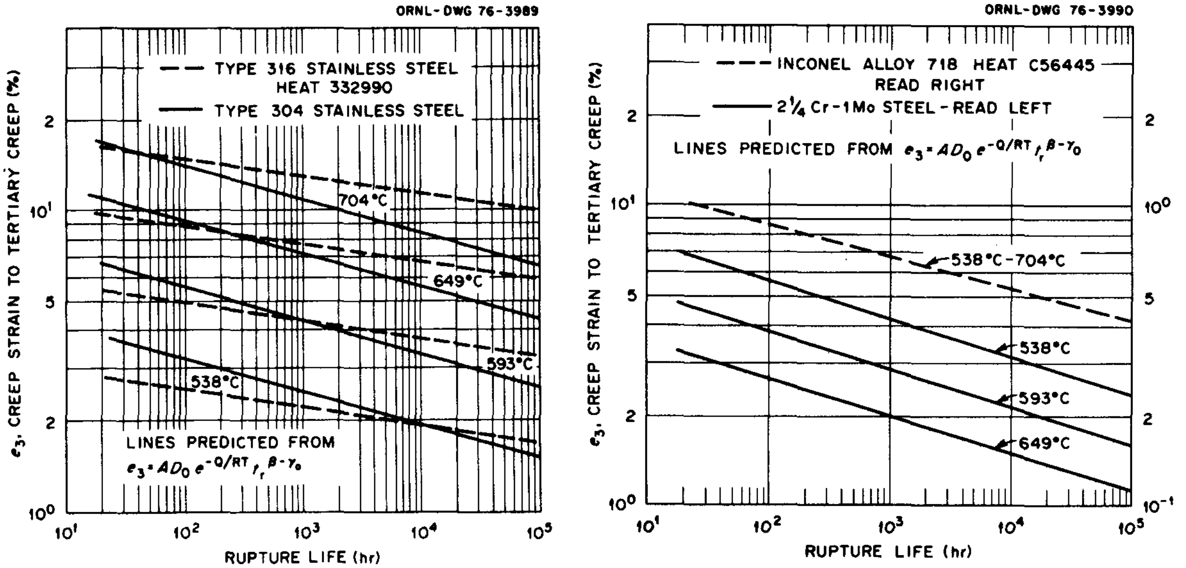

Fig. 18. Predicted Trends in Creep Strain to Tertiary Creep from Eq. (21).

DISCUSSION

Possible uses of ductility or strain limits in design have been briefly reviewed in ref. 35. Of the current methods, the creep equation method is preferred to establish a tertiary cutoff on the common primary-secondary creep equations for the sake of consistency. Otherwise, the parametric and empirical methods [Eqs. (8), (9), and (21)] are probably the most accurate, although the wide availability of data for e_s makes its use promising. Obviously, none of the above analytical procedures can yield a precise prediction for e_3, since, due to scatter, no single exact value exists. The current methods do, however, allow one to identify trends that might otherwise be hidden by the scatter. Thus, a designer might use such predictions to get some feel for how changes in operating conditions might affect material ductility or to aid in material selection. Also, the current predictions provide a basis for examining the current 1% strain limits in ASME Code Case 1592.[36] Tables 7–9 show predictions for strain to tertiary creep for the materials examined here for various values of rupture life, including estimated lower limits. It can be seen from these tables that

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[35] M. K. Booker, C. R. Brinkman, and V. K. Sikka, "Correlation and Extrapolation of Creep Ductility Data for Four Elevated-Temperature Structural Materials," pp. 108–45 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, American Society of Mechanical Engineers, New York, 1975.

[36] *Interpretations of the ASME Boiler and Pressure Vessel Code, Code Case 1592*, American Society of Mechanical Engineers, New York, 1974.

the predicted values for e_3 are in general well above 1%, except for the Inconel alloy 718 data. The lower-limit values can fall below 1% for all materials. However, the 1% strain limit includes both plastic and creep strains, whereas the predictions herein include creep strains only. Thus the current strain limits probably generally preclude the onset of tertiary creep under constant load, isothermal loading, except perhaps for Inconel alloy 718. Under conditions of variable load and/or temperature, the same will be true if strain hardening is indeed applicable, since in that case the ultimate values of e_3 would be the same as those in the former case. Unfortunately, actual data obtained under variable load and/or temperature conditions are relatively scarce.

Figure 19 illustrates results obtained from data generated in a recent investigation[37] on a 15.9-mm (5/8-in.) bar product of heat 9T2796 of type 304 stainless steel. For the variable-load tests, the stress in this figure is the stress level at which onset of tertiary creep occurred. As can be seen, e_3 under variable loading is at least comparable to constant load values of e_3, although the scatter in the variable loading data appears greater. If anything, the values of e_3 under variable loading seem larger than those in the constant-load case.

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[37] Babcock and Wilcox Corporation, private communication.

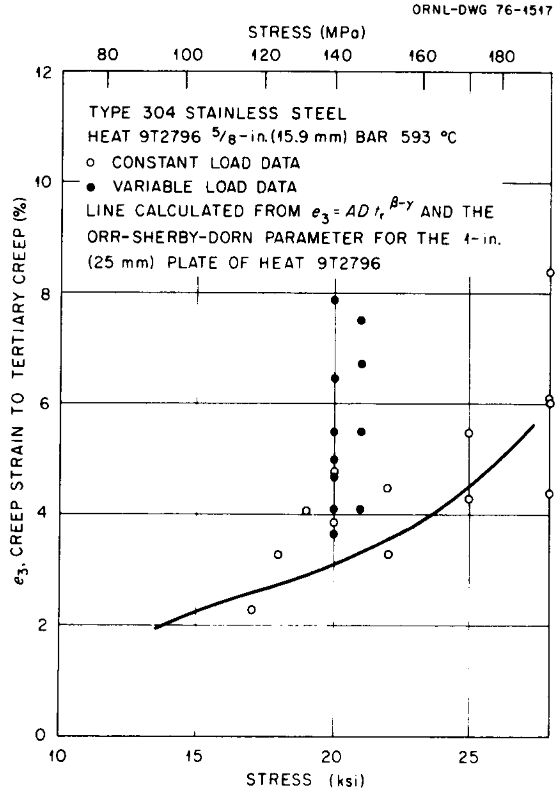

Fig. 19. Comparison of Strain to Tertiary Creep from Variable Load and Constant Load Tests on Type 304 Stainless Steel Heat 9T2796 (5/8-in. bar). Data from ref. 37.

These results tend to support $\dot{e}_3$ as a tertiary creep cutoff for variable-load data. It should be noted that onset of tertiary creep in these tests was determined by the 0.2% offset method. This quantity can be difficult to measure under variable loading conditions, since tertiary creep may be immediately entered as a result of a load change. Without a linear secondary creep portion preceding the onset of tertiary creep, it is of course impossible to determine the offset. In the present case, however, at least an apparent linear portion was present in all tests before the onset of tertiary creep at the final stress level. If this portion were actually part of the tertiary regime and the secondary regime, measured values of e_3 would thus be overestimated. Such difficulties may be one reason why the mean of the variable loading data is slightly above that for the constant-load data in Fig. 19.

The flexibility of the current method is decreased by the intrinsic property of Eqs. (8) through (10), which require e_3 to be a monotonically increasing or decreasing function of time [actually Eq. (8) could conceivably yield a maxima or minima in e_3 as a function of t_r]. Many investigators[38] have found creep ductility to pass through minima or maxima with time. If this situation is the case, however, one need merely express e_3 and t_3 as more flexible functions of $\dot{e}_m$ and t_r, yielding more flexible forms of the equations for e_3.

Finally, the general applicability of Eqs. (3), (6), (7), (18), and (19) and thus Eqs. (4), (8), (9), (10), (20), and (21) for a variety of materials is still open to question, since no fundamental physical reason for their applicability is apparent. Still, from an empirical standpoint, the equations appear applicable to the materials considered here. Although all are nuclear structural materials, they present a reasonably wide range of metallurgical characteristics.

The literature on tertiary creep deals with two basic questions. For example, Hart,[39] Franklin,[40] Burke and Nix,[41] and Soderberg[42] have tried to offer mechanical meaning to tertirary creep, whereas Garofalo,[43]

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[38] R. Viswanathan, "Strength and Ductility of 2 1/4 Cr-1 Mo Steels in Creep at Elevated Temperatures," *Met. Technol.* 1: 284–94 (June 1974).

[39] E. W. Hart, "Theory of Tensile Test," *Acta. Metall.* 15: 351–55 (1967).

[40] D. Franklin, "Theory of Plastic Instability in Thin-Wall Tubes," *Acta. Metall.* 20: 839–43 (1972).

[41] M. A. Burke and W. D. Nix, "Plastic Instabilities in Tension Creep," *Acta. Metall.* 23: 793–98 (1975).

[42] Rolf Soderberg, "Relationship Between Strain Rate and True Stress in the Tertiary Stage of Creep," *Scand. J. Metall.* 3: 268–72 (1974).

[43] F. Garofalo, "Ductility in Creep," pp. 88–129 in *Ductility*, American Society for Metals, Metals Park, Ohio, 1967.

Davies and Dutton,[44] Davies and Evans,[45] and Weaver[46] have contributed to the understanding of *metallurgical* phenomena relating to tertiary creep. Garofalo[43] indicated that no one single factor is responsible for the inception of tertiary creep. The factors generally mentioned in the literature include:

1. increasing stress under constant load (result of decrease in cross-section area caused by uniform deformation),
2. increasing stress due to necking,
3. void formation and cracking,
4. recovery,
5. recrystallization, and
6. precipitation or resolution of one or more phases.

In a given situation, one or several factors could be responsible for tertiary creep. For example, test results on an Al—2.6% Mg alloy at 0.6 to 0.7 T_m (melting temperature) showed[43] nucleation of intergranular cracking or necking, or both, to be responsible for initiation of tertiary creep. At high stress levels, tertiary creep was associated with necking. At intermediate stresses, tertiary creep was associated with the nucleation of rounded cavities just beneath the surface of the specimen. At low stresses no detectable necking occurred, and the onset of tertiary creep was associated with the nucleation of thin intergranular cavities throughout the entire test section.

It has further been mentioned[43] that although voids are considered to be responsible for the onset of tertiary creep, they can form long before the onset of the second stage. Garofalo[43] suggested that when voids are observed by the end of the primary stage, extensive secondary creep deformation is observed prior to the onset of tertiary creep. The initiation of tertiary creep in the absence of necking or void formation has also been indicated by Garofalo.[43] Based on what has been said above, the exact mechanism of tertiary creep appears to be quite complex and may vary from material to material. However, intuitively, tertiary creep strain is expected to depend on at least the following factors:

1. stress,
2. temperature,
3. composition and microstructure, and
4. environment.

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[44] P. W. Davies and R. Dutton, "On the Mechanisms of Tertiary Creep in Face-Centered Cubic Metals," *Acta. Metall.* 15: 1365—72 (1967).

[45] P. W. Davies and R. W. Evans, "The Contribution of Voids to the Tertiary Creep of Gold," *Acta. Metall.* 13: 353—61 (1965).

[46] C. W. Weaver, "Intergranular Cavitation, Structure, and Creep of a Nimonic 80A-Type Alloy," *J. Inst. Met.* 88: 296—300 (1959—60).

Materials studied in the present investigation had several differences in composition and microstructure. Moreover, the 2 1/4 Cr-1 Mo steel has a bcc crystal structure, while the other three materials are fcc. The general characteristics of these four materials are summarized in Table 13.

The strain at the onset of tertiary creep can be equated to the sum of intra- and intergranular deformation before the initiation of accelerated creep rate. Thus

$$e_3 = e_g + e_{gb} ,$$

where e_g and e_{gb} are intra- and intergranular strains respectively and depend on the relative strength of grain matrix and grain boundaries. Heat treatment causes the formation of no strengthening phases, so that the matrix and grain boundary strengths of annealed austenitic stainless steel are expected to be not too different. Applied creep stress can produce deformation both in the matrix and at grain boundaries. The matrix deformation results in a dislocation cell or subgrain structure which increases the matrix strength relative to the grain boundaries and thus causes stress concentration points at the grain boundaries. For test temperatures below 649°C (1200°F), precipitates at the grain boundaries are continuous and thus prevent[47] both grain boundary sliding and migration. The stress concentrations generated at triple points can nucleate[43] cracks, causing the onset of tertiary creep with only small strain at lower temperatures. At higher temperatures, $\geqslant$649°C (1200°F), precipitates at the grain boundary grow and make possible both grain boundary sliding and migration. The migration of grain boundaries can relax stresses, and thus a greater intergranular deformation can be tolerated before the initiation of tertiary creep. Such a mechanism causes an increase in the strain to tertiary creep with increasing temperature, which is consistent with the analytical predictions made in the present investigation. Likewise, higher stresses result in more extensive intragranular deformation and thus more strain before the onset of tertiary creep.

For Inconel alloy 718,[48] the matrix is greatly strengthened by the presence of a γ' phase, while carbides are precipitated. In the matrix near the grain boundaries, however, is a γ phase which is denuded of hardening elements and this is relatively weak. Thus, the strain before the onset of tertiary creep is expected to concentrate only in these

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[47] F. Garofalo, R. W. Whitmore, and F. Von Gemmingen, "Creep and Creep-Rupture Relationships in an Austenitic Stainless Steel," *Trans. Metall. Soc. AIME* 221: 310–19 (1961).

[48] H. L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," pp. 62–78 in *Advances in the Technology of Stainless Steels and Related Alloys*, ASTM STP No. 369, American Society for Testing and Materials, Philadelphia, 1965.

Table 13. Summary of Typical Characteristics of Four Materials Used in the Present Investigation

Material	Crystal Structure	Heat Treating Characteristics	Precipitate Phases	Crack Initiation Creep Stage	Type of Fracture	Tertiary Creep Strain Behavior
304 Stainless	fcc	Insensitive to heat treatment, except through grain growth Aging makes this steel unstable	Carbides in matrix and grain boundaries	Before onset of tertiary creep[a]	Intergranular[a]	For a fixed stress, increase with increasing test temperature
316 Stainless	fcc	Same as 304	Carbides, eta, chi, and sigma phase	Before onset of tertiary creep[a]	Intergranular[a]	Same as 304
2 1/4 Cr-1 Mo	bcc	Sensitive to cooling[b] rates from solution treating temperature	Bainite, pearlite, and carbides	No cracks[b]	Transgranular[b]	Independent or slightly decreasing with test temperature, but remains above 1%
Inconel 718	fcc	Age hardenable[c] alloy	CbTi(CN), M_6C, Laves A_2B, Ni_3Cb, gamma prime, $Ni_3(CbTiAl)$	Not known	Intergranular[d]	Low ductility, independent or slightly increasing with test temperature

[a] Work in progress at ORNL and the University of Cincinnati, Cincinnati, Ohio.

[b] Private communications with R. L. Klueh of Mechanical Properties group at ORNL.

[c] From ref. 48.

[d] Observation made from microstructure presented in refs. 46 and 48.

denuded zones at the grain boundaries. Consequently, intergranular cracks are nucleated by a grain boundary shear process. The strain to the onset of tertiary creep for this alloy is expected to be small. The temperature dependence of e_3 is expected to result from changes in the relative strengths of the matrix and the grain boundaries with temperature. However, for the temperature range used in this investigation, 538–760°C (1000–1400°F), greater intragranular strength due to γ' phase is not expected to change.[48]

Some temperature dependence can result from the agglomeration of grain boundary carbides and the possibility of some grain boundary migration. Such a temperature dependence cannot be ruled out and probably falls within the accuracy of predicting strain to onset of tertiary creep from the methods used in this report. Thus the predicted relative insensitivity of e_3 to temperature for this material is consistent with microstructural observations.

For 2 1/4 Cr-1 Mo steel, onset of tertiary creep is not associated with nucleation of grain boundary cracks. However, the possibility of spheriodization[49] of precipitates in the matrix under creep test conditions can initiate the accelerated creep rate tertiary stage.[50,51] Thus it is possible that while intra- and intergranular deformation are in progress, spheroidization of precipitates can occur and accelerate the deformation rates in the matrix. Although the strain to onset of tertiary creep may be small for 2 1/4 Cr-1 Mo steel, the strain during the tertiary stage could be very large due to intragranular deformation, which results in a transgranular fracture for this steel. In fact, predictions of strain to rupture for this material show that quantity to be relatively large, although e_3 is small.[52] If the above mechanism is correct, stress-induced spheroidization of pearlite and bainite at higher temperatures should occur at lower strains, and this should produce a decrease in strain to onset of tertiary creep with increasing temperature, consistent with the findings in this report.

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[49] M. A. Cardovi, J.J.B. Rutherford, A. B. Wilder, and C. P. Weigel, "Effects of High-Temperature Steam Exposure on the Properties of Superheater Alloy," pp. 8–55 in *Behavior of Superheater Alloys in High-Temperature, High-Pressure Steam*, American Society of Mechanical Engineers, New York, 1968.

[50] K. F. Hale, "An Electron Microscope Study of Changes in a 2 1/4 Cr-1 Mo Super-Heater Tube Steel During Tempering and Creep," pp. 650–58 in *Proc. 4th International Conf. on Electron Microscopy*, Springer-Verlag, Berlin, 1960.

[51] K. F. Hale, "Creep Failure Prediction from Observation of Microstructure in 2 1/4 Cr-1 Mo Steel," pp. 193–201 in *Physical Metallurgy of Reactor Fuel Elements*, The Metals Society, London, 1973.

[52] M. K. Booker, C. R. Brinkman, and V. K. Sikka, "Correlation and Extrapolation of Creep Ductility Data for Four Elevated-Temperature Structural Materials," pp. 108–45 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, American Society of Mechanical Engineers, New York, 1975.

CONCLUSIONS

1. The creep strain incurred before the onset of tertiary creep under either constant load, isothermal conditions, or under variable load-variable temperature conditions can be an important and useful design criterion.

2. The creep strain to tertiary creep, e_3, can be predicted from constant-load isothermal data as a function of stress and temperature, or as a function of rupture life and minimum creep rate. The plasticity resource, $e_s = \dot{e}_m t_r$, can also be used as an estimate of e_3.

3. The hypothesis of strain hardening implies that e_3 for variable load and/or variable temperature conditions is a function only of the instantaneous stress and temperature, and not of the loading history.

4. Scatter in data for e_3 prevents precise predictions, but calculation of e_3 by the above methods yields information about trends in the data.

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APPENDIX

Data Tabulation

2 1/4 Cr-1 Mo Steel[a]

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
454.	52.0	358.5	0.0	0.0	800.	1435.
454.	55.0	379.2	0.0	0.0	325.	539.
454.	60.0	413.7	0.0	0.0	0.	0.
454.	65.0	448.2	0.0	0.0	38.	49.
482.	46.0	317.2	3.00	0.014700	118.	262.
482.	40.0	275.8	1.60	0.002500	445.	969.
482.	32.0	220.6	0.50	0.000160	2100.	4885.
510.	40.0	275.8	0.0	0.0	59.	136.
510.	35.0	241.3	0.0	0.0	193.	476.
510.	30.0	206.8	0.0	0.0	330.	1089.
510.	27.5	189.6	0.0	0.0	230.	1396.
538.	22.0	151.7	0.0	0.0	0.	414.
538.	20.0	137.9	8.50	0.008700	0.	278.
538.	18.0	124.1	0.0	0.0	720.	1804.
538.	16.0	110.3	9.50	0.002860	180.	1070.
538.	15.5	106.9	8.50	0.005230	1600.	3954.
538.	13.5	93.1	8.50	0.005230	1600.	4219.
538.	18.0	124.1	4.20	0.000500	2600.	6012.
538.	28.0	193.1	1.60	0.003080	415.	790.
538.	20.0	137.9	1.95	0.000963	1250.	3003.
538.	22.0	151.7	1.25	0.001430	480.	1326.
538.	17.5	120.7	3.60	0.000389	6400.	14620.
538.	18.0	124.1	7.20	0.001480	890.	1781.
538.	18.0	124.1	7.80	0.000870	2000.	3273.
538.	26.0	179.3	5.50	0.066700	81.	239.
538.	20.0	137.9	0.0	0.003080	0.	1630.
538.	17.0	117.2	3.80	0.001700	1700.	5628.
538.	22.5	155.1	0.0	0.0	0.	285.
538.	25.2	173.5	2.50	0.009670	210.	467.
538.	20.0	137.9	1.50	0.008110	180.	1041.
538.	16.0	110.3	0.0	0.000381	0.	7596.
538.	22.0	151.7	1.05	0.000686	1020.	3058.
538.	17.0	117.2	3.80	0.000060	12400.	19153.
538.	18.0	124.1	6.50	0.001710	1250.	2710.
538.	18.0	124.1	4.80	0.000375	1950.	4635.
538.	18.0	124.2	2.00	0.000323	800.	1400.
538.	20.0	137.9	3.80	0.007600	495.	1045.
538.	16.6	114.6	4.40	0.001900	2125.	4013.
538.	18.0	124.1	0.0	0.000980	0.	3679.
538.	16.0	110.3	1.40	0.000242	4500.	10854.
566.	30.0	206.8	0.0	0.510000	10.	40.
566.	25.0	172.4	0.0	0.115000	23.	78.
566.	22.0	151.7	0.0	0.030000	18.	223.
566.	18.0	124.1	0.0	0.005500	840.	1805.
566.	20.6	142.0	0.0	0.0	175.	0.

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[a] An entry of 0.0 represents missing data.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
566.	18.0	124.1	0.0	0.0	325.	0.
566.	16.0	110.3	0.0	0.0	1300.	0.
566.	14.0	96.5	0.0	0.0	4250.	0.
566.	15.0	103.4	2.30	0.001820	970.	1634.
566.	15.0	103.5	1.00	0.000097	7600.	10673.
566.	15.2	104.5	2.70	0.0	565.	982.
566.	15.2	104.5	1.10	0.000158	5430.	0.
566.	15.0	103.6	6.30	0.007410	762.	1666.
566.	17.0	117.2	7.10	0.003640	475.	969.
566.	16.5	113.8	6.00	0.006320	780.	1824.
566.	16.5	113.8	7.40	0.001380	840.	1602.
593.	12.0	82.7	0.0	0.0	0.	923.
593.	9.0	62.1	0.0	0.0	0.	7085.
593.	7.5	51.7	0.0	0.000072	13000.	23168.
593.	15.1	104.3	2.35	0.005680	367.	617.
593.	12.0	82.7	2.30	0.000812	2150.	5014.
593.	10.0	68.9	4.60	0.001330	2850.	5628.
593.	12.0	82.7	1.70	0.002470	570.	1208.
593.	9.5	65.5	1.60	0.000294	3800.	6316.
593.	7.8	53.8	3.50	0.000333	7200.	13703.
593.	12.0	82.7	1.80	0.004840	355.	1012.
593.	8.0	55.2	0.0	0.000172	0.	15694.
593.	13.5	93.1	0.0	0.055600	153.	274.
593.	11.7	81.0	1.50	0.000339	3400.	4667.
593.	15.0	103.5	1.00	0.000543	1270.	1929.
593.	13.5	93.1	2.30	0.007810	256.	433.
593.	13.5	93.1	1.10	0.000968	847.	0.
593.	14.3	98.7	6.30	0.021600	250.	542.
593.	15.0	103.5	6.80	0.023900	253.	522.
593.	14.0	96.5	7.20	0.008330	460.	678.
593.	13.5	93.1	7.50	0.012700	510.	1013.
593.	15.0	103.5	2.00	0.009820	174.	370.
593.	12.0	82.7	0.60	0.000417	1060.	2573.
593.	10.0	68.9	0.80	0.000086	4800.	8132.
593.	9.8	67.6	1.50	0.001110	1175.	2589.
593.	9.0	61.8	1.70	0.000500	2980.	4853.
593.	15.0	103.4	13.00	0.100000	142.	238.
593.	13.0	89.6	1.60	0.000882	1260.	2316.
593.	10.0	68.9	1.80	0.000303	5850.	10082.
593.	12.0	82.7	0.0	0.001090	0.	1116.
593.	9.5	65.5	7.80	0.001050	2250.	3434.
593.	12.0	82.7	8.00	0.000368	2800.	4077.
593.	15.0	103.4	6.20	0.028200	192.	460.
593.	13.5	93.1	5.30	0.009500	490.	1156.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
593.	12.0	82.7	3.20	0.001950	1290.	3173.
593.	11.0	75.8	2.50	0.000250	3000.	6388.
593.	10.0	68.9	2.30	0.000067	7400.	12758.
593.	16.5	113.8	8.40	0.070000	109.	236.
593.	12.5	86.2	3.00	0.002550	920.	2342.
593.	15.4	106.5	12.50	0.062600	140.	266.
593.	10.0	68.9	1.80	0.000300	4000.	9338.
593.	15.0	103.4	3.00	0.011300	170.	638.
593.	14.0	96.5	3.00	0.022000	125.	428.
593.	12.0	82.7	4.70	0.009380	480.	1276.
593.	11.0	75.8	9.00	0.029400	290.	756.
593.	10.0	68.9	4.20	0.001740	1960.	3861.
593.	8.5	58.6	6.00	0.002940	1700.	3703.
593.	9.5	65.5	9.90	0.005770	1080.	2013.
621.	12.2	83.8	1.76	0.005200	267.	415.
621.	12.0	82.9	0.50	0.000325	860.	1465.
621.	12.0	82.8	0.0	0.0	0.	231.
621.	13.7	94.2	0.60	0.001390	405.	0.
621.	12.0	82.9	2.00	0.008330	205.	326.
621.	11.5	79.5	2.80	0.004520	530.	1089.
621.	11.5	79.5	4.50	0.011300	340.	674.
621.	12.0	82.8	6.20	0.026300	212.	415.
621.	12.1	83.4	4.00	0.010200	340.	766.
621.	12.0	82.7	5.60	0.018600	263.	542.
621.	12.1	83.2	6.80	0.037800	156.	350.
649.	4.0	27.6	0.0	0.000053	10450.	16182.
649.	5.0	34.5	1.60	0.000500	3150.	6115.
649.	4.2	29.0	1.80	0.000263	5000.	9945.
649.	6.2	42.7	0.0	0.001060	0.	2619.
649.	10.3	71.1	1.62	0.006250	186.	311.
649.	8.0	55.2	1.20	0.000492	1400.	2632.
649.	9.0	62.1	1.20	0.002730	362.	548.
649.	9.0	62.1	0.60	0.000469	685.	1086.
649.	10.0	68.9	3.40	0.018600	162.	346.
649.	9.5	65.5	1.80	0.003870	380.	747.
649.	10.0	68.9	3.50	0.013000	265.	484.
649.	10.0	68.9	4.80	0.033100	172.	285.
649.	4.5	31.0	3.60	0.000400	4550.	6849.
649.	8.0	55.2	6.00	0.042500	134.	339.
649.	5.5	37.9	2.80	0.000941	2360.	3374.
649.	7.5	51.7	0.95	0.001260	540.	1294.
649.	6.0	41.4	2.00	0.000718	2300.	3519.
649.	7.0	48.3	1.70	0.001330	950.	2339.
649.	8.0	55.2	1.20	0.002500	400.	1222.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
649.	8.0	55.2	3.30	0.008000	365.	796.
649.	8.0	55.2	8.00	0.054500	135.	294.
649.	6.0	41.4	2.20	0.001540	1050.	2463.
649.	6.5	44.8	4.00	0.008330	430.	978.
649.	9.5	65.5	3.60	0.055200	60.	197.
649.	5.0	34.5	1.60	0.001250	1170.	3883.
649.	5.0	34.5	2.40	0.000919	1950.	4623.
649.	4.5	31.0	3.80	0.000800	3900.	6667.
649.	4.5	31.0	1.80	0.000300	3100.	6902.
677.	7.0	48.4	0.36	0.000333	250.	512.
677.	6.0	41.5	0.40	0.000278	650.	1025.
677.	7.0	48.3	3.40	0.000728	154.	446.
677.	7.1	48.6	0.37	0.000400	400.	634.
677.	6.2	42.5	0.40	0.000261	615.	979.
677.	7.0	48.4	0.60	0.002310	164.	493.
677.	5.0	34.6	1.00	0.001280	470.	1156.
677.	6.5	45.1	0.70	0.001920	214.	656.

Inconel Alloy 718 (Heat Y8509)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	130.0	896.3	0.0	0.0	0.	3791.
538.	130.0	896.3	1.40	0.000200	2320.	2876.
593.	130.0	896.3	1.50	0.021500	58.	87.
593.	120.0	827.4	0.0	0.0	0.	194.
593.	100.0	689.5	0.80	0.000190	2750.	6189.
593.	105.0	724.0	0.69	0.000330	1235.	2705.
593.	110.0	758.4	0.25	0.000088	266.	788.
649.	80.0	551.6	0.60	0.000410	780.	1349.
649.	90.0	620.5	0.68	0.002000	214.	573.
649.	80.0	551.6	0.68	0.000263	1416.	2067.
649.	100.0	689.5	0.0	0.0	0.	32.
649.	100.0	689.5	0.0	0.0	0.	138.
649.	100.0	689.5	0.0	0.0	0.	126.
649.	70.0	482.6	0.36	0.000024	4680.	6951.
649.	60.0	413.7	0.50	0.000024	10700.	14324.
649.	60.0	413.7	0.20	0.000008	10000.	13248.
704.	35.0	241.3	0.50	0.000700	2600.	5266.
704.	45.0	310.3	0.38	0.000120	1045.	1923.
704.	50.0	344.7	0.38	0.000200	825.	1346.
704.	60.0	413.7	0.30	0.000380	295.	508.
704.	70.0	482.6	0.0	0.006000	0.	174.
760.	40.0	275.8	0.72	0.005200	85.	151.
760.	30.0	206.8	0.60	0.000650	200.	475.
760.	25.0	172.4	0.33	0.000460	270.	793.

Inconel Alloy 718 (Heat C56445)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	158.0	1089.4	5.30	0.140000	27.	28.
538.	150.0	1034.2	2.15	0.019000	85.	133.
538.	145.0	999.8	0.0	0.010000	0.	256.
538.	140.0	965.3	0.68	0.000615	805.	815.
538.	134.0	923.9	0.80	0.000375	1500.	1731.
538.	124.0	855.0	0.61	0.000055	6200.	8473.
538.	118.0	813.6	0.48	0.000020	13200.	21524.
593.	130.0	896.3	1.00	0.016000	47.	62.
593.	135.0	930.8	1.90	0.067000	25.	28.
593.	123.0	848.1	0.95	0.006250	112.	152.
593.	117.0	806.7	0.56	0.002700	190.	368.
593.	105.0	724.0	0.70	0.000360	1520.	2328.
593.	94.0	648.1	0.40	0.000017	10200.	10606.
593.	86.0	593.0	0.50	0.000012	21000.	32991.
649.	115.0	792.9	0.55	0.055000	5.	11.
649.	108.0	744.7	0.65	0.023000	20.	31.
649.	96.0	661.9	0.60	0.006200	68.	150.
649.	78.0	537.8	0.68	0.000185	2230.	3132.
649.	68.0	468.9	0.73	0.000087	4800.	7263.
649.	63.0	434.4	0.69	0.000071	5700.	10232.
649.	87.0	599.9	0.57	0.000900	417.	747.
704.	86.0	593.0	1.25	0.140000	7.	18.
704.	76.0	524.0	0.0	0.0	0.	71.
704.	68.0	468.9	1.40	0.015000	80.	183.
704.	60.0	413.7	0.70	0.001540	310.	477.
704.	55.0	379.2	0.88	0.000930	580.	808.
704.	44.0	303.4	0.80	0.000270	2120.	2871.
704.	37.0	255.1	0.70	0.000120	4350.	6048.

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TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
593.	28.8	198.9	17.60	0.004000	1300.	1637.
593.	28.8	198.9	12.30	0.003600	1200.	1658.
593.	28.8	198.9	12.20	0.002500	1950.	2437.
593.	28.8	198.9	13.00	0.004500	1300.	1709.
593.	28.8	198.9	14.00	0.005500	985.	1267.
593.	28.8	198.9	11.00	0.003400	960.	1785.
593.	31.6	218.1	15.70	0.015000	546.	779.
593.	31.6	218.1	12.30	0.018000	195.	265.
593.	31.6	218.1	13.00	0.021000	204.	257.
593.	31.6	218.1	14.70	0.017000	375.	570.
593.	31.6	218.1	15.30	0.017000	480.	594.
593.	31.6	218.1	12.70	0.029000	150.	170.
593.	34.7	239.1	14.40	0.059000	99.	132.
593.	34.7	239.1	13.50	0.074000	66.	96.
593.	34.7	239.1	13.80	0.074000	60.	76.
593.	34.7	239.1	12.70	0.038000	74.	122.
593.	34.7	239.1	14.40	0.053000	90.	115.
593.	34.7	239.1	13.40	0.055000	72.	67.
593.	38.0	262.1	16.90	0.200000	31.	43.
593.	38.0	262.1	15.50	0.270000	17.	22.
593.	38.0	262.1	17.40	0.180000	31.	39.
593.	38.0	262.1	15.90	0.150000	29.	42.
593.	38.0	262.1	15.40	0.170000	28.	41.
593.	38.0	262.1	15.50	0.150000	24.	37.
593.	41.7	287.5	16.90	0.570000	6.	10.
593.	41.7	287.5	17.90	1.030000	4.	7.
593.	41.7	287.5	18.10	0.590000	8.	11.
593.	41.7	287.5	17.50	0.380000	15.	20.
593.	41.7	287.5	18.20	0.580000	10.	12.
593.	41.7	287.5	15.70	0.270000	13.	20.
593.	45.7	315.2	17.00	1.469999	2.	4.
593.	45.7	315.2	20.30	1.040000	3.	4.
593.	45.7	315.2	20.00	1.230000	3.	5.
593.	45.7	315.2	20.40	1.389999	4.	6.
593.	45.7	315.2	20.60	2.599999	1.	2.
593.	45.7	315.2	21.60	0.950000	6.	9.
704.	9.5	65.8	8.90	0.004200	1575.	3343.
704.	9.5	65.8	6.80	0.004500	1340.	3184.
704.	9.5	65.8	8.20	0.004600	1315.	3122.
704.	9.5	65.8	11.00	0.004200	2400.	4500.
704.	9.5	65.8	12.50	0.004200	2500.	4414.
704.	9.5	65.8	11.20	0.004300	2150.	4087.
704.	11.2	77.4	13.00	0.011000	1050.	2037.
704.	11.2	77.4	16.50	0.012000	1120.	2045.
704.	11.2	77.4	13.00	0.011000	1075.	2028.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
704.	11.2	77.4	15.50	0.013000	1120.	1873.
704.	11.2	77.4	9.00	0.012000	720.	1542.
704.	11.2	77.4	15.00	0.012000	1140.	2046.
704.	13.2	90.9	19.50	0.035000	472.	950.
704.	13.2	90.9	17.00	0.029000	550.	996.
704.	13.2	90.9	18.00	0.035000	470.	867.
704.	13.2	90.9	16.90	0.034000	475.	839.
704.	13.2	90.9	22.00	0.036000	575.	902.
704.	13.2	90.9	15.20	0.035000	400.	852.
704.	15.5	106.8	20.30	0.102000	184.	326.
704.	15.5	106.8	17.10	0.088000	164.	376.
704.	15.5	106.8	17.60	0.109000	142.	290.
704.	15.5	106.8	17.10	0.095000	150.	357.
704.	15.5	106.8	18.20	0.105000	169.	343.
704.	15.5	106.8	16.00	0.096000	152.	346.
704.	18.2	125.6	19.90	0.240000	75.	134.
704.	18.2	125.6	14.50	0.260000	50.	121.
704.	18.2	125.6	20.20	0.270000	62.	116.
704.	18.2	125.6	16.50	0.260000	55.	118.
704.	18.2	125.6	19.20	0.410000	40.	95.
704.	18.2	125.6	17.00	0.290000	50.	95.
704.	21.4	147.4	16.30	0.680000	19.	40.
704.	21.4	147.4	15.80	0.720000	17.	40.
704.	21.4	147.4	22.50	0.900000	18.	32.
704.	21.4	147.4	20.30	0.850000	19.	34.
704.	21.4	147.4	15.00	0.990000	10.	29.
704.	21.4	147.4	16.40	0.960000	11.	29.
704.	25.1	173.2	14.90	2.309999	5.	11.
704.	25.1	173.2	20.50	2.980000	5.	10.
704.	25.1	173.2	20.50	2.839998	5.	10.
704.	25.1	173.2	20.00	2.860000	5.	10.
704.	25.1	173.2	17.50	3.549998	3.	8.
704.	25.1	173.2	19.50	3.120000	5.	10.
704.	29.5	203.5	23.50	12.099999	1.	2.
704.	29.5	203.5	22.00	11.400000	1.	2.
704.	29.5	203.5	21.50	12.799999	1.	2.
704.	29.5	203.5	19.00	13.099999	1.	2.
704.	29.5	203.5	23.50	12.500000	1.	2.
704.	29.5	203.5	21.50	13.000000	1.	2.
816.	3.4	23.4	0.0	0.0	0.	5962.
816.	3.4	23.4	0.0	0.0	0.	5636.
816.	3.4	23.4	0.0	0.0	0.	4133.
816.	3.4	23.4	0.0	0.0	0.	4263.
816.	3.4	23.4	0.0	0.0	0.	3664.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
816.	3.4	23.4	0.0	0.0	0.	3864.
816.	4.3	29.4	0.0	0.0	0.	2169.
816.	4.3	29.4	0.0	0.0	0.	1993.
816.	4.3	29.4	0.0	0.0	0.	1681.
816.	4.3	29.4	0.0	0.0	0.	1589.
816.	4.3	29.4	0.0	0.0	0.	1595.
816.	4.3	29.4	0.0	0.0	0.	1748.
816.	5.4	37.2	6.70	0.015000	430.	987.
816.	5.4	37.2	7.70	0.014000	517.	1075.
816.	5.4	37.2	8.30	0.022000	320.	683.
816.	5.4	37.2	7.40	0.018000	320.	810.
816.	5.4	37.2	12.50	0.030000	380.	710.
816.	5.4	37.2	8.30	0.028000	320.	651.
816.	7.1	48.8	17.10	0.083000	198.	302.
816.	7.1	48.8	16.70	0.100000	159.	297.
816.	7.1	48.8	13.10	0.075000	147.	288.
816.	7.1	48.8	11.20	0.084000	130.	272.
816.	7.1	48.8	15.30	0.107000	138.	244.
816.	7.1	48.8	13.00	0.084000	147.	274.
816.	8.5	58.7	15.00	0.260000	54.	104.
816.	8.5	58.7	13.00	0.230000	55.	115.
816.	8.5	58.7	15.00	0.210000	68.	111.
816.	8.5	58.7	16.00	0.210000	70.	133.
816.	8.5	58.7	15.30	0.260000	57.	104.
816.	8.5	58.7	17.70	0.320000	54.	102.
816.	10.7	74.0	12.60	1.000000	11.	31.
816.	10.7	74.0	13.20	0.910000	15.	36.
816.	10.7	74.0	12.40	0.960000	13.	33.
816.	10.7	74.0	20.70	0.920000	20.	36.
816.	10.7	74.0	15.80	1.219998	12.	26.
816.	10.7	74.0	13.90	1.160000	11.	29.
816.	13.5	93.3	15.80	3.209998	4.	8.
816.	13.5	93.3	15.00	2.660000	5.	11.
816.	13.5	93.3	15.60	4.070000	4.	8.
816.	13.5	93.3	14.50	4.429998	3.	7.
816.	13.5	93.3	17.10	3.709998	3.	7.
816.	13.5	93.3	16.50	3.290000	4.	9.
816.	17.0	117.4	18.00	15.000000	1.	2.
816.	17.0	117.4	15.50	11.500000	1.	3.
816.	17.0	117.4	17.50	15.599999	1.	2.
816.	17.0	117.4	14.00	15.299999	1.	2.
816.	17.0	117.4	14.90	19.799988	1.	1.
816.	17.0	117.4	15.50	17.500000	1.	2.

Type 316 Stainless Steel (Heat 332990)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	63.0	434.4	4.70	0.102000	49.	61.
538.	60.0	413.7	2.50	0.022500	106.	106.
538.	60.0	413.7	3.00	0.036500	84.	130.
538.	58.0	399.9	1.40	0.015600	90.	204.
538.	55.0	379.2	1.70	0.009250	188.	263.
538.	50.0	344.7	1.00	0.003250	268.	433.
538.	45.0	310.3	0.0	0.002000	0.	1032.
538.	40.0	275.8	2.30	0.000840	2160.	2795.
593.	54.0	372.3	14.10	3.419999	3.	6.
593.	52.0	358.5	5.80	0.803000	5.	9.
593.	50.0	344.7	8.00	0.975000	8.	11.
593.	45.0	310.3	3.80	0.250000	15.	23.
593.	40.0	275.8	6.10	0.054400	92.	197.
593.	38.0	262.0	10.50	0.034200	260.	481.
593.	38.0	262.0	6.10	0.046400	105.	158.
593.	36.0	248.2	6.70	0.017200	300.	359.
593.	36.0	248.2	5.30	0.027600	148.	236.
593.	34.0	234.4	4.40	0.015000	212.	338.
593.	32.0	220.6	7.00	0.007370	780.	1113.
593.	31.0	213.7	7.00	0.003700	1500.	2395.
649.	48.0	331.0	12.80	23.859985	0.	1.
649.	46.0	317.2	16.10	19.299988	1.	1.
649.	43.0	296.5	11.20	6.080000	2.	4.
649.	40.0	275.8	8.60	3.000000	3.	5.
649.	35.0	241.3	9.80	0.911000	9.	25.
649.	30.0	206.8	12.60	0.212000	85.	141.
649.	30.0	206.8	13.90	0.342000	53.	95.
649.	29.0	200.0	8.30	0.144000	52.	115.
649.	28.0	193.1	6.20	0.094400	54.	168.
649.	25.0	172.4	6.90	0.063800	94.	375.
649.	23.0	158.6	9.70	0.019800	424.	989.
649.	22.0	151.7	4.10	0.015900	220.	1294.
760.	19.0	131.0	10.95	1.839999	5.	18.
760.	17.0	117.2	9.65	0.878000	10.	28.
760.	15.0	103.4	18.65	0.460000	39.	72.
760.	15.0	103.4	10.65	0.412000	25.	69.
760.	12.0	82.7	14.80	0.090400	146.	275.
760.	10.0	68.9	18.61	0.028500	630.	1051.
760.	9.0	62.1	16.02	0.016100	900.	1810.

Type 304 Stainless Steel (Heat 55697)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	50.0	344.7	0.90	0.230000	5.	20.
538.	50.0	344.7	0.0	0.0	0.	27.
538.	50.0	344.7	0.60	0.133000	6.	29.
538.	45.0	310.3	3.60	0.051200	70.	81.
538.	45.0	310.3	4.70	0.064000	74.	88.
538.	45.0	310.3	0.0	0.0	0.	112.
538.	45.0	310.3	4.20	0.105000	40.	57.
538.	45.0	310.3	4.30	0.095000	45.	76.
538.	45.0	310.3	4.20	0.035800	106.	136.
538.	45.0	310.3	4.60	0.039500	110.	142.
538.	40.0	275.8	3.60	0.010900	238.	262.
538.	40.0	275.8	4.50	0.017500	188.	209.
538.	40.0	275.8	2.30	0.012600	150.	182.
538.	35.0	241.3	3.90	0.001920	1380.	1506.
538.	30.0	206.8	3.50	0.000540	3880.	4022.
538.	25.0	172.4	4.20	0.000250	6750.	7034.
593.	50.0	344.7	0.0	12.500000	1.	1.
593.	45.0	310.3	9.10	2.320000	4.	5.
593.	40.0	275.8	3.40	0.758000	3.	16.
593.	40.0	275.8	6.40	0.742000	7.	22.
593.	35.0	241.3	0.0	0.197000	0.	49.
593.	30.0	206.8	7.60	0.042400	132.	199.
593.	30.0	206.8	0.0	0.045500	0.	196.
593.	28.0	193.1	7.50	0.033800	164.	241.
593.	28.0	193.1	0.0	0.010000	200.	375.
593.	26.5	182.7	6.40	0.018000	260.	440.
593.	25.0	172.4	6.20	0.011600	384.	629.
593.	25.0	172.4	4.80	0.011200	268.	372.
593.	25.0	172.4	6.30	0.010000	360.	627.
649.	40.0	275.8	13.20	31.299988	0.	1.
649.	38.0	262.0	12.00	19.199997	1.	1.
649.	35.0	241.3	11.90	16.069977	1.	1.
649.	35.0	241.3	16.20	11.400000	1.	2.
649.	30.0	206.8	12.90	1.910000	6.	8.
649.	28.0	193.1	0.0	0.0	0.	22.
649.	25.0	172.4	14.00	0.531000	22.	45.
649.	24.0	165.5	11.80	0.289000	36.	67.
649.	23.0	158.6	13.00	0.207000	54.	89.
649.	22.0	151.7	17.10	0.301000	50.	83.
649.	22.0	151.7	10.20	0.145000	64.	148.
649.	21.0	144.8	9.30	0.087100	90.	239.
649.	20.0	137.9	3.60	0.044700	76.	217.
649.	20.0	137.9	14.50	0.076600	176.	258.
649.	18.0	124.1	6.30	0.034100	150.	590.
649.	16.0	110.3	2.90	0.015900	176.	625.

Type 304 Stainless Steel, 51-mm Plate (Heat 9T2796)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	46.0	317.2	0.50	0.034000	9.	32.
593.	30.0	206.8	6.70	0.074000	75.	87.
593.	35.0	241.3	6.50	0.356000	18.	22.
593.	30.0	206.8	7.20	0.078000	77.	93.
593.	25.0	172.4	3.40	0.010000	253.	291.
593.	25.0	172.4	3.80	0.007200	375.	453.
593.	25.0	172.4	3.35	0.008000	343.	423.
593.	25.0	172.4	4.17	0.012000	250.	294.
593.	16.0	110.3	2.07	0.000068	14200.	14647.
593.	25.0	172.4	4.25	0.014700	209.	244.
593.	18.0	124.1	1.15	0.000280	2500.	4544.
649.	14.0	96.5	2.60	0.008200	250.	761.
649.	16.0	110.3	3.10	0.017000	198.	304.
649.	12.0	82.7	7.60	0.003100	2175.	2674.
649.	25.0	172.4	13.63	0.909700	14.	17.
649.	10.0	68.9	4.10	0.000630	5650.	7279.
649.	16.0	110.3	3.30	0.027500	100.	245.
704.	10.0	68.9	7.20	0.020000	360.	568.
704.	8.0	55.2	8.70	0.004100	2150.	2760.
704.	10.0	68.9	12.63	0.025000	475.	653.

Type 304 Stainless Steel, 25-mm Plate (Heat 9T2796)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
482.	50.0	344.7	0.44	0.000280	675.	885.
538.	30.0	206.8	2.30	0.000650	2219.	2219.
538.	50.0	344.7	3.00	0.240000	16.	21.
538.	40.0	275.8	3.10	0.021000	130.	163.
538.	40.0	275.8	2.60	0.024000	110.	140.
538.	35.0	241.3	2.50	0.004000	510.	595.
538.	35.0	241.3	2.70	0.006500	345.	350.
593.	40.0	275.8	9.00	2.099998	5.	5.
593.	35.0	241.3	7.30	0.340000	20.	25.
593.	35.0	241.3	6.30	0.230000	24.	30.
593.	30.0	206.8	4.50	0.046000	80.	111.
593.	30.0	206.8	6.20	0.076000	70.	99.
593.	25.0	172.4	3.90	0.011000	280.	440.
593.	21.3	146.5	2.30	0.002140	770.	1230.
593.	22.5	155.1	2.85	0.002800	720.	1063.
593.	22.5	155.1	2.70	0.003000	620.	1247.
593.	22.5	155.1	2.70	0.003500	550.	878.
593.	25.0	172.4	4.50	0.009000	390.	619.
593.	25.0	172.4	4.80	0.010600	350.	553.
621.	20.0	137.9	3.10	0.007650	260.	650.
621.	30.0	206.8	8.00	0.590000	14.	21.
621.	25.0	172.4	7.20	0.072500	81.	119.
649.	30.0	206.8	11.10	4.700000	2.	3.
649.	12.5	86.2	12.00	0.003200	3000.	3960.
649.	13.8	94.8	2.80	0.009700	240.	1053.
649.	15.0	103.4	4.50	0.017000	230.	1524.
649.	15.0	103.4	2.80	0.015000	150.	730.
649.	20.0	137.9	5.20	0.087000	50.	111.
649.	30.0	206.8	14.00	3.700000	3.	5.
649.	25.0	172.4	9.50	0.460000	18.	28.
649.	25.0	172.4	12.50	0.870000	13.	19.
649.	22.5	155.1	9.80	0.330000	27.	40.
649.	22.5	155.1	10.00	0.270000	32.	54.
649.	19.5	134.5	7.00	0.077000	80.	178.
649.	17.5	120.7	4.20	0.050000	70.	250.
649.	17.5	120.7	4.00	0.040000	83.	288.
649.	17.5	120.7	5.10	0.029000	140.	485.
704.	20.0	137.9	13.50	2.799998	5.	9.
704.	17.5	120.7	19.00	1.049998	17.	23.
704.	7.5	51.7	8.20	0.004200	1710.	2296.
704.	10.0	68.9	20.50	0.028000	650.	1027.
704.	15.0	103.4	7.50	0.330000	20.	47.
704.	13.8	94.8	7.50	0.210000	35.	83.
704.	12.5	86.2	16.00	0.120000	130.	244.
704.	11.3	77.6	20.00	0.050000	375.	563.

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
760.	7.5	51.7	26.00	0.044000	500.	698.
760.	20.0	137.9	21.00	42.000000	1.	1.
760.	17.5	120.7	19.00	14.299999	1.	2.
760.	15.0	103.4	14.00	5.200000	3.	5.
760.	12.5	86.2	13.30	1.500000	9.	16.
760.	12.5	86.2	18.50	1.429998	13.	20.
760.	10.0	68.9	15.70	0.355000	42.	61.
760.	10.0	68.9	13.50	0.430000	30.	46.
760.	8.5	58.6	19.00	0.140000	120.	196.
816.	12.5	86.2	17.00	14.299999	1.	2.
816.	10.0	68.9	19.00	3.599998	5.	8.
816.	7.5	51.7	21.30	0.380000	50.	78.
816.	5.0	34.5	23.00	0.035000	530.	731.

Type 304 Stainless Steel (Heat 8043813)

TEMP IN C	STRESS (KSI)	STRESS (MPA)	STRAIN TO TERTIARY CREEP (%)	MINIMUM CREEP RATE (%/HR)	TIME TO TERTIARY CREEP (HR)	RUPTURE TIME (HRS)
538.	55.0	379.2	8.20	0.320000	26.	34.
538.	50.0	344.7	6.09	0.021000	275.	348.
538.	45.0	310.3	3.75	0.005200	625.	837.
593.	45.0	310.3	15.75	2.200000	7.	10.
593.	40.0	275.8	16.56	0.330000	45.	55.
593.	35.0	241.3	9.38	0.036000	175.	287.
593.	33.0	227.5	7.82	0.010000	375.	723.
593.	32.0	220.6	4.22	0.003300	900.	1570.
593.	30.0	206.8	7.25	0.001500	2750.	3184.
649.	35.0	241.3	0.0	7.700000	0.	5.
649.	30.0	206.8	18.00	1.099999	12.	23.
649.	28.0	193.1	18.00	0.764000	21.	35.
649.	27.5	189.6	20.00	0.290000	40.	75.
649.	25.0	172.4	14.99	0.179000	75.	104.
649.	25.0	172.4	14.62	0.045000	225.	299.
649.	22.5	155.1	8.15	0.007000	625.	1072.
649.	22.0	151.7	8.00	0.012500	375.	577.
649.	20.0	137.9	5.31	0.004150	800.	1642.
704.	30.0	206.8	14.00	40.000000	0.	1.
704.	25.0	172.4	20.00	6.700000	3.	5.
704.	17.0	117.2	8.75	0.068000	80.	178.
760.	25.0	172.4	15.00	0.0	0.	0.
760.	17.0	117.2	18.50	8.000000	2.	5.
816.	17.0	117.2	17.50	92.000000	0.	0.