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COMPARISON OF THE MECHANICAL STRENGTH PROPERTIES OF SEVERAL HIGH-CHROMIUM FERRITIC STEELS*

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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 annealed 2 1/4 Cr-1 Mo steel is currently being used. Different 9 Cr-1 Mo steels are already being used commercially in both Britain and the United States, and a 9 Cr-2 Mo steel (EM12) is being used commercially in France. The 12% Cr steel alloy HT9 is also often recommended for high-temperature service.

Creep-rupture data for all six 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 per Section VIII, Division 1 and S_m per Code Case N-47 to Section III of 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 from room temperature to about 625°C.

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DATA FOR SEVERAL FERRITIC STEELS WERE EXAMINED

1. MODIFIED 9 Cr-1 Mo STEEL
2. AMERICAN COMMERICAL 9 Cr-1 Mo STEEL (ANNEALED)
3. BRITISH COMMERCIAL 9 Cr-1 Mo STEEL
4. HT9
5. 2 1/4 Cr-1 Mo STEEL
6. 304 STAINLESS STEEL EXAMINED FOR COMPARISON

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

HC REGRESSION ALLOWS CONVENIENT TREATMENT OF MULTIHEAT DATA

1. FOR EACH HEAT, SUBTRACT THE AVERAGE VALUE OF EACH VARIABLE FROM THE VALUE FOR EACH TEST
2. FIT THE "HEAT-CENTERED" DATA BY STANDARD TECHNIQUES
3. PREDICTED CURVES FOR DIFFERENT HEATS WILL BE PARALLEL WITH DIFFERENT INTERCEPTS OR "HEAT CONSTANTS"
4. AVERAGE AND MINIMUM HEAT CONSTANTS CAN EASILY BE ESTIMATED

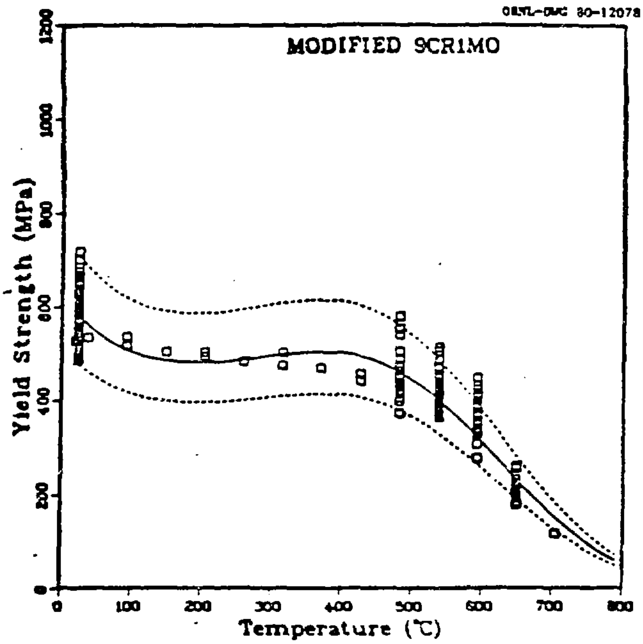

Fig. 1. Comparison of Experimental and Predicted Yield Strengths as a Function of Temperature for Modified 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

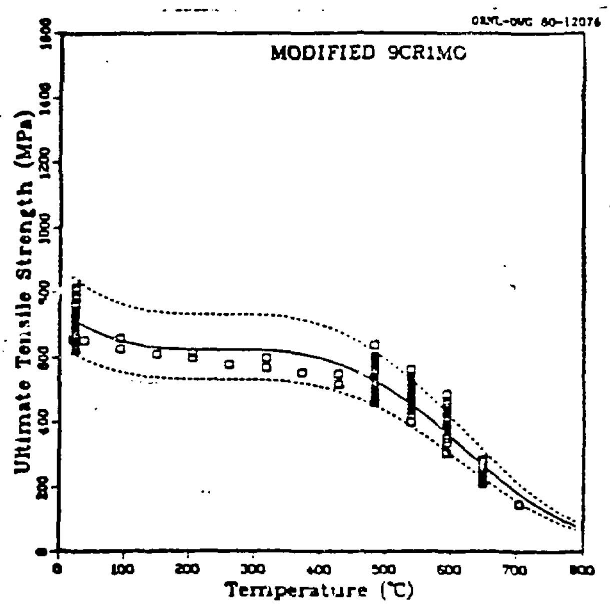

Fig. 2. Comparison of Experimental and Predicted Ultimate Tensile Strengths as a Function of Temperature for Modified 9 Cr-1 Mo Steel. Solid line — predicted average; dashed lines — predicted average ±1.65 standard errors of estimate.

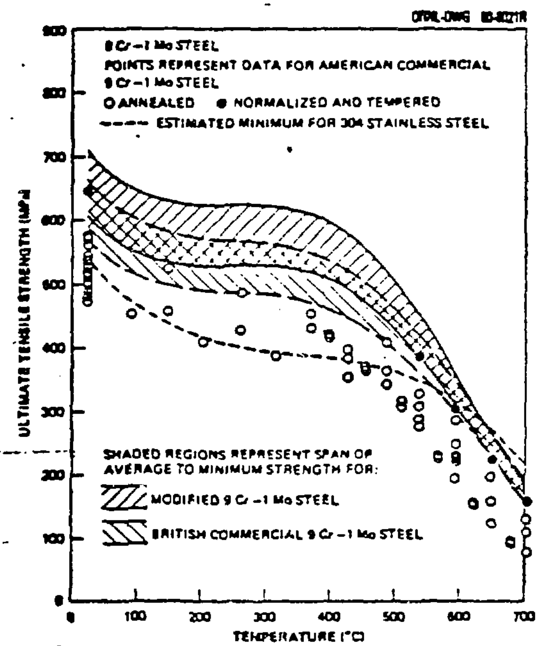

Fig. 5. Comparison of Yield Strength Values for Several Materials as a Function of Temperature.

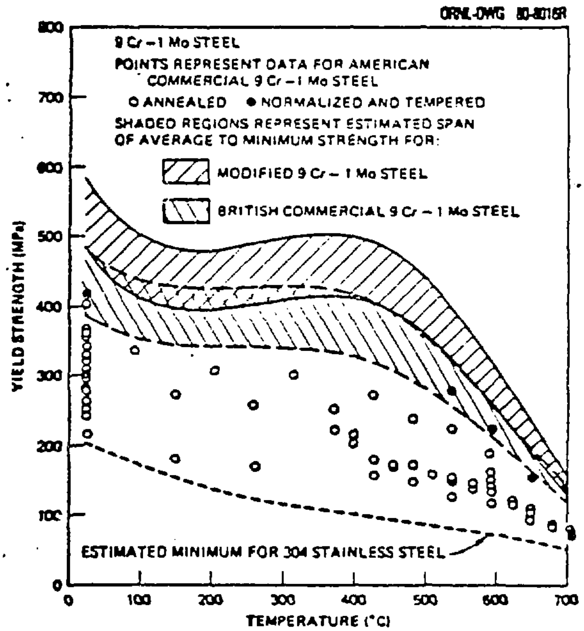

Fig. 6. Comparison of Ultimate Tensile Strength Values for Several Materials as a Function of Temperature.

CONCLUSIONS — TENSILE PROPERTIES

1. MODIFIED 9 Cr-1 Mo STEEL EQUALS OR EXCEEDS COMMERCIAL 9 Cr-1 Mo STEELS IN YIELD AND TENSILE STRENGTH FROM ROOM TEMPERATURE TO AT LEAST 700°C

2. ALL OF THE 9 Cr-1 Mo STEELS EXAMINED HAVE YIELD STRENGTHS HIGHER THAN 304 STAINLESS STEEL TO 700°C. THE MODIFIED AND BRITISH MATERIALS EXCEED 304 IN TENSILE STRENGTH TO ABOUT 600°C.

3. HT9 WAS NOT EXAMINED

HC REGRESSION IS USED WITH GENERALIZED MODEL SELECTION

1. PRELIMINARY ANALYSIS IDENTIFY POSSIBLE TERMS
2. COMPUTER PROGRAM SCANS SUBSET MODELS AND IDENTIFIES CANDIDATES
3. FINAL MODEL CHOSEN BASED ON FIT, EXTRAPOLATION, MODEL FORM, ETC.

STANDARD REGRESSION TECHNIQUE CAN BE APPLIED
TO CREEP-RUPTURE DATA

1. ASSUME GENERAL LINEAR REGRESSION MODEL

$$y = \sum_{i=0}^{n} a_i r_i$$

$y = \log t_r$

$r_i = f(\sigma, T)$, $r_o = 1$

a_i = coefficients

2. APPLY GENERAL FORMULA TO HEAT-CENTERED DATA FOR MULTI-HEAT DATA BASE

3. VARIOUS METHODS EXIST FOR CHOICE OF "BEST" MODEL

HEAT CENTERING RESULTS IN A SIMPLE TRANSFORMATION ON DATA

1. $y = \sum_{i=0}^{n} a_i r_i$

2. $y - \bar{y} = \sum_{i=1}^{n} a_i (r_i - \bar{r}_i)$

3. $y = \bar{y} + \sum_{i=1}^{n} a_i (r_i - \bar{r}_i)$

4. $y = (\bar{y} - \sum_{i=1}^{n} a_i \bar{r}_i) + \sum_{i=1}^{n} a_i r_i$

5. $\bar{y} - \sum_{i=1}^{n} a_i \bar{r}_i$ = lot constant

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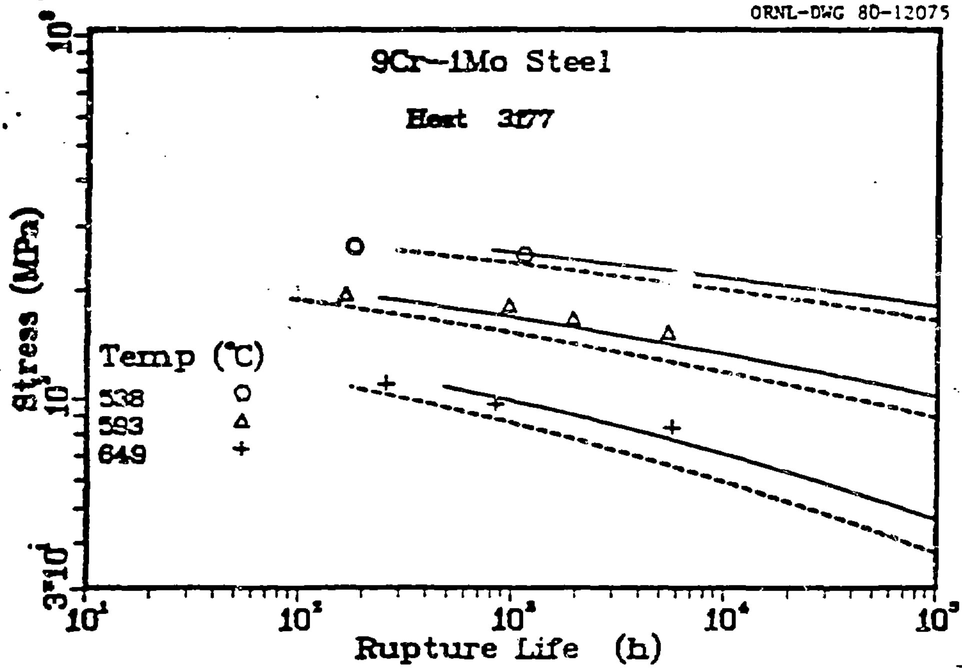

Fig. 8. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 3177 of Modified 9 Cr-1 Mo Steel.

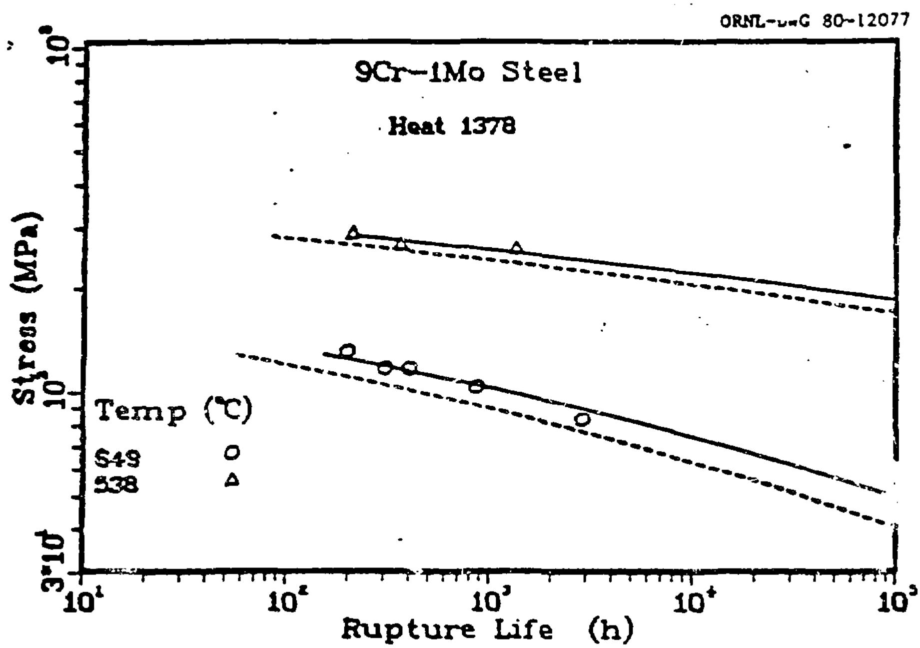

Fig. 9. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 1378 of Modified 9 Cr-1 Mo Steel.

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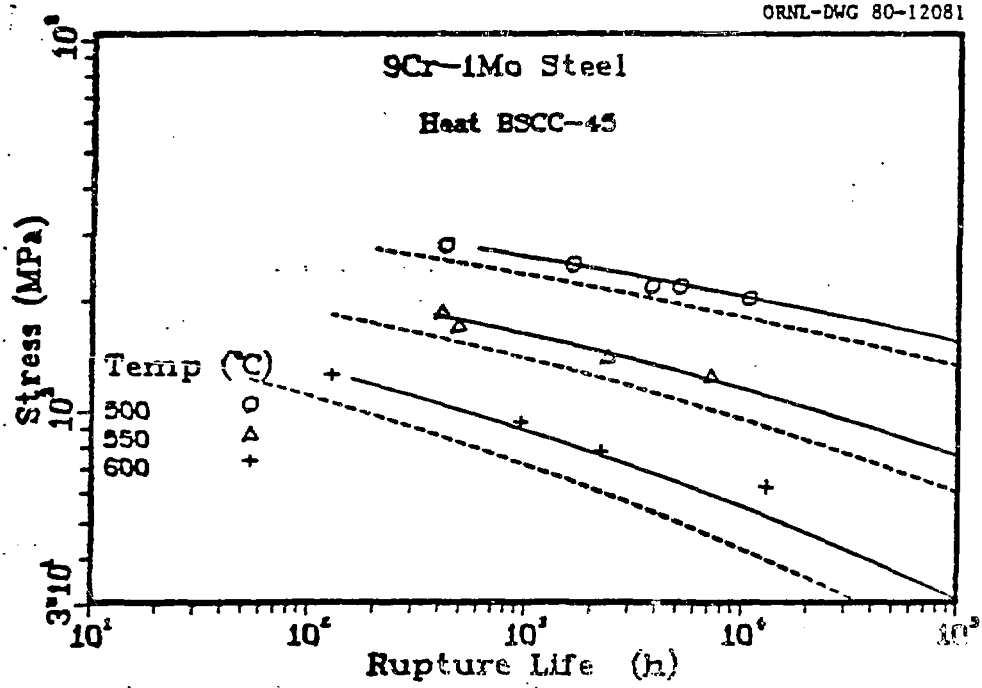

Fig. 12. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-45 of British Commercial 9 Cr-1 Mo Steel.

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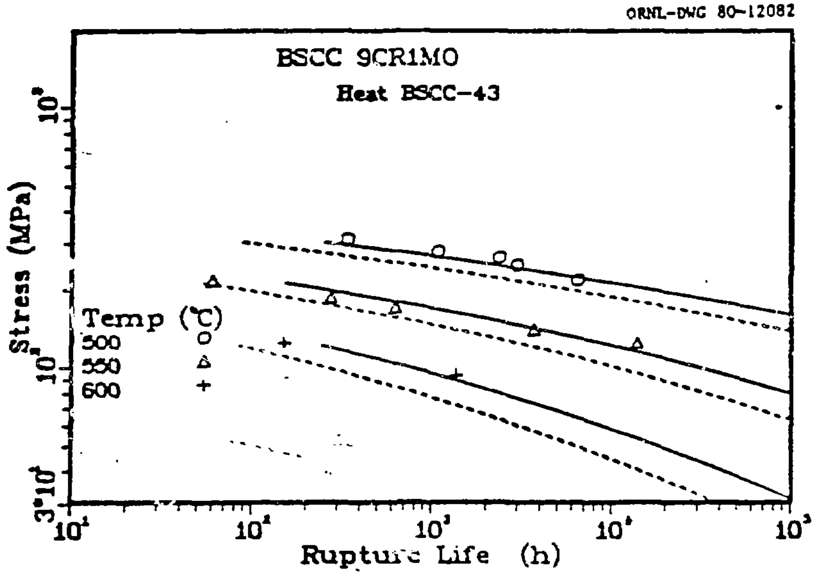

Fig. 13. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot BSCC-43 of British Commercial 9 Cr-1 Mo Steel.

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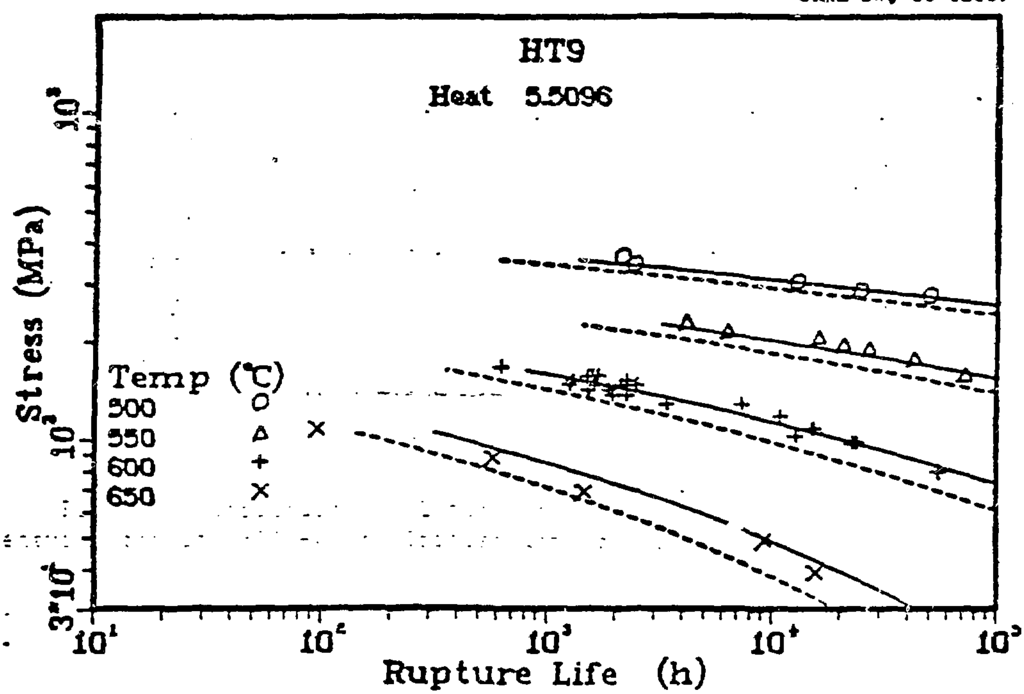

Fig. 20. Comparison of Experimental and Predicted Creep-Rupture Beha'ior for Lot 5.5096 of Alloy HT9.

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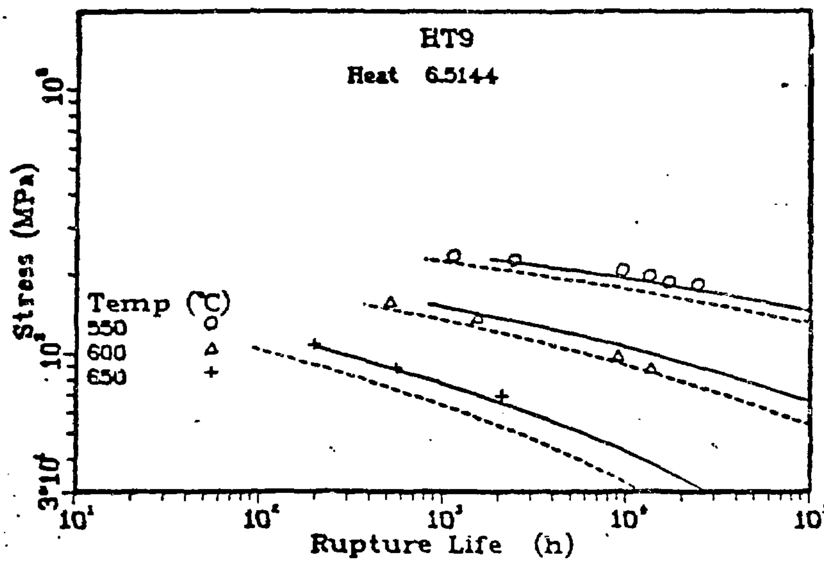

Fig. 21. Comparison of Experimental and Predicted Creep-Rupture Behavior for Lot 6.5144 of Alloy HT9.

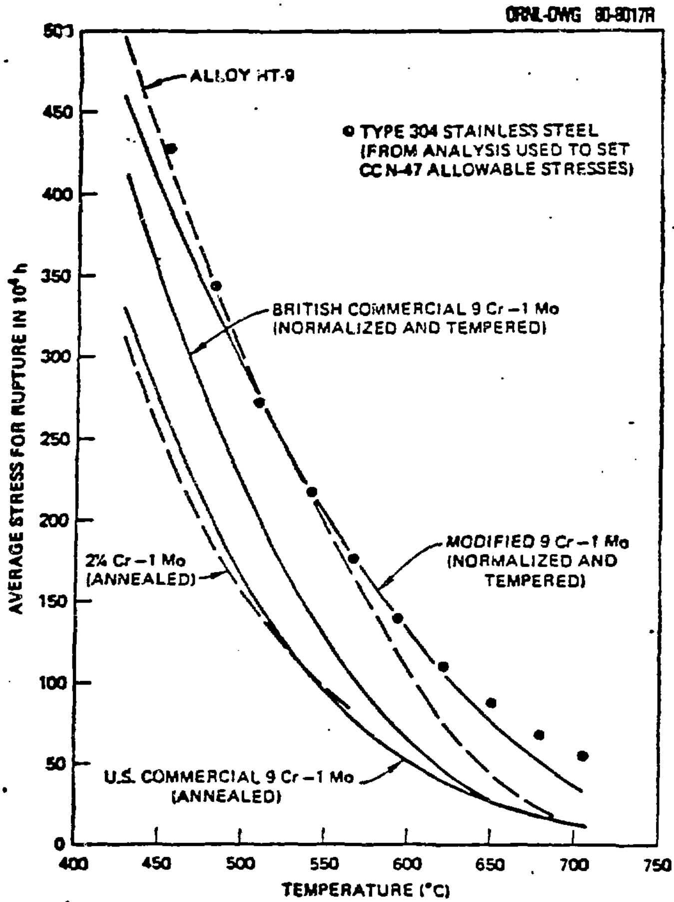

Fig. 28. Variation of 10^4-h Creep-Rupture Strength with Temperature for Several Materials.

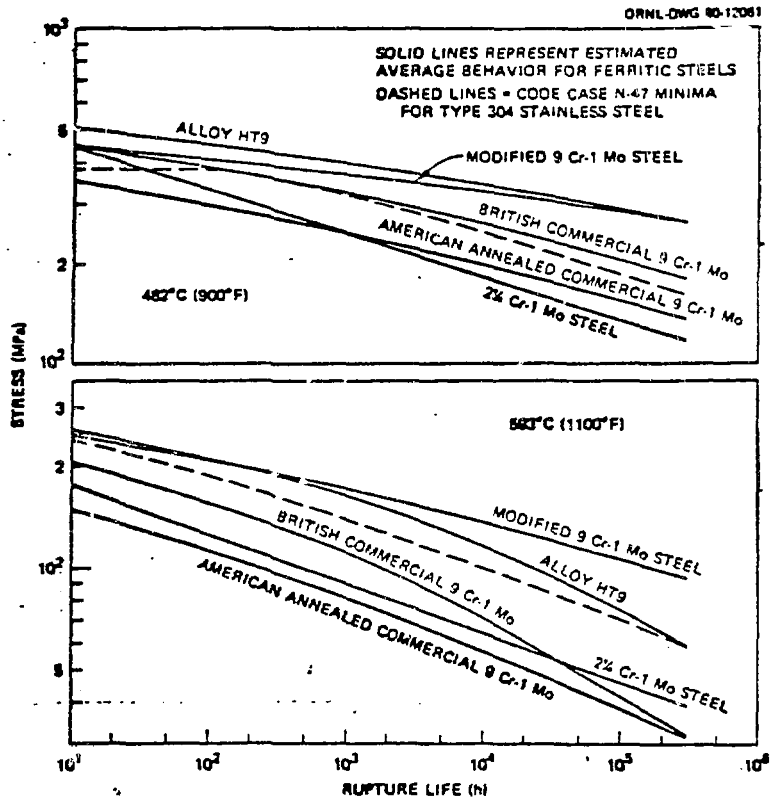

Fig. 27. Comparison of Estimated Stress-Rupture Isothermals for Several Materials.

CONCLUSIONS — CREEP-RUPTURE PROPERTIES

1. MODIFIED 9 Cr-1 Mo, EM12, and HT9 SURPASS ALL THE OTHER FERRITICS IN CREEP RUPTURE STRENGTH IN THE RANGE 427–704°C

2. FIRST HT9 AND THEN EM12 GRADUALLY FALL BELOW THE MODIFIED 9 Cr-1 Mo STEEL IN CREEP-RUPTURE STRENGTH AS TIME AND TEMPERATURE INCREASES; THE MODIFIED 9 Cr-1 Mo SHOWS CREEP RUPTURE STRENGTH COMPARABLE TO THAT OF TYPE 304 STAINLESS STEEL TO ABOUT 625°C

3. ANNEALED COMMERCIAL 9 Cr-1 Mo STEEEL IS COMPARABLE TO ANNEALED 2 1/4 Cr-1 Mo STEEL IN CREEP-RUPTURE STRENGTH

ASME CODE CASE N-47 INCLUDES ALLOWABLE STRESSES FOR ELEVATED TEMPERATURE NUCLEAR COMPONENTS

1. S_o, ALLOWABLE STRESS INTENSITY FOR DESIGN CONDITIONS (FUNCTION OF TEMPERATURE ONLY)

2. S_{mt}, ALLOWABLE STRESS INTENSITY FOR OPERATING CONDITIONS (FUNCTION OF TIME AND TEMPERATURE)

S_{mt} IS THE LOWER OF S_m AND S_t

1. S_m (TIME-INDEPENDENT) IS LOWER OF:

   a. 1/3 TENSILE STRENGTH AT TEMPERATURE
   b. 2/3 MINIMUM YIELD STRENGTH AT TEMPERATURE

2 S_t (TIME-DEPENDENT) IS LOWEST OF:

   a. 2/3 MINIMUM STRESS FOR RUPTURE IN TIME t
   b. 4/5 MINIMUM STRESS TO CAUSE ONSET OF TERTIARY CREEP IN TIME t
   c. MINIMUM STRESS TO PRODUCE 1% TOTAL STRAIN IN TIME t

S_o IS THE LOWEST OF SEVERAL VALUES

1. 1/4 TENSILE STRENGTH AT TEMPERATURE (LOWER OF ROOM TEMPERATURE MINIMUM SPECIFIED TENSILE STRENGTH AND 110% OF MINIMUM TENSILE STRENGTH AT TEMPERATURE)
2. 5/8 MINIMUM YIELD STRENGTH AT TEMPERATURE
3. 2/3 AVERAGE STRESS FOR RUPTURE IN 100,000 HOURS
4. 4/5 MINIMUM STRESS FOR RUPTURE IN 100,000 HOURS
5. AVERAGE STRESS FOR A SECONDARY CREEP RATE OF 0.01% PER 1000 HOURS

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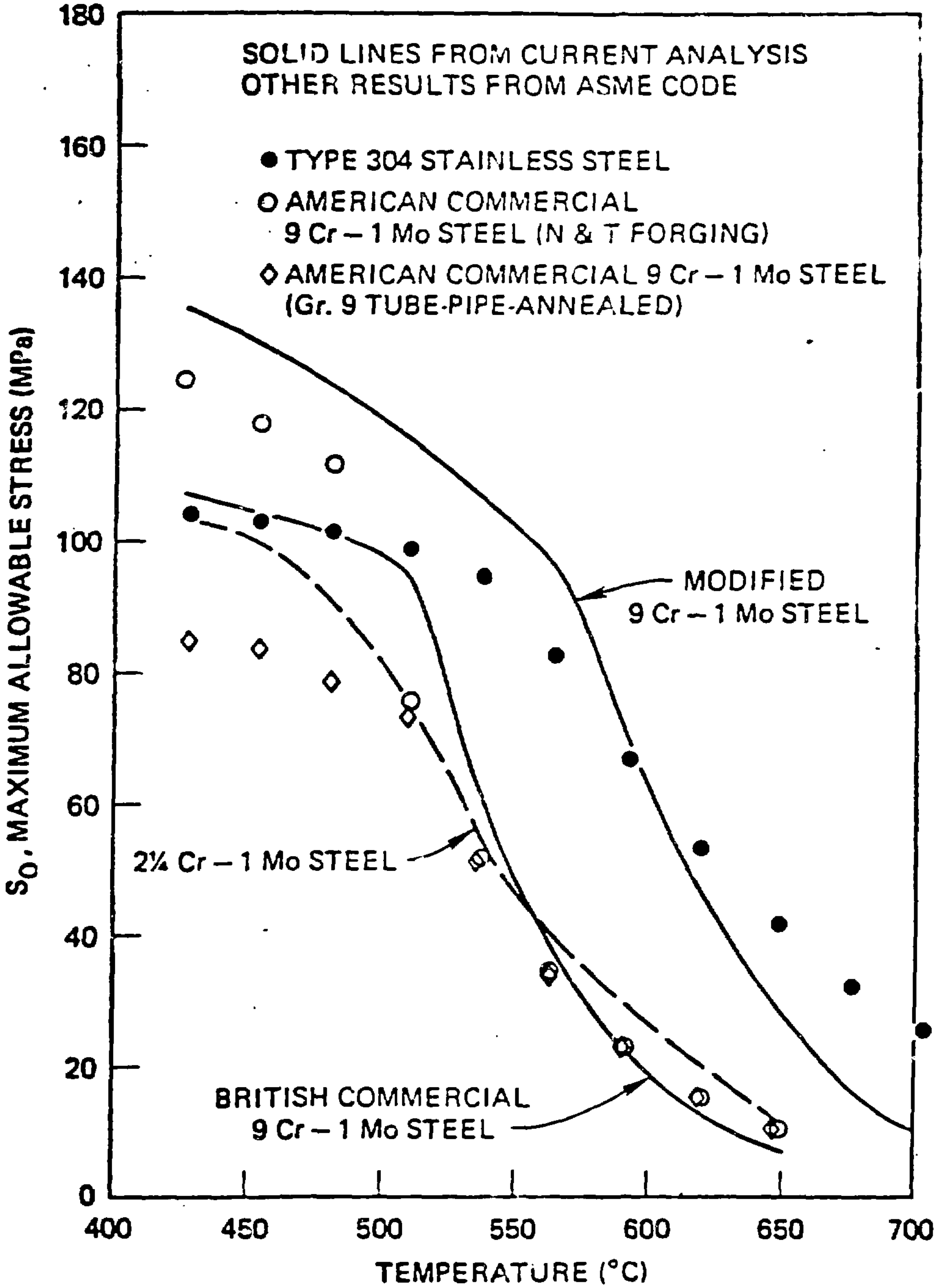

Fig. 30. Variation of Estimated Design Allowable Stress Intensity, S_o, with Temperature for Several Materials.

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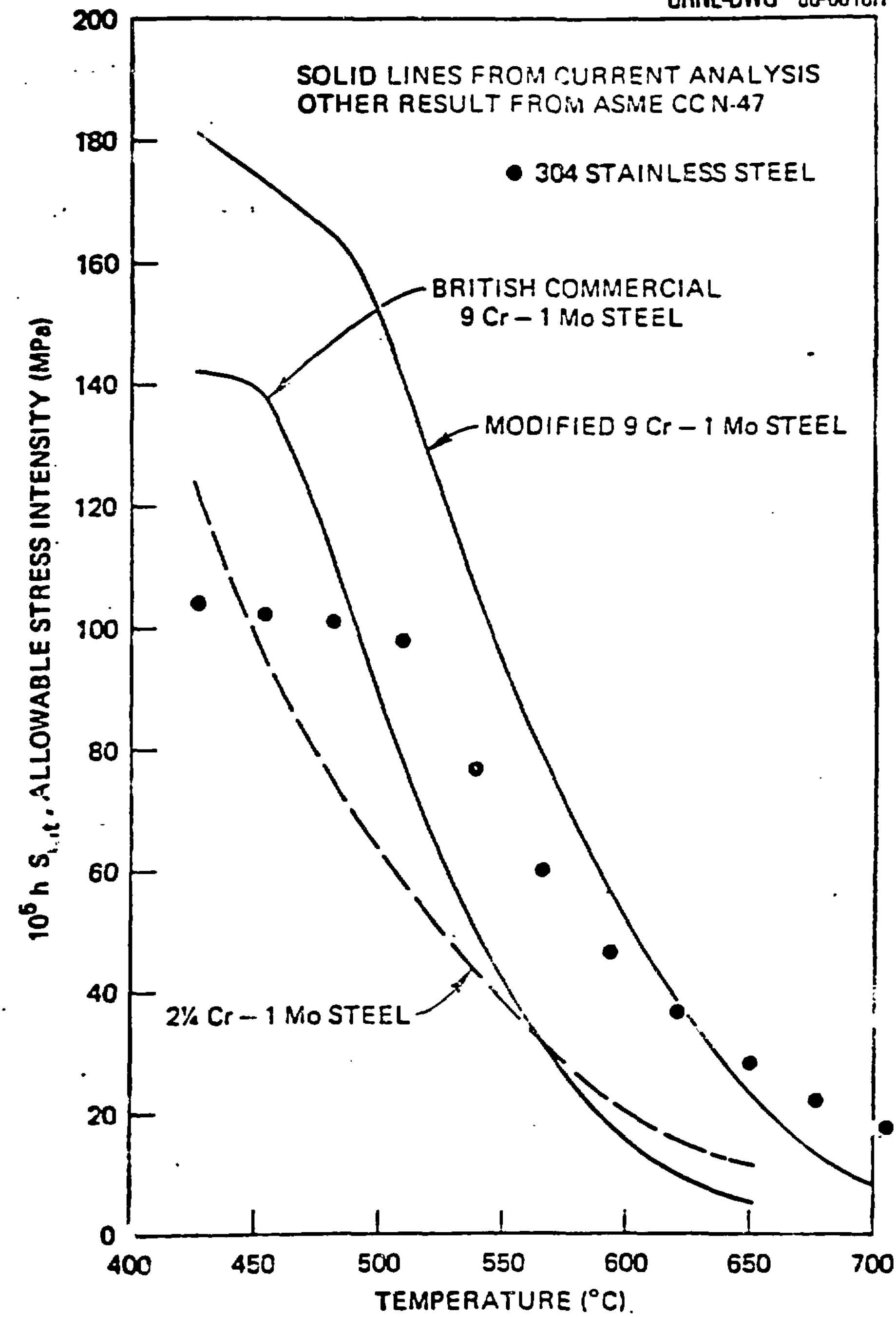

Fig. 31. Variation of Estimated Allowable Stress Intensity, S_{mt}, for 10^5 h with Temperature for Several Materials.

CONCLUSIONS — ALLOWABLE STRESSES

1. MODIFIED 9 Cr-1 Mo EXCEEDS OTHER FERRITICS IN TERMS OF S_o AND S_{mt}
2. MODIFIED 9 Cr-1 Mo HAS S_o VALUES GREATER THAN OR EQUAL TO THOSE FOR 304 STAINLESS STEEL TO ABOUT 600°C
3. MODIFIED 9 Cr-1 Mo HAS S_{mt} VALUES GREATER THAN OR EQUAL TO THOSE FOR 304 STAINLESS STEEL TO ABOUT 625°C
4. S_o AND S_{mt} NOT CALCULATED FOR HT9, EM12 BUT WOULD PROBABLY FOLLOW TRENDS SIMILAR TO THOSE FOR CREEP-RUPTURE STRENGTH