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Comparison of Several High-Chromium Ferritic Steels

M. K. Booker
V. K. Sikka
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METALS and CERAMICS
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COMPARISON OF SEVERAL HIGH-CHROMIUM FERRITIC STEELS

M. K. Booker, V. K. Sikka, and B.L.P. Booker

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COMPARISON OF SEVERAL HIGH-CHROMIUM FERRITIC STEELS*

M. K. Booker, V. K. Sikka, and B.L.P. Booker

ABSTRACT

A modified 9 Cr-1 Mo ferritic steel has been selected for development by the U.S. Department of Energy as an alternative structural material for breeder reactor applications in which type 304 stainless steel or 2 1/4 Cr-1 Mo steel is currently being used. The 9 Cr-1 Mo steels are already being used commercially in both Britain and the United States, and the 12% Cr steel alloy HT9 is also often recommended for high-temperature service.

Creep-rupture data for all five of the above ferritic steels were collected and analyzed to yield rupture life as a function of stress, temperature, and lot-to-lot variations in strength. Yield and tensile strength data for the three 9 Cr-1 Mo materials were also examined. All results were compared with the behavior of type 304 stainless steel, and the tensile and creep properties of the modified and British 9 Cr-1 Mo materials were used to calculate allowable stress values S_o and S_m according to the ASME Boiler and Pressure Vessel Code. These values were compared with those currently listed in the code for American commercial 9 Cr-1 Mo steel, 2 1/4 Cr-1 Mo steel, and type 304 stainless steel.

The overall conclusion of this work is that the modified 9 Cr-1 Mo steel displays tensile and creep strengths significantly superior to those of the other ferritic materials examined and is at least comparable to type 304 stainless steel for room temperature to about 625°C.

INTRODUCTION

The current reference breeder reactor materials in the United States are types 304 or 316 stainless steel for pressure boundary and structural applications in the primary circuit (cladding, cold- and hot-leg piping,

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*Work performed under DOE/RRT AF 15 10 15, Task OR-1.8, Documentation, Liaison, and Implementation.

ducts, and pressure vessel), 2 1/4 Cr-1 Mo steel and alloy 800 for steam generator applications, and alloy 718 for special applications such as upper internals. There are sound technical justifications for these selections, and the adoption of these alloys for a wide range of nuclear and nonnuclear applications has generated much industrial technology and experience. However, there are sufficient incentives to develop other materials for future concepts of commercial breeder and fusion reactors. For example, components would be easier to handle and less expensive if they were fabricated from alloys less susceptible to intergranular attack and stress-corrosion cracking. Alloys in which the properties of welds can be more easily controlled by welding procedures and heat treatment would improve fabrication and inspection of components. There are other areas in which better alloy properties could enhance performance characteristics and reduce the cost of plant components.

A task group review of commercial alloys that might be considered as alternative structural materials for elevated-temperature nuclear service concluded that several materials have advantageous characteristics. The recommendations of the task group were intended to accommodate future trends toward either higher or lower temperatures and possibly major changes in design. The materials suggested by the task group include (1) strengthened ferritic martensitic steels in the 8 to 12% Cr range, (2) austenitic steels containing ~15% Cr and 15% Ni that have higher elevated-temperature strength than types 304 and 316 stainless steel; (3) certain grades of non-age-hardening nickel-base alloys, and (4) partially stabilized types 304 and 316 stainless steel with reduced susceptibility to intergranular attack and stress-corrosion cracking. Problems peculiar to each of these alloys are discussed in the task group report.[1]

The alloy selected for development as part of the U.S. Department of Energy Breeder Reactor Base Technology Program is a modified 9 Cr-1 Mo steel, which is typical of the strengthened ferritic/martensitic steels listed in (1) above. It is anticipated that this new material can be used as a replacement for both the austenitic stainless steels and the 2 1/4 Cr-1 Mo steel in breeder reactor and other applications. This material is

recommended for use in the normalized and tempered condition, which yields a microstructure of tempered martensite. A typical heat treatment involves normalization for 1 h at 1040°C (1904°F) followed by air cooling and then tempering for 1 h at 760°C (1400°F) followed again by air cooling. The many excellent aspects of the physical properties, corrosion resistance, and mechanical properties of this modified 9 Cr-1 Mo material are reviewed elsewhere.[2]

The commercial (or standard) 9 Cr-1 Mo material in the United States is recommended for use in the annealed condition in which the microstructure consists of ferrite and carbides (Mo_2C, Fe_3C, and $M_{23}C_6$). The tensile and creep strength of this alloy is considerably lower than that of stainless steels, and thus it is not recommended for use at temperatures where creep damage is expected to be significant.

The United Kingdom uses an alloy of essentially the same composition, but in contrast to U.S. practice the United Kingdom uses the alloy in a tempered martensitic condition. The heat treatment used is similar to that for the modified 9 Cr-1 Mo steel above. Although normalizing and tempering increases the yield and ultimate strength of the U.K. alloy, creep strength is not significantly different from that of the annealed material at temperatures above about 600°C.

The Sandvik Company of Sweden developed several alloys in the 9 to 12% Cr class. The alloy most frequently recommended for high-temperature service is commonly known as HT9, which contains 11 to 12% Cr and 0.17 to 0.25% C and is strengthened by vanadium and tungsten. The alloy composition is balanced to minimize δ-ferrite content, and thus it contains ~0.5% Ni. Alloy HT9 is again typically used in a normalized and tempered condition, with the actual heat treatment similar to that for the 9 Cr-1 Mo materials above. This alloy has creep strength that exceeds the ASME Code Case minimum curve for type 304 stainless steel for temperatures $\leq$600°C; however, at 650°C the strength values fall below the minimum curve. Furthermore, several heats of this alloy show a decrease in ductility with increasing rupture time.

In this study, available creep-rupture data for the modified 9 Cr-1 Mo steel, American (annealed) commercial 9 Cr-1 Mo steel, British commercial 9 Cr-1 Mo steel, and alloy HT9 were collected and examined using a common

methodology. The results from these analyses yield comparisons among the various materials in terms of creep-rupture strength. Available creep-rupture data for annealed 2 1/4 Cr-1 Mo steel were also examined for comparison, and yield tensile strength data for the three 9 Cr-1 Mo alloys were examined.

DATA

Typical chemical composition ranges for the five materials examined are given in Table 1. The actual data used were obtained from several lots of material in all cases. The modified 9 Cr-1 Mo steel data were generated in the ORNL–Combustion Engineering development program[2] for this material. The data for the British 9 Cr-1 Mo steel were taken from the compilation of the British Steelmakers' Creep Committee (BSCC).[3] The data for the American commercial 9 Cr-1 Mo steel were taken from an unpublished compilation.[4] The HT9 data were supplied by Sandvik, Inc.,[5] and the 2 1/4 Cr-1 Mo data are from the set discussed in ref. 6. Table 2 summarizes the creep-rupture data bases examined.

TENSILE DATA ANALYSIS

Available tensile data for the modified 9 Cr-1 Mo steel and the British 9 Cr-1 Mo steel were analyzed by a lot-centered regression procedure similar to that proposed earlier[7,8] for austenitic stainless steels. This method allows an analytical description of temperature effects on properties while directly accounting for lot-to-lot variability in the data. It was implemented in such a way[7] that the assumptions on lot-to-lot variability are similar to those involved in the widely known "ratio technique."[9] Properties examined included 0.2% offset yield strength and ultimate tensile strength.

The modified 9 Cr-1 Mo data (220 tests on 51 lots of material) were described by

$$\log \sigma_u = C_h^u - 1.010 \times 10^{-3}T + 4.152 \times 10^{-6}T^2 - 5.644 \times 10^{-9}T^3 \qquad (1)$$

Table 1. Typical Ranges of Concentrations (wt %) of Important Alloying Elements for Materials Examined

Element	Material				
	U.S. 9 Cr-1 Mo	British 9 Cr-1 Mo	Modified 9 Cr-1 Mo	HT9	2 1/4 Cr-1 Mo
C	0.15 max	0.15 max	0.08–0.12	0.17–0.23	0.15 max
Mn	0.3–0.6	0.3–0.6	0.3–0.5	0.4–0.7	0.3–0.6
P	0.03 max	0.03 max	0.02 max		0.03 max
S	0.03 max	0.03 max	0.01 max		0.03 max
Si	0.25–1.00	0.25–0.80	0.25 max	0.2–0.3	0.50 max
Cr	8.0–10.0	8.0–10.0	8.0–9.0	11.0–12.5	1.9–2.6
Mo	0.9–1.1	0.9–1.1	0.85–1.05	0.8–1.2	0.87–1.13
V			0.18–0.25	0.25–0.35	
Nb			0.06–0.1		
W				0.4–0.6	

Table 2. Summary of Creep-Rupture Data Sets Examined

Data Set	Number of Lots	Number of Tests	Temperature Range (°C)	Longest Rupture Life (h)
Modified 9 Cr-1 Mo	37	179	482–704	23,334
American 9 Cr-1 Mo	24	191	482–704	19,453
British 9 Cr-1 Mo	45	376	450–650	30,243
Alloy HT9	15	199	500–650	54,853
2 1/4 Cr-1 Mo	14	121	454–566	12,059

and

$$\log \sigma_y = C_h^y - 1.508 \times 10^{-3}T + 6.150 \times 10^{-6}T^2 - 7.481 \times 10^{-9}T^3 , \quad (2)$$

while the British 9 Cr-1 Mo data (431 tests on 61 lots of material) were described by

$$\log \sigma_u = C_h^u - 9.888 \times 10^{-4}T + 3.751 \times 10^{-6}T^2 - 4.980 \times 10^{-9}T^3 \quad (3)$$

and

$$\log \sigma_y = C_h^y - 9.019 \times 10^{-4}T + 3.690 \times 10^{-6}T^2 - 5.009 \times 10^{-9}T^3 , \quad (4)$$

where σ_u is ultimate tensile strength (MPa), σ_y is 0.2% offset yield strength (MPa), and T is temperature (°C). (All logarithms are base 10 in this report.) The terms C_h^u and C_h^y are lot constants, which reflect lot-to-lot variability in ultimate strength and yield strength, respectively. Each lot* of material has its own lot constant. This direct treatment of

*In all analyses in this report, the term lot refers to material from a given heat of material that has undergone a given thermomechanical processing history. Thus several lots may stem from the same heat.

lot-to-lot variability also allows a separate estimation[7,8] of the within-lot (V_W) and between-lot (V_B) variances for the data. The average lot constants, variances, and coefficient of determination (R^2) values for these data are shown in Table 3.

Figures 1 to 4 display the tensile data examined, along with predicted average lines and "minimum-maximum" lines arbitrarily estimated by substracting or adding 1.65 × SEE (SEE = overall standard error of estimate = $\sqrt{V_B + V_W}$) from the calculated average log strength values. The slight peak noted in the modified 9 Cr-1 Mo steel yield strength values around 400°C may be an artifact of the particular distribution of the available data and we place no special significance on it at this time. Additional data will be developed in the future to investigate this phenomenon.

Figures 5 and 6 compare the predicted behavior (range from minimum to average) of the British and the modified 9 Cr-1 Mo materials, along with available data[4] from the American commercial material. The modified material is consistently stronger than the British material (except for ultimate tensile strength above 400°C), which is in turn stronger than the annealed American material. The one lot of normalized and tempered American material for which data were available shows strength values comparable to those of the British normalized and tempered material. All the 9 Cr-1 Mo materials have yield strengths well above the estimated[10] minimum for as-received 304 stainless steel. The British and modified materials show ultimate tensile strengths above the 304 stainless steel minimum for temperatures up to about 600°C.

CREEP-RUPTURE DATA ANALYSIS

The creep-rupture data sets described in Table 2 were analyzed using lot-centered regression[7,11] with a generalized model selection procedure.[12,13] Using this procedure we found a number of models that

Table 3. Summary of Fits to Tensile Data

Data Set	Number of Data	Coefficient of Determination, R^2 (%)	Average Lot Constant[a]	Within-Heat Variance	Between-Heat Variance
		Ultimate Tensile Strength			
Modified 9 Cr-1 Mo	220	98.7	2.8758	4.265×10^{-4}	1.360×10^{-3}
British 9 Cr-1 Mo	431	92.4	2.8453	6.4934×10^{-4}	9.911×10^{-4}
		0.2% Offset Yield Strength			
Modified 9 Cr-1 Mo	220	96.3	2.7972	1.020×10^{-3}	1.688×10^{-3}
British 9 Cr-1 Mo	431	91.1	2.7019	6.646×10^{-4}	2.676×10^{-3}

[a]Note that a direct comparison among different values of average lot constant is meaningless, since other equation parameters are also involved in determining strength.

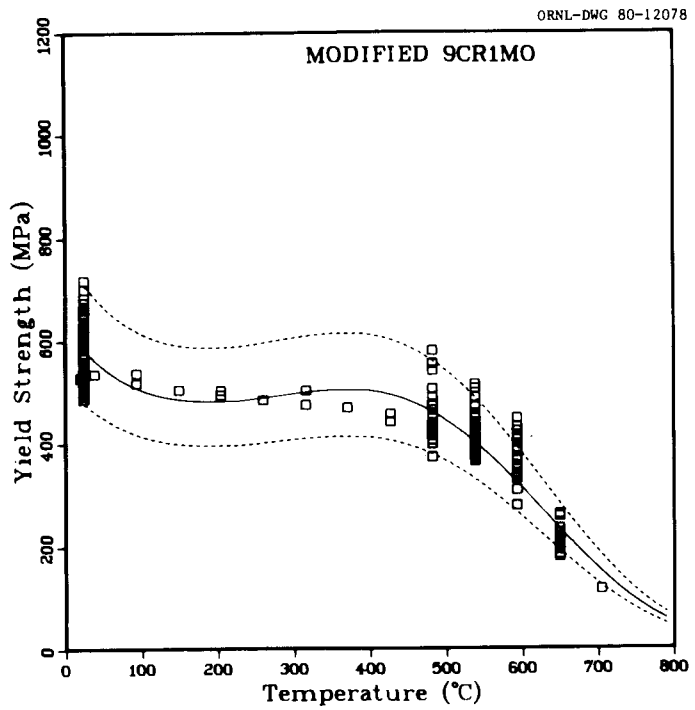

Fig. 1. Comparison of Experimental and Predicted Yield Strengths as a Function of Temperature for Modified 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

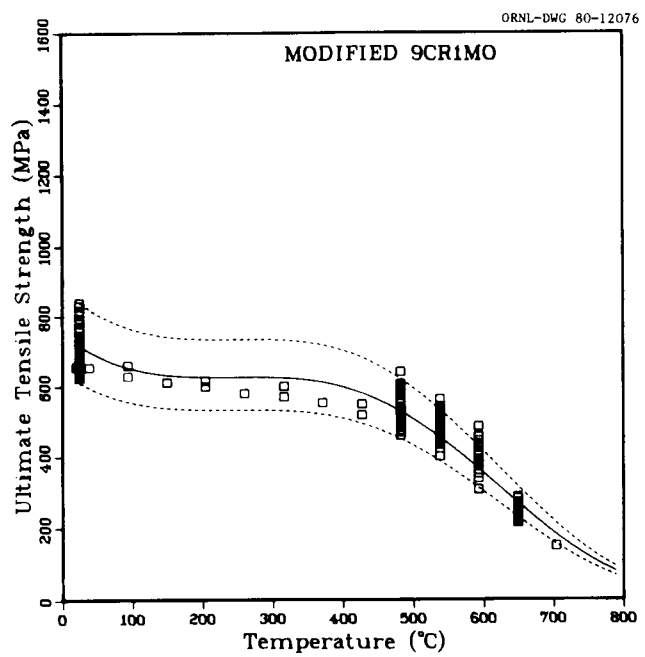

Fig. 2. Comparison of Experimental and Predicted Ultimate Tensile Strengths as a Function of Temperature for Modified 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

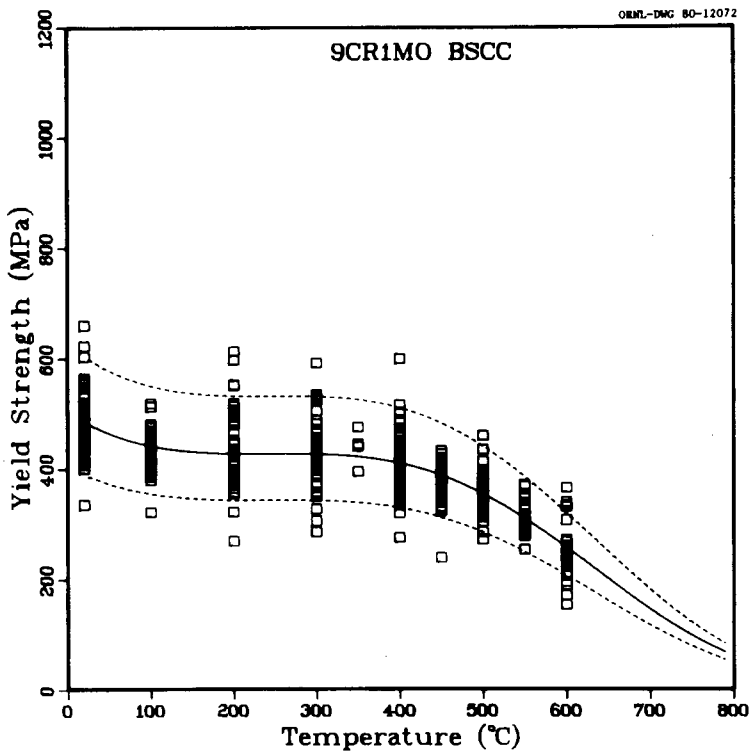

Fig. 3. Comparison of Experimental and Predicted Yield Strengths as a Function of Temperature for British Commercial 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

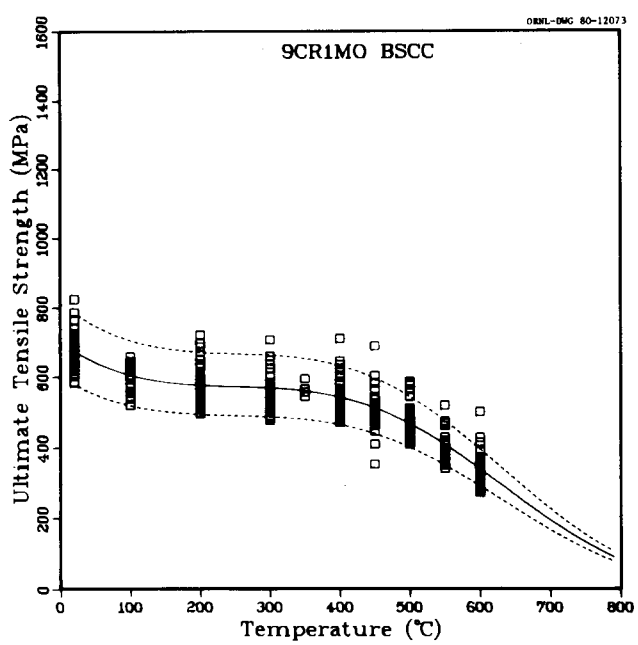

Fig. 4. Comparison of Experimental and Predicted Ultimate Tensile Strengths as a Function of Temperature for British Commercial 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

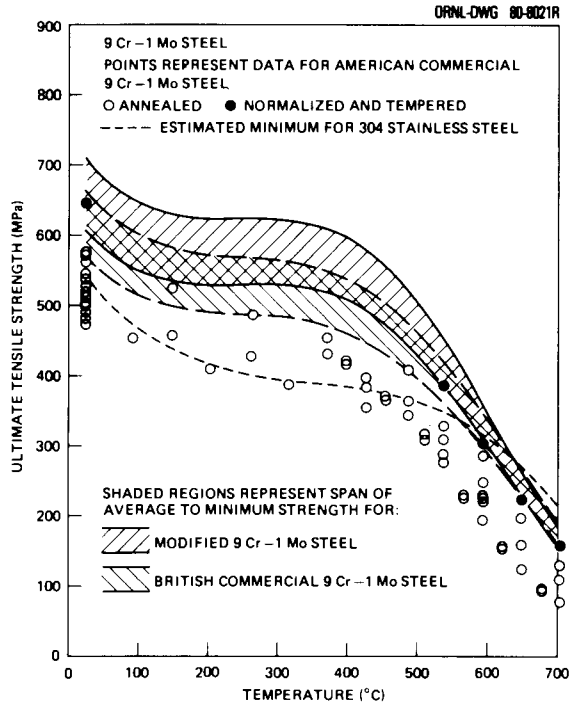

Fig. 5. Comparison of Yield Strength Values for Several Materials as a Function of Temperature.

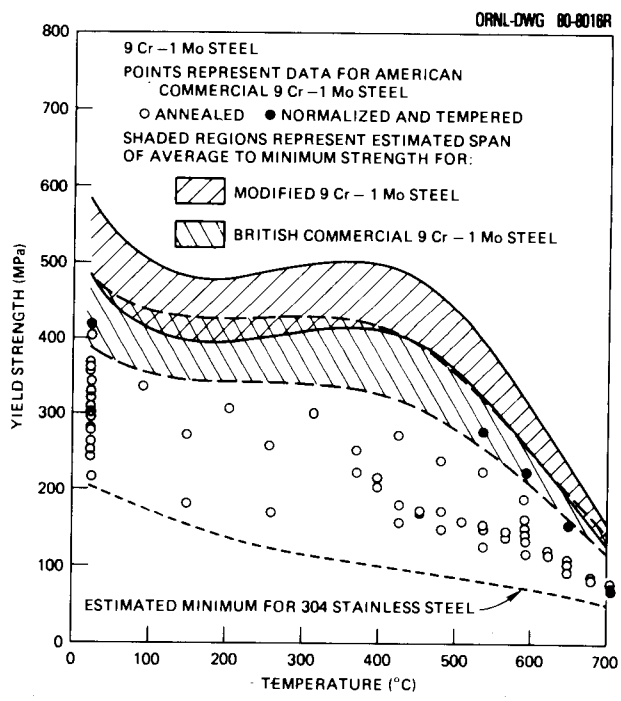

Fig. 6. Comparison of Ultimate Tensile Strength Values for Several Materials as a Function of Temperature.

adequately described the data, but we found that all the data for high-chromium materials could be described quite well by a simple model of the form

$$\log t_r = C_h + a_1\sigma + a_2 \log \sigma + a_3/T \ , \tag{5}$$

where

t_r = rupture life (h),
σ = stress (MPa),
T = temperature (K),
a_1–a_3 = regression constants.

The term C_h is again a lot constant that describes variations in creep-rupture strength among the different lots. Table 4 summarizes the fits of this model to the various data sets.

The 2 1/4 Cr-1 Mo steel data were analyzed by a similar procedure but were found to be best described by

$$\log t_r = C_h - \frac{5941.4 \log \sigma}{T} + 31{,}790/T \ , \tag{6}$$

for which R^2 = 87.1%, V_W = 0.0661, V_B = 0.293, and $\overline{C}_h$ (average lot constant) = –20.294.

Figures 7 to 26 compare predictions (lines) from these fits with experimental data (points) for individual lots of the various materials. The solid lines estimate average behavior for the lot shown, using the lot constant for that particular lot of material. The dashed lines which are shown to give an idea of the uncertainty in the model, were calculated by subtracting two within-heat errors ($\sqrt{V_W}$) in log t_r from the average predictions.

Figure 27 shows estimated overall average stress-rupture isothermals for the various materials examined at temperatures of 482°C (900°F) and 593°C (1100°F). Also shown for comparison are the minimum stress-rupture isothermals for type 304 stainless steel from ASME Code Case N-47.[14] In

Table 4. Summary of Fits to Various Rupture Life Data Sets Using a Standard Model[a,b]

Parameter	Data Set			
	U.S. 9 Cr-1 Mo	British 9 Cr-1 Mo	Modified 9 Cr-1 Mo	HT9
Number of Data	191	376	179	199
a_1	−0.01283	−0.01366	−0.02158	−0.01706
a_2	−4.3533	−2.3491	−2.6552	−1.5737
a_3	24920	23074	29850	27240
R^2, %	95.5	88.6	84.9	92.2
V_B	0.0894	0.110	0.142	0.0193
V_W	0.0213	0.0520	0.0491	0.0315
$\overline{C}_h$	−16.399	−17.329	−21.762	−22.183

[a]Model was $\log t_r = C_h + a_1\sigma + a_2 \log \sigma + a_3/T$.

[b]Direct comparisons among the regression parameters ($a_1 - a_3$, $\overline{C}_h$) for different sets are meaningless, since their effects are synergistic.

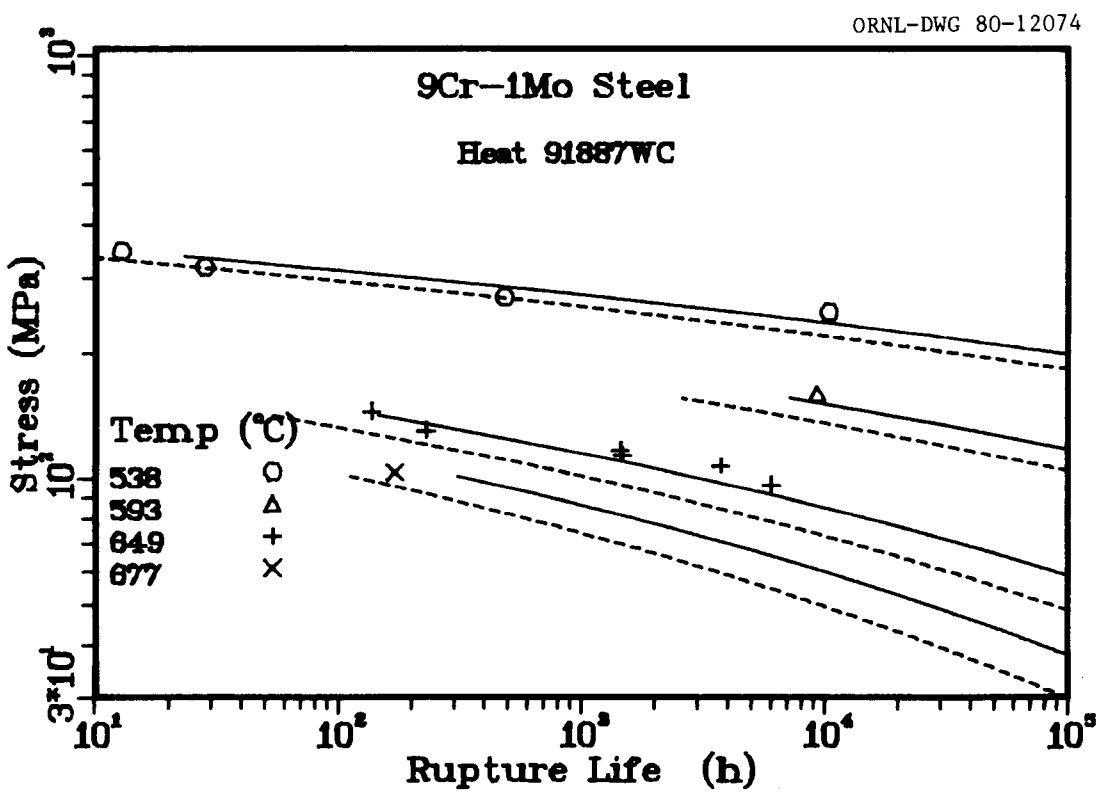

Fig. 7. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 91887WC of Modified 9 Cr-1 Mo Steel.

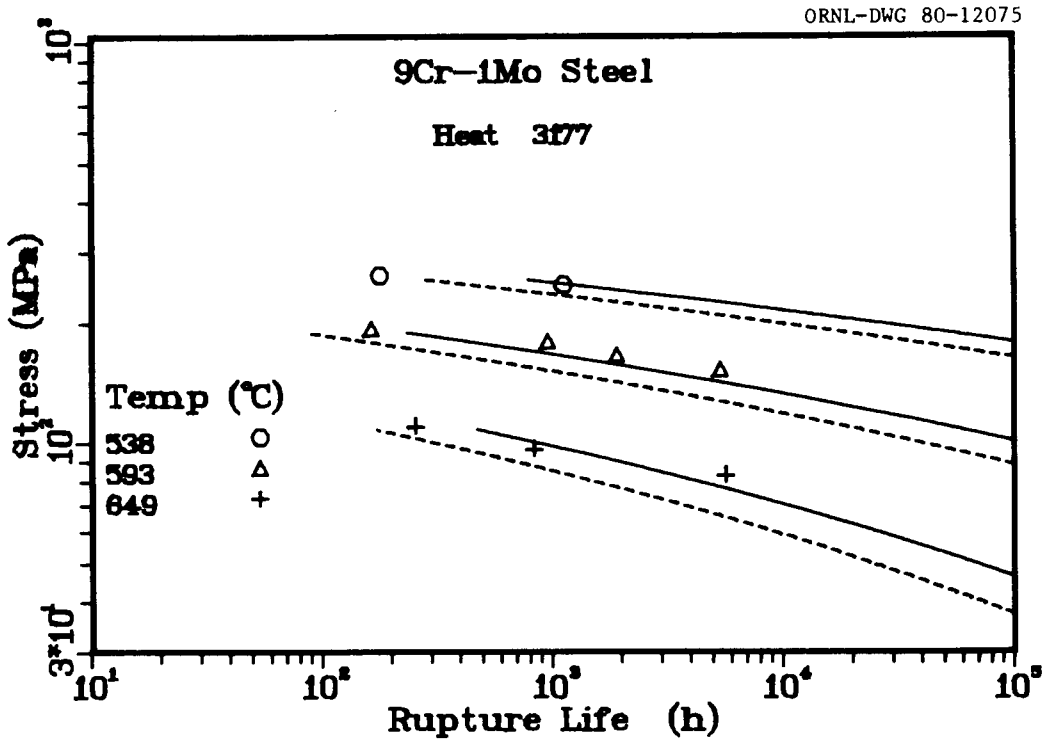

Fig. 8. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 3177 of Modified 9 Cr-1 Mo Steel.

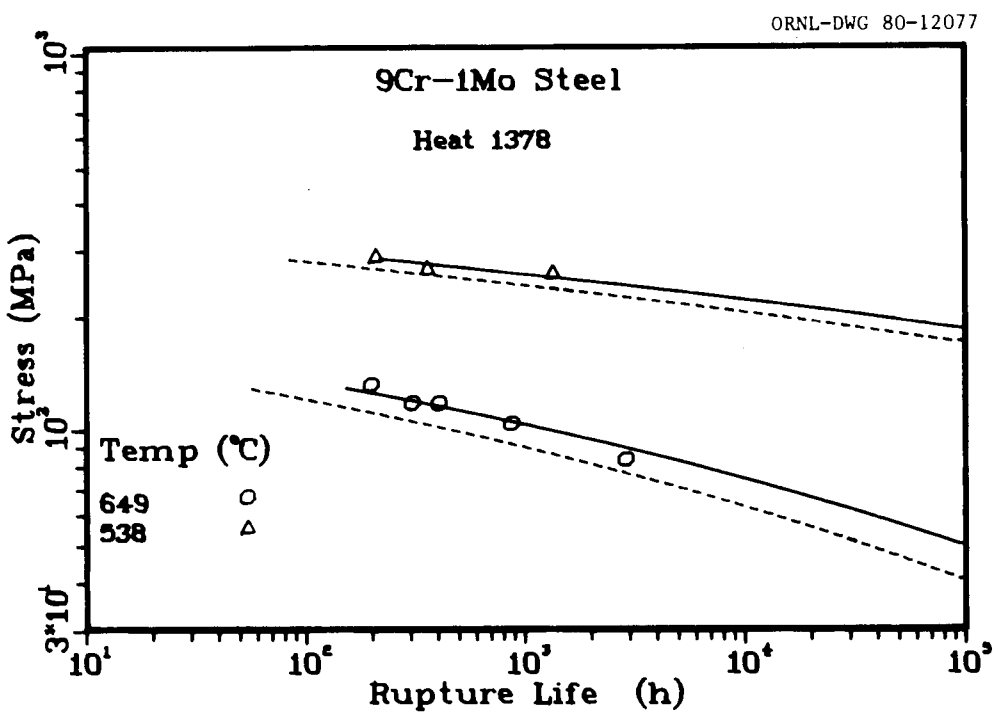

Fig. 9. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 1378 of Modified 9 Cr-1 Mo Steel.

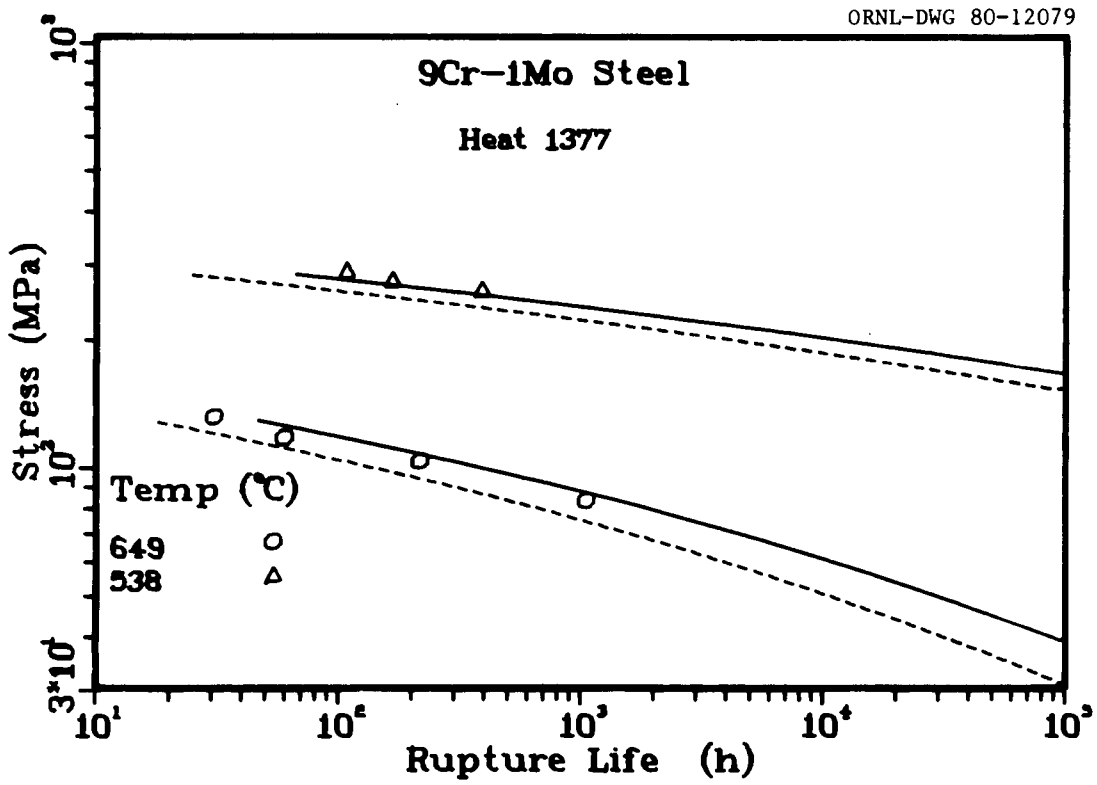

Fig. 10. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 1377 of Modified 9 Cr-1 Mo Steel.

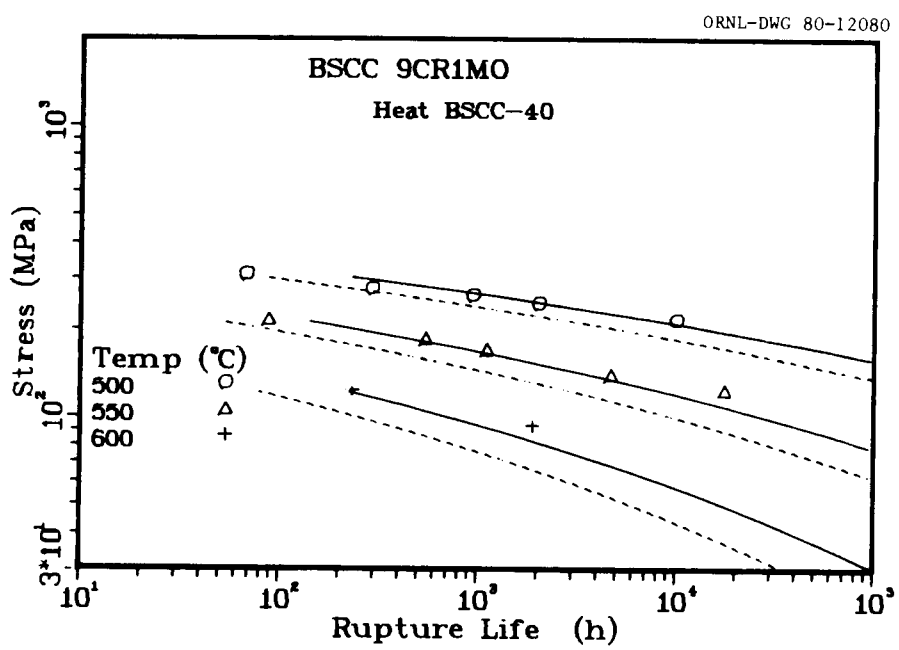

Fig. 11. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-40 of British Commercial 9 Cr-1 Mo Steel.

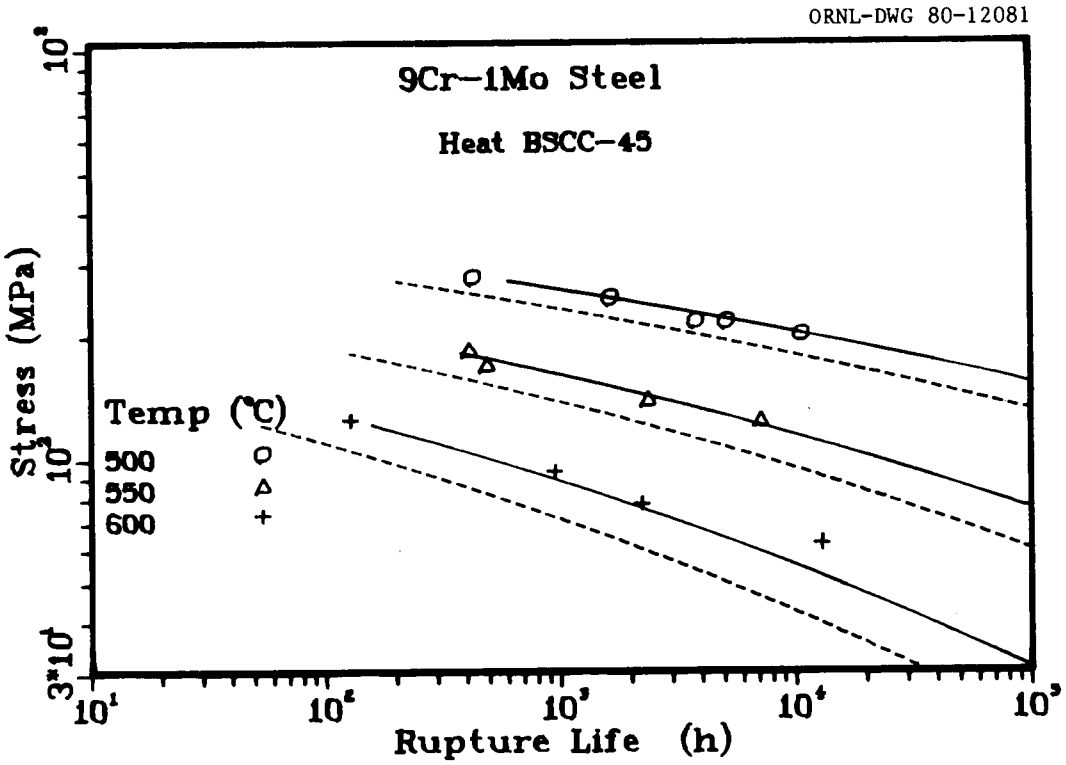

Fig. 12. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-45 of British Commercial 9 Cr-1 Mo Steel.

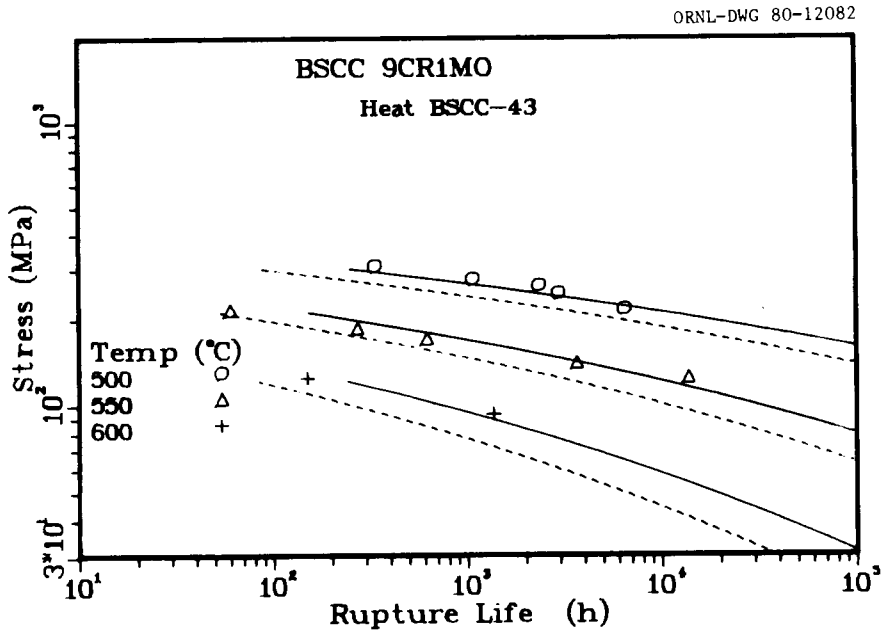

Fig. 13. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-43 of British Commercial 9 Cr-1 Mo Steel.

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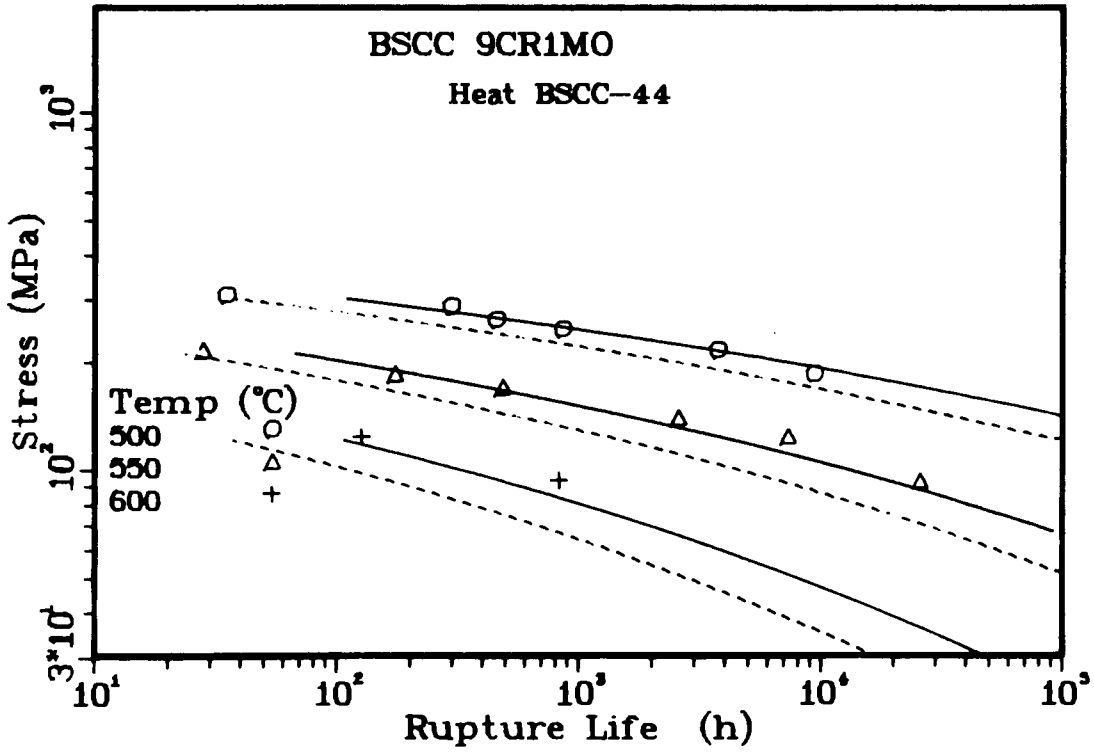

Fig. 14. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-44 of British Commercial 9 Cr-1 Mo Steel.

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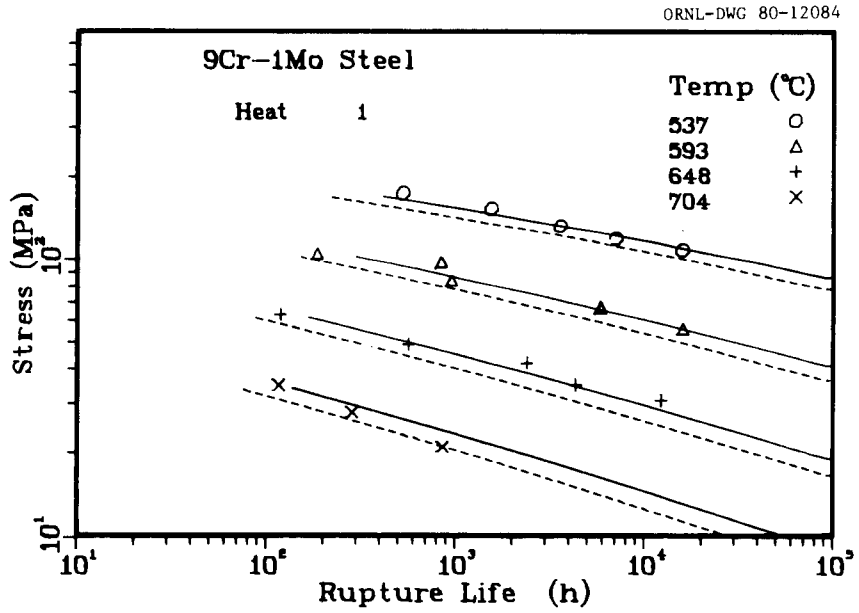

Fig. 15. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 1 of American Commercial 9 Cr-1 Mo Steel.

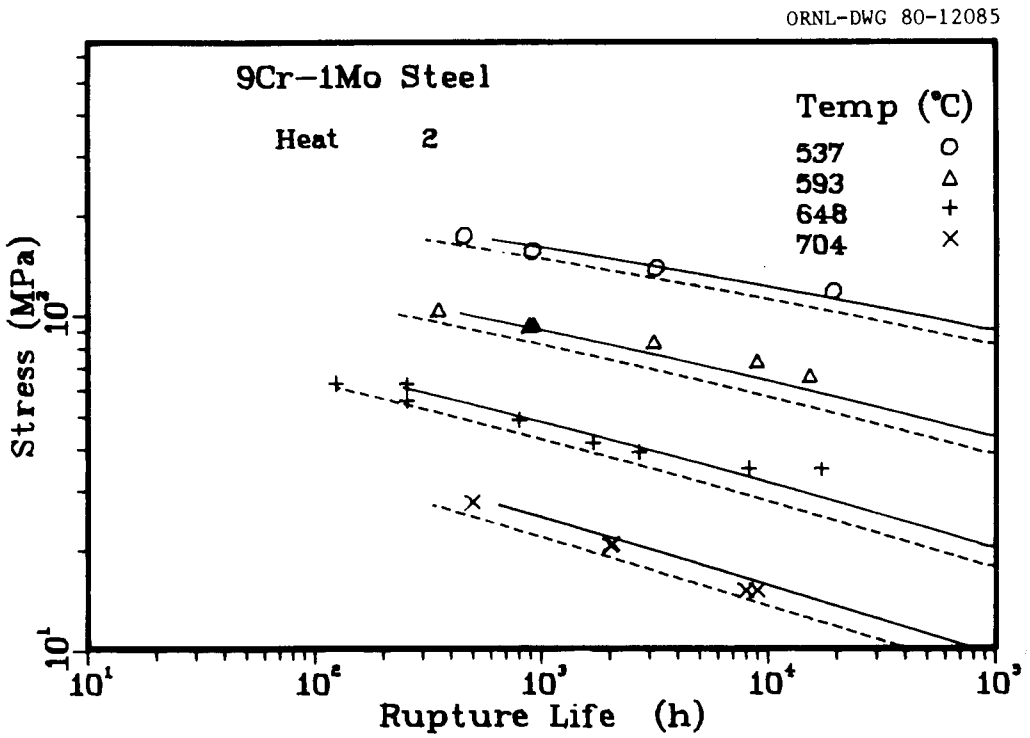

Fig. 16. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 2 of American Commercial 9 Cr-1 Mo Steel.

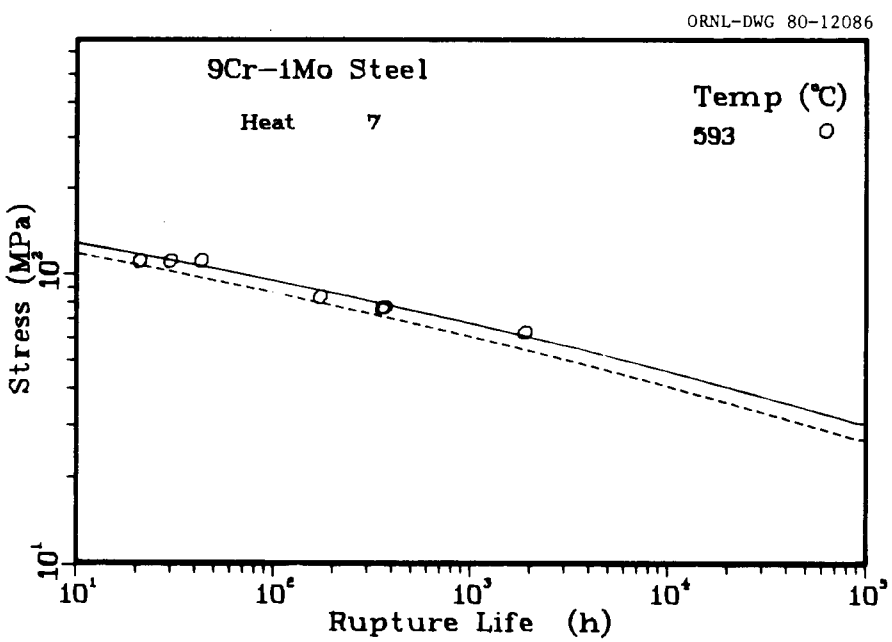

Fig. 17. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 7 of American Commercial 9 Cr-1 Mo Steel.

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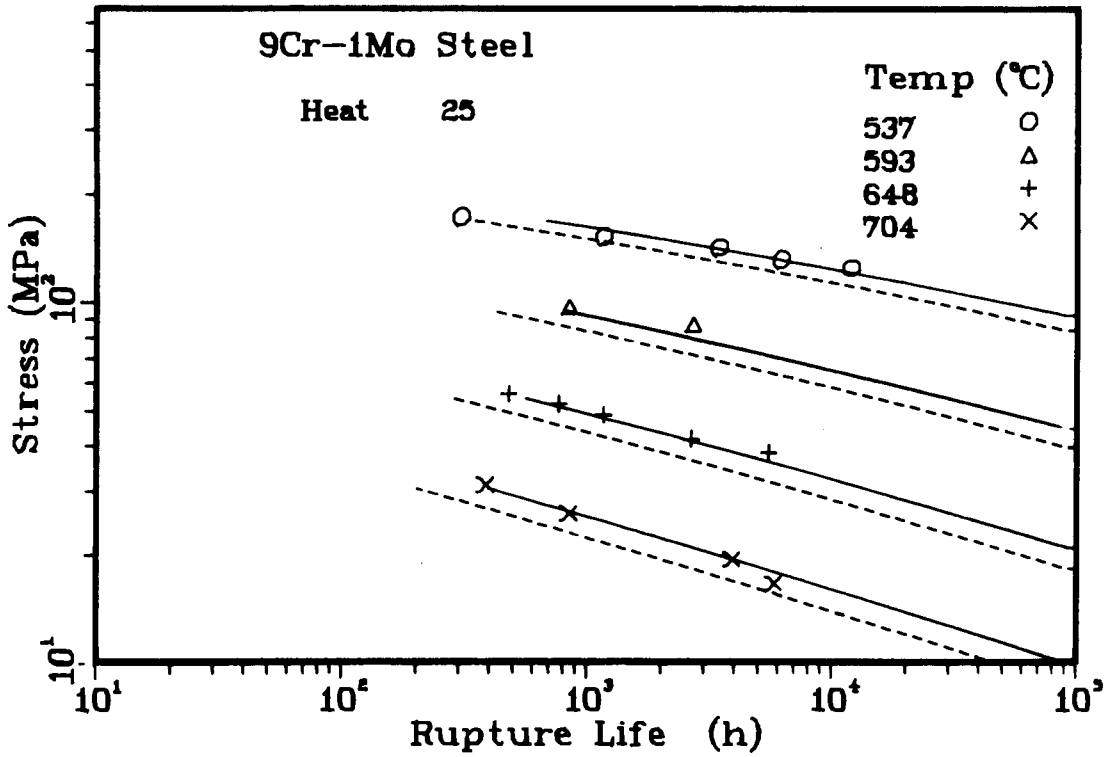

Fig. 18. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 25 of American Commercial 9 Cr-1 Mo Steel.

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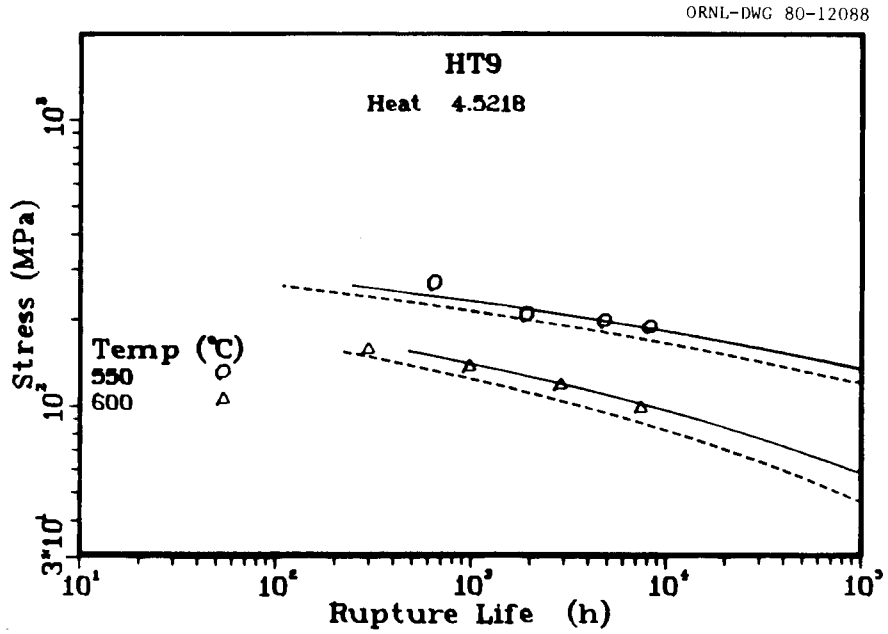

Fig. 19. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 4.5218 of Alloy HT9.

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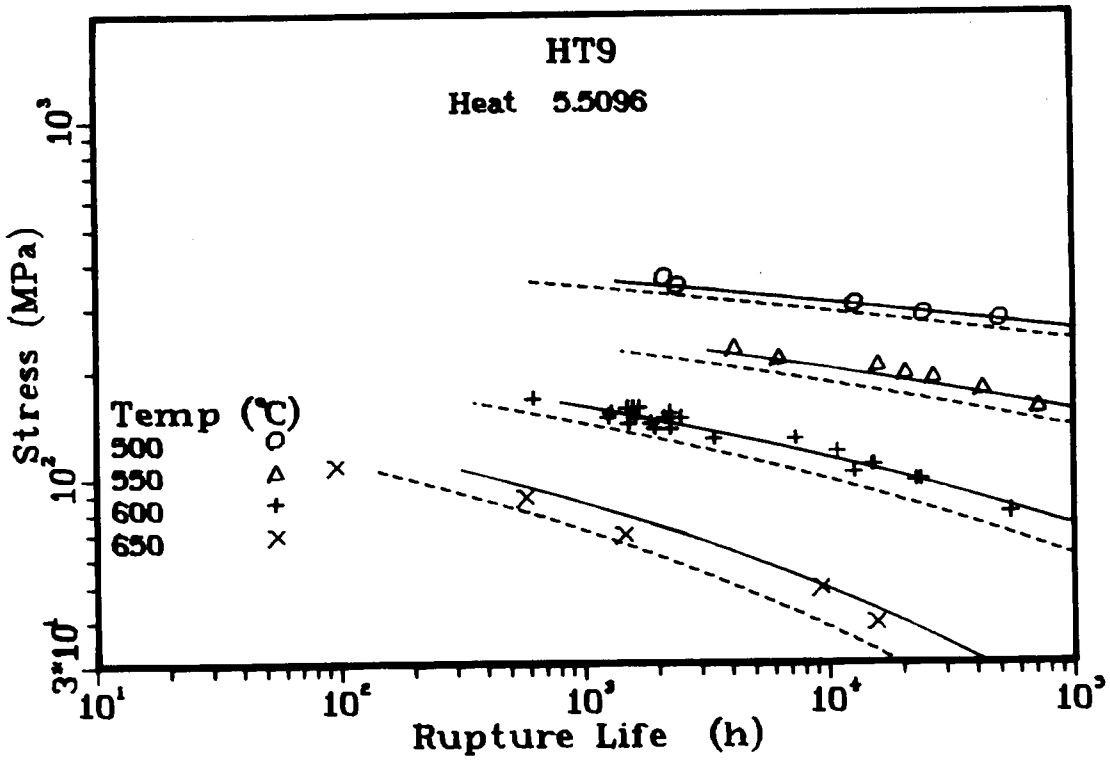

Fig. 20. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 5.5096 of Alloy HT9.

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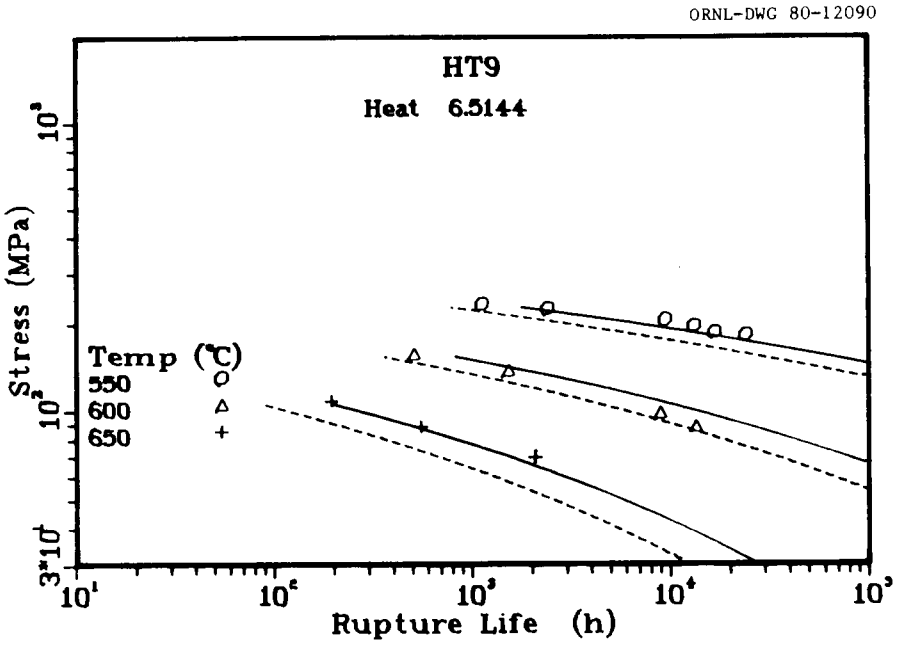

Fig. 21. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 6.5144 of Alloy HT9.

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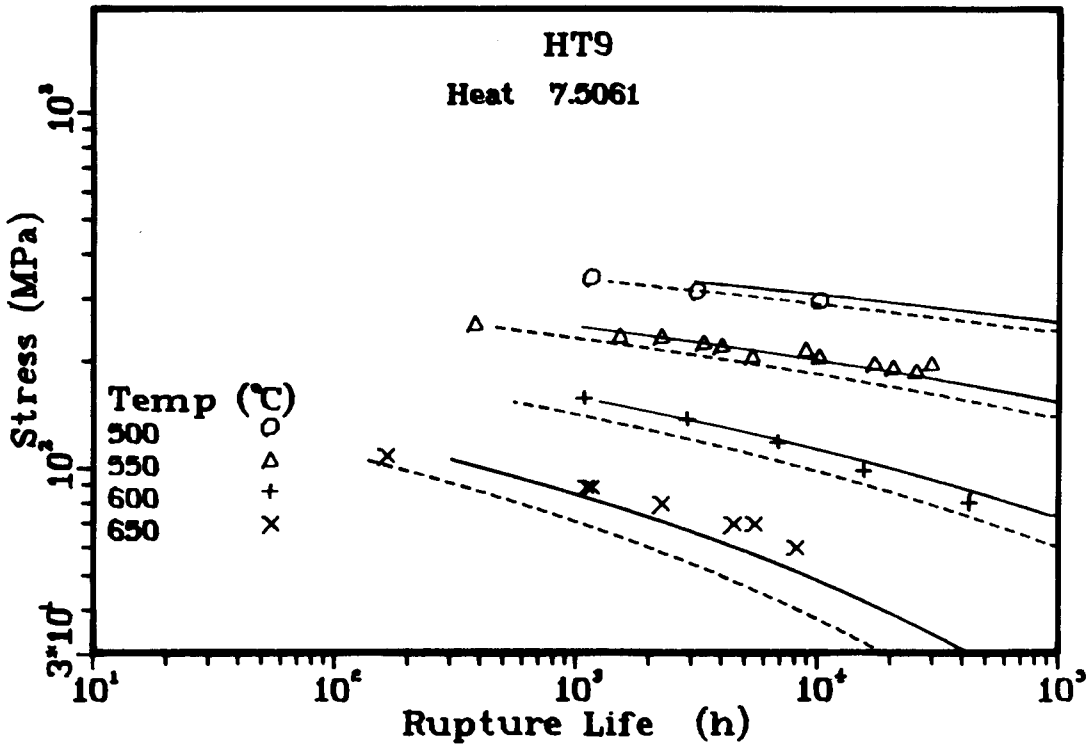

Fig. 22. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 7.5061 of Alloy HT9.

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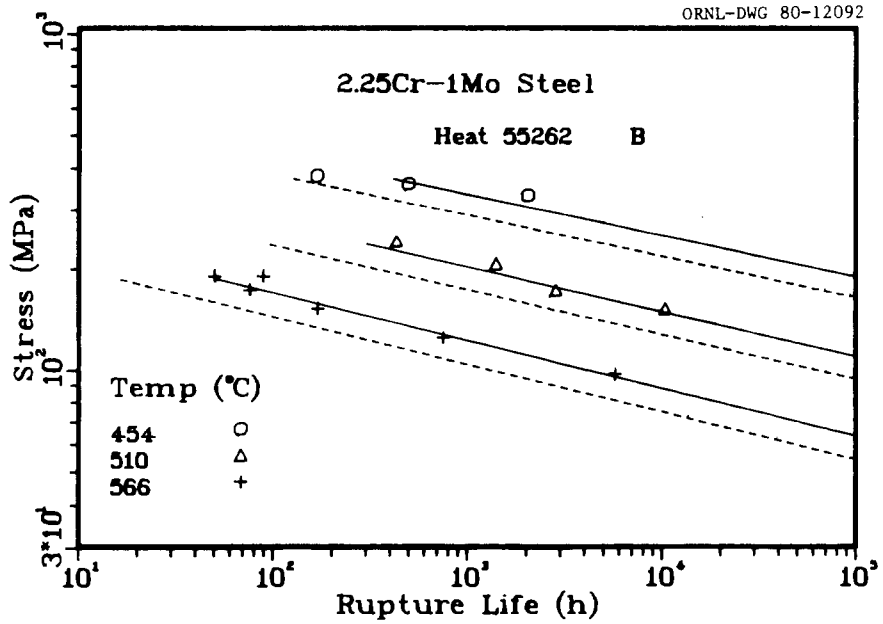

Fig. 23. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 55262B of 2 1/4 Cr-1 Mo Steel.

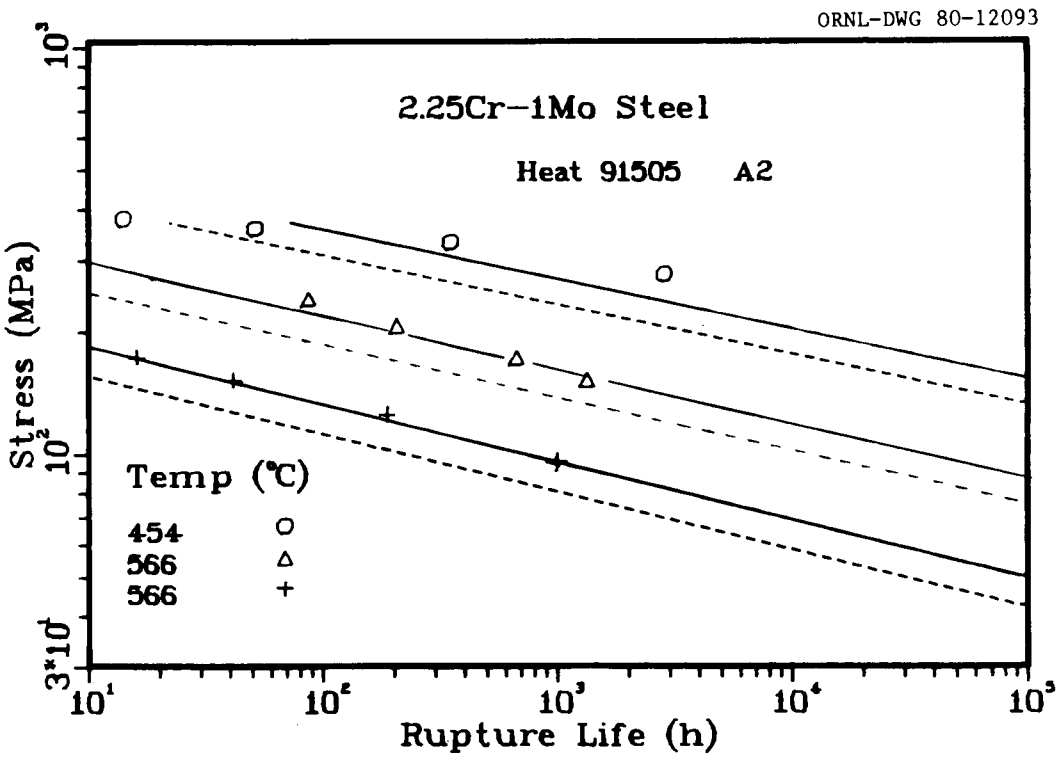

Fig. 24. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 91505A2 of 2 1/4 Cr-1 Mo Steel.

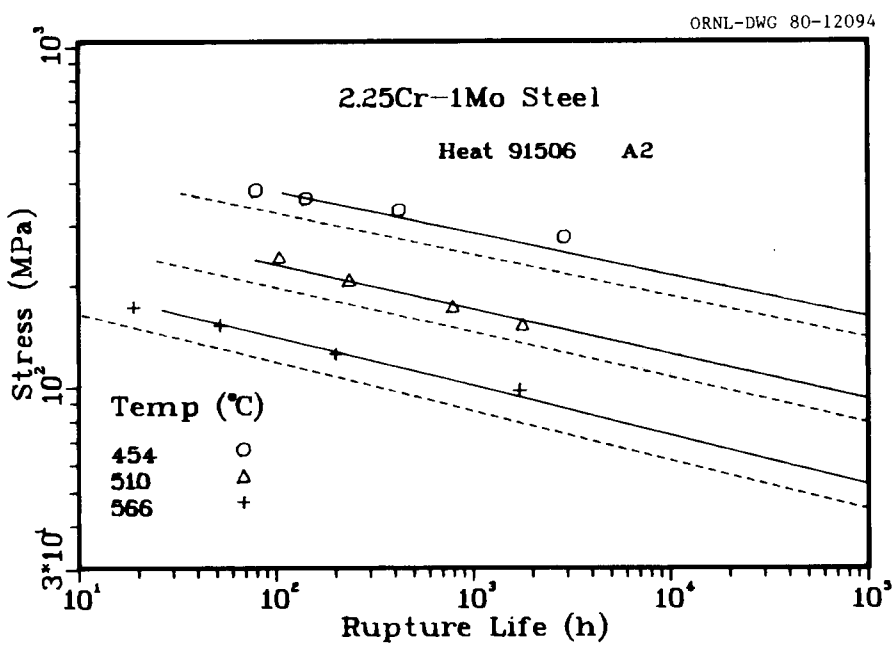

Fig. 25. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 91506A2 2 1/4 Cr-1 Mo Steel.

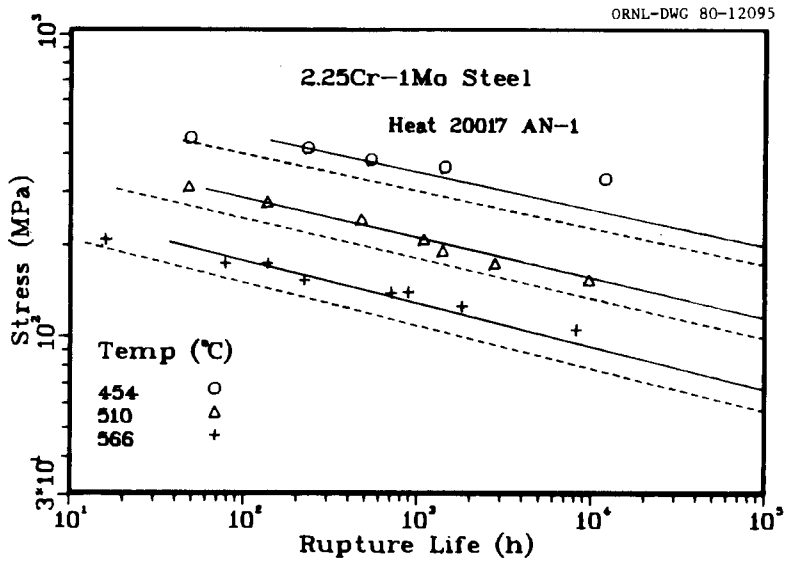

Fig. 26. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 20017AN-1 2 1/4 Cr-1 Mo Steel.

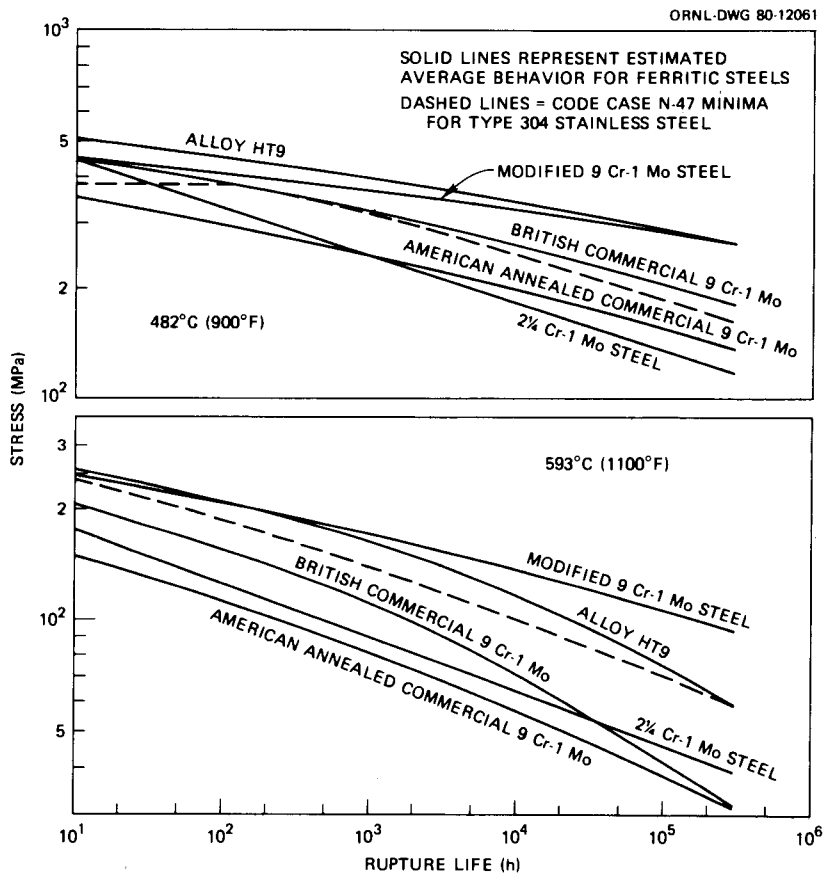

Fig. 27. Comparison of Estimated Stress-Rupture Isothermals for Several Materials.

general, the modified 9 Cr-1 Mo steel and alloy HT9 have the highest estimated strengths (above the 304 stainless steel minimum at both temperatures), while the annealed 9 Cr-1 Mo steel and the annealed 2 1/4 Cr-1 Mo steel have the lowest (below the 304 stainless steel minimum at both temperatures). The British commercial 9 Cr-1 Mo steel is generally intermediate in strength among these materials, although it does fall below the 2 1/4 Cr-1 Mo steel in strength for the longest times at 593°C.

Figure 28 illustrates the variation in estimated average 10^4-h rupture strength with temperature for the various materials examined. Shown for comparison are average values estimated for 304 stainless steel in the

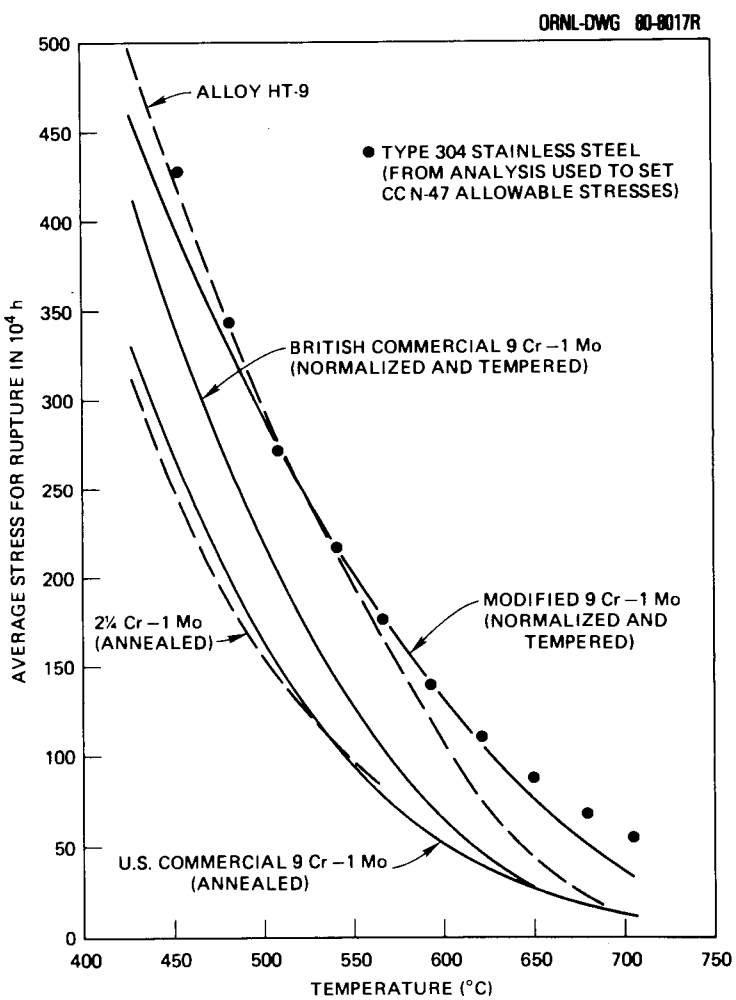

Fig. 28. Variation of 10^4-h Creep-Rupture Strength with Temperature for Several Materials.

analysis[15] that was used to calculate the minimum values now given in Code Case N-47. (This time was chosen because it is the longest time for which verifiable strengths can be calculated for all data sets.) The modified 9 Cr-1 Mo steel is comparable in strength to the type 304 stainless steel for temperatures up to about 625°C, after which it begins to fall below the stainless steel in strength. Alloy HT9 maintains a strength comparable to that of the stainless steel only up to about 550°C, after which it drops off to lower values. Again, the two annealed materials are lowest in strength, with the British material being intermediate. Above about 675°C, however, all the ferritics (except modified 9 Cr-1 Mo) converge to about the same low strength value. Even as high as 700°C the modified 9 Cr-1 Mo material remains intermediate between the stainless steel and the other ferritics.

ALLOWABLE STRESS VALUES

The analyses performed here for the modified 9 Cr-1 Mo steel and the British commercial 9 Cr-1 Mo steel allow an estimation of design allowable stresses per the ASME Boiler and Pressure Vessel Code. However, it must be remembered that such estimates are preliminary, especially for the modified material. It is expected that these estimates will change as more data (especially long-term data) become available from this ongoing program.

Code Case N-47 considers two sets of allowable stress intensities for nuclear service at elevated temperature. The first criterion, denoted S_O, is a function of temperature only and is the allowable stress intensity for design conditions. For operating conditions, the allowable stress intensity is S_{mt}, which varies with both time and temperature. (Operating conditions are the pressure, temperature, and flow conditions at which a plant is actually intended to operate.) Design conditions are merely a set of arbitrarily specified conditions somewhat more severe than the normal operating conditions. Use of design conditions as criteria can be regarded[16] as a vestige of earlier design concepts for which no time dependence was considered in setting allowable stresses. Thus, for

elevated-temperature nuclear design, the value of S_{mt} is far more important than the value of S_o. However, in lower-temperature nuclear service or in nonnuclear service, S_o may be the only allowable stress intensity and thus is still important. (The S_o values are simply S in Sect. VIII, Div. 1 of the code.)

For a ferritic steel, S_o is given as the lowest of the following four stress values at a given temperature:

1. Tensile: one-fourth the tensile strength at temperature, which is defined as the smaller of (a) the specified minimum tensile strength at room temperature or (b) a value 10% greater than the minimum tensile strength at temperature.

2. Yield: five-eighths the minimum yield strength at temperature.

3. Rupture: (a) 0.67 average rupture stress for 100,000 h or (b) 0.8 minimum rupture stress for 100,000 h. (It should be noted that many materials currently in the code used a value of 0.60 on average 100,000-h rupture stress rather than 0.67.)

4. Secondary (or minimum) creep rate: the average secondary creep rate for 0.01% creep per 1000 h (equivalent to 1%/100,000 h).

The term S_{mt} is the lower of S_m (the time-independent allowable stress intensity) and S_t (the time-dependent allowable stress intensity). For ferritic steels, these values are given by the following criteria:[17]

The S_m value is given by the lower of (a) one-third the tensile strength at temperature, defined as the smaller of specified minimum tensile strength at room temperature or 110% of the minimum tensile strength at the temperature of interest; or (b) two-thirds the minimum yield strength at temperature.

The S_t value is given by the lowest of (a) two-thirds the minimum stress to cause rupture in time t; (b) 80% of the minimum stress to cause onset of tertiary creep in time t; or (c) 100% of the minimum stress to produce 1% total strain in time t.

An estimate of the stress to cause 1% strain is beyond the scope of this analysis, but the behavior of the modified 9 Cr-1 Mo steel is such that we believe this criterion would never control S_t (or S_{mt}). We have taken this assumption to hold for the British material as well, though we

have few actual data to back up the assumption in that case. All the other criteria were considered, however. For all tensile properties, minimum values were calculated by subtracting 1.65 $V_B + V_W$ in log strength for the averages given in Eqs. (1) to (4). Minimum rupture behavior was calculated by subtracting $1.65\sqrt{V_B + V_W}$ in log time from estimated average behavior. The time to tertiary creep was found to be approximately one-half the time to rupture for the modified material (Fig. 29) and was assumed to be the same for the British material. Minimum time to tertiary creep was taken as half the minimum time to rupture.

The minimum creep rate, $\dot{e}_m$ (%/h), for the modified material was determined using measurements from essentially the same tests used to determine the rupture life equation. The equation found for $\dot{e}_m$ from 184 data was

$$\log \dot{e}_m = C_{\dot{h}} + 0.02292 + 3.980 \log - (33{,}610/T) \ , \qquad (7)$$

for which $\overline{C}_{\dot{h}} = 23.403$, $R^2 = 82.2\%$, $V_W = 0.0820$, and $V_B = 0.281$.

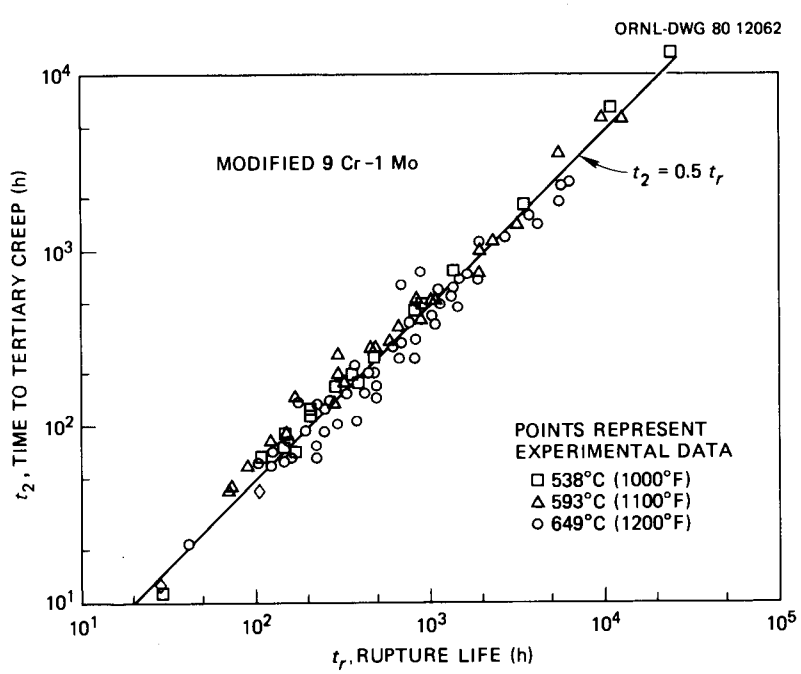

Fig. 29. Relationship Between Time to the Onset of Tertiary Creep and Rupture Life for ORNL Modified 9 Cr-1 Mo Steel.

Minimum creep rate data for British material were not available. It is likely, however, that the minimum creep rate criterion will never control allowable stresses, as indeed it never did for the modified material. Therefore, this criterion was ignored in calculating S_o for the British material.

Table 5 displays the estimated values of S_o for both the modified and the British materials, while Tables 6 and 7 display the estimated values of S_{mt} for the modified and for the British material, respectively.

Figures 30 and 31 compare the estimated allowable stresses for these two material with those given in the ASME code for several others. Again, the modified 9 Cr-1 Mo steel demonstrates a marked strength advantage over the other ferritic materials over the entire temperature range from 427 to 704°C (800 to 1300°F). This material was estimated to have S_o values above or equal to those of 304 stainless steel to about 600°C and to have S_{mt} values above or equal to those of the stainless steel to about 625°C.

Table 5. Estimated Design Allowable Stress Intensities, S_o (MPa)

Temperature (°C)	Temperature (°F)	Modified 9 Cr-1 Mo	British 9 Cr-1 Mo
427	800	135	107
454	850	130	104
482	900	123	101
510	950	115	94.6
538	1000	106	61.7
566	1050	95.4	37.9
593	1100	68.6	22.5
621	1150	45.8	12.6
649	1200	28.5	7.0
677	1250	16.5	3.9
704	1300	9.2	2.2

Table 6. Allowable Stress Intensity, S_{mt}, for Modified 9 Cr-1 Mo Steel (MPa)

Temperature		Time, h									
(°C)	(°F)	10	30	100	300	10^3	3×10^3	10^4	3×10^4	10^5	3×10^5
427	800	181	181	181	181	181	181	181	181	181	181
454	850	173	173	173	173	173	173	173	173	173	173
482	900	164	164	164	164	164	164	164	164	164	162
510	950	154	154	154	154	154	154	154	153	138	127
538	1000	141	141	141	141	141	141	131	119	107	96.0
566	1050	128	128	128	128	125	114	102	91.0	79.6	70.0
593	1100	113	113	113	111	99.3	88.6	77.3	67.4	57.2	48.4
621	1150	98.3	98.3	97.5	86.8	75.6	65.8	55.6	46.9	38.2	30.9
649	1200	83.4	83.4	75.3	65.5	55.4	46.7	38.0	30.7	23.8	18.3
677	1250	76.3	66.4	56.2	47.5	38.7	31.4	24.3	18.8	13.6	9.8
704	1300	58.8	49.9	40.8	33.3	26.0	20.2	14.8	10.8	7.4	5.2

Table 7. Allowable Stress Intensity, S_{mt}, for British Commercial 9 Cr-1 Mo Steel (MPa)

Temperature		Time, h									
(°C)	(°F)	10	30	100	300	10^3	3×10^3	10^4	3×10^4	10^5	3×10^5
427	800	142	142	142	142	142	142	142	142	142	142
454	850	139	139	139	139	139	139	139	139	139	139
482	900	135	135	139	139	139	139	139	132	114	98.2
510	950	132	132	132	132	132	128	110	94.7	78.8	65.5
538	1000	129	129	129	127	109	93.6	77.8	64.6	51.5	40.9
566	1050	125	125	110	94.6	78.8	65.5	52.3	41.6	31.6	23.8
593	1100	114	98.7	82.6	68.9	55.3	44.3	33.9	25.8	18.4	13.2
621	1150	87.1	73.1	59.1	47.7	36.7	28.2	20.4	14.7	10.1	7.1
649	1200	64.4	52.4	40.8	31.6	23.2	17.0	11.7	8.2	5.5	3.8
677	1250	46.1	36.2	27.1	20.0	14.0	9.9	6.7	4.6	3.0	2.1
704	1300	32.4	24.6	17.5	12.5	8.5	5.9	3.9	2.7	1.8	1.2

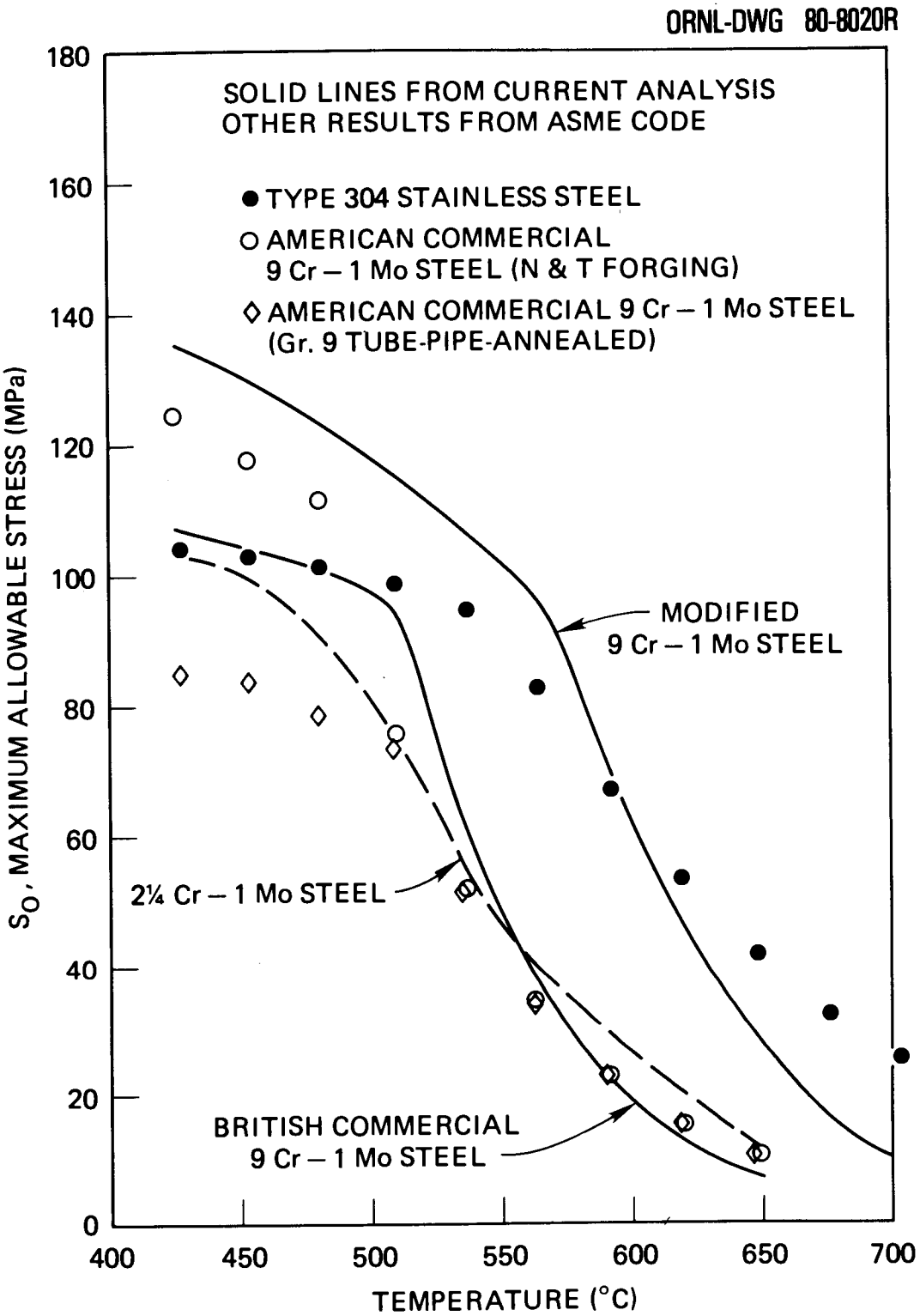

Fig. 30. Variation of Estimated Design Allowable Stress Intensity, S_O, with Temperature for Several Materials.

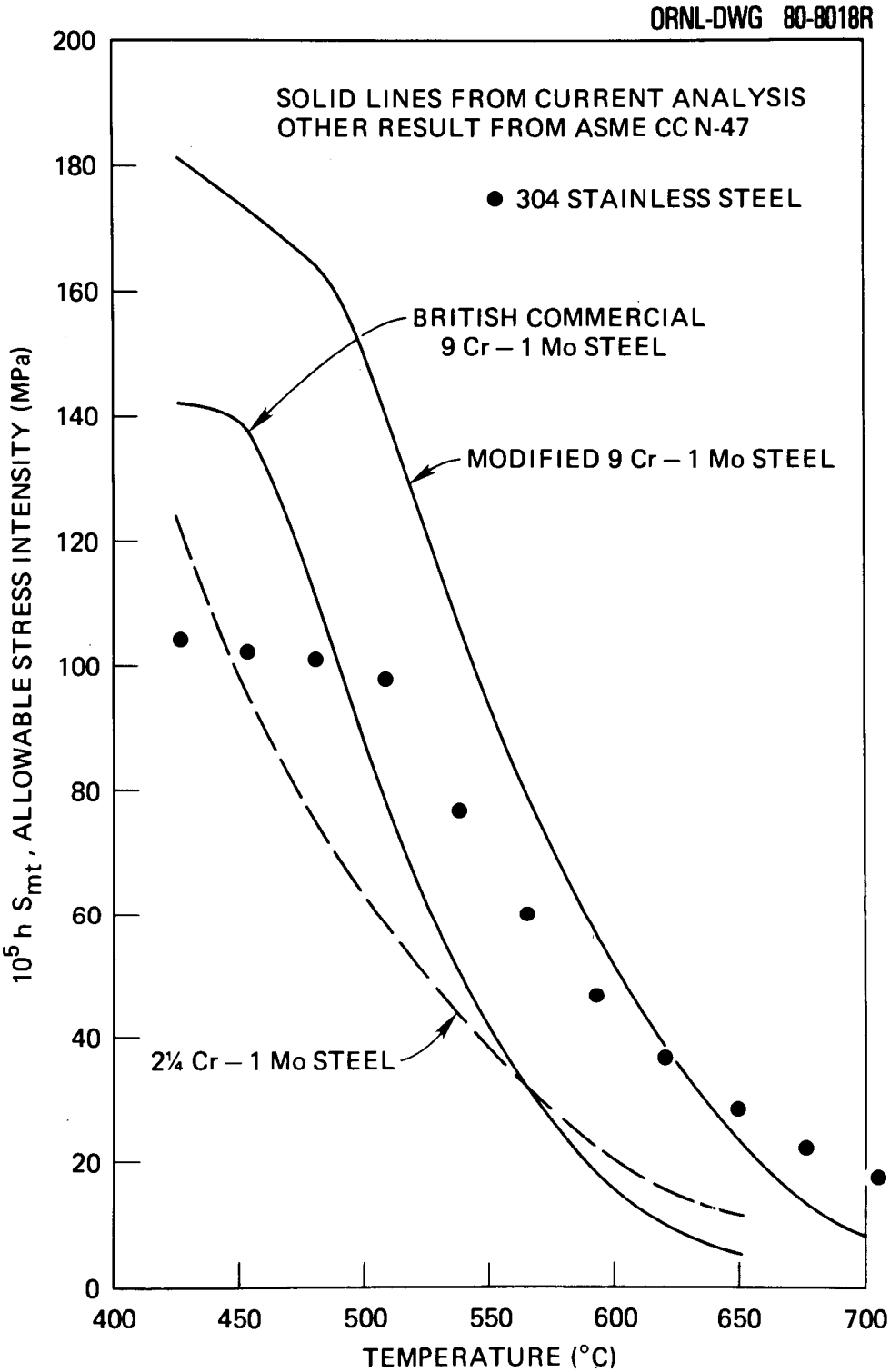

Fig. 31. Variation of Estimated Allowable Stress Intensity, S_{mt}, for 10^5 h with Temperature for Several Materials.

SUMMARY AND CONCLUSIONS

The tensile and creep-rupture behaviors of the ORNL modified 9 Cr-1 Mo steel, the British commercial 9 Cr-1 Mo steel, the American commercial (annealed) 9 Cr-1 Mo steel, and the 12% Cr alloy HT9 have been examined and compared. Comparisons have also been made with the behavior of 2 1/4 Cr-1 Mo steel and type 304 austenitic stainless steel. The following conclusions emerge from these analyses and comparisons.

1. In terms of yield and ultimate tensile strengths, the modified 9 Cr-1 Mo steel is consistently stronger than the British material from room temperature to 700°C; above 600°C the ultimate tensile strengths of the two materials appear to be quite close. The American annealed 9 Cr-1 Mo is weaker than any of the above materials. All the 9 Cr-1 Mo steels have yield strengths above those expected for mill-annealed type 304 stainless steel over the entire temperature range. The modified and British materials exceed 304 stainless steel in ultimate tensile strength up to about 600°C.

2. In terms of creep-rupture strength, the modified 9 Cr-1 Mo steel and alloy HT9 surpass all the other ferritic materials over the range 427 to 704°C (800 to 1300°F), with the modified 9 Cr-1 Mo material gaining an advantage over alloy HT9 at higher temperatures and longer times. The American commercial 9 Cr-1 Mo steel shows creep-rupture strength similar to that of 2 1/4 Cr-1 Mo steel and well below that of the modified 9 Cr-1 Mo steel. The British 9 Cr-1 Mo steel shows creep-rupture strength intermediate between that of the modified material and the American commercial material. The modified 9 Cr-1 Mo steel shows creep-rupture strength comparable to that of type 304 stainless steel up to about 625°C.

3. Allowable stress values S_o and S_{mt} were calculated for the modified 9 Cr-1 Mo steel and the British commercial 9 Cr-1 Mo steel. These values were compared with those listed in the ASME Boiler and Pressure Vessel Code for American commercial 9 Cr-1 Mo steel, 2 1/4 Cr-1 Mo steel, and type 304 stainless steel. The modified 9 Cr-1 Mo steel surpasses all the other ferritic materials in terms of allowable stress, yielding S_o values greater than or equal to those for 304 stainless steel up to about 600°C and S_{mt} values greater than or equal to those for the stainless steel up to about 625°C.

4. The overall conclusion of this work is that the modified 9 Cr-1 Mo steel displays tensile and creep strengths significantly superior to those of the other ferritic materials examined and it is at least comparable to type 304 stainless steel from room temperatures to about 625°C.

ACKNOWLEDGMENTS

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