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Final Analysis of ORNL Creep-Rupture and Tensile Data on 2.25 Cr-1 Mo Steel in Support of HTGR Development

H. E. McCoy

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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FINAL ANALYSIS OF ORNL CREEP-RUPTURE AND TENSILE DATA ON 2.25 CR-1 MO STEEL IN SUPPORT OF HTGR DEVELOPMENT*

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ABSTRACT

The tensile and creep properties of 2.25 Cr-1 Mo steel were measured over the temperature range of 482 to 649°C (900 to 1200°F). The creep test environments were air and helium with controlled impurities, and the maximum test times were about 100,000 h. No effect of environment on the creep strength was discernible. Creep test information, including the stresses, times, and temperature to 1% strain, tertiary creep, and rupture, were used to approximate values of the design stress, S_t, by the rules used in American Society of Mechanical Engineers Code Case N-47. Comparisons were made between the design stress estimates from these analyses and those from other sources. Some of the test specimens were pretest aged. Tensile and creep results showed that the material was weakened slightly by aging.

1. INTRODUCTION

The 2.25 Cr-1 Mo steel has been in service for many years in steam environments up to 566°C (1050°F), and the material has a very good service record under these operating conditions.[1-3] This material is of interest for steam generators in gas-cooled reactors and has been under evaluation for that application for several years. In this application, the material is exposed to helium containing small amounts of hydrogen, methane, carbon dioxide, carbon monoxide, and moisture. Much of the work was directed toward determining whether the mechanical properties are the same in air and the impure helium.

2. MATERIALS

Four heats of Cr-Mo steel were used in this study, and several characteristics of the test material are listed in Table 1. The chemical analyses and room-temperature

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Table 1. Characterization of 2.25 Cr-1 Mo steel test materials

Heat	Source	Product form	Grain size[a] (µm)
X6216	Babcock and Wilcox	51-mm-OD (2-in.) by 25-mm-ID (1-in.) tube	27
36202	Babcock and Wilcox	51-mm-OD (2-in.) by 25-mm-ID (1-in.) tube	20-17
72768	Babcock and Wilcox	51-mm-OD (2-in.) by 25-mm-ID (1-in.) tube	27
56448	Cameron/Republic Steel	51-mm-diam (2-in.) rod	40

[a]All material isothermally annealed prior to testing: 927 ± 14°C for 30 min, cooled to 704 ± 14°C at a maximum rate of 83°C/h, held at 704 ± 14°C for 2 h, and cooled to room temperature at a maximum rate of 6°C/min.

tensile properties of the four heats are given in Table 2. All four heats satisfy the chemical and mechanical requirements of the American Society of Mechanical Engineers (ASME). The footnote to Table 1 describes the "isothermal" anneal that all material was given before testing. With this heat treatment, the main microconstituents are proeutectoid ferrite and bainite.

3. TEST CONDITIONS

Creep tests were run over the temperature range of 482 to 649°C (900 to 1200°F) in test environments of air and controlled-impurity helium. Several reports on this study carry the details of the test procedure.[4, 5] The test specimen is shown in Fig. 1, and it has a small-diameter gage section that should magnify any environmental effects.

4. TEST RESULTS

The creep test results are given in Tables 3 through 6 for the four heats. These materials were tested in the isothermally annealed condition. In the ASME Boiler and Pressure Vessel Code Case N-47, the design stress (S_t) for this material is determined on the basis of the stresses to produce 1% strain, tertiary creep, and rupture. Hence, the data were divided into several subsets that allowed the separate analysis of each property.

Table 2. Room-temperature tensile properties and chemical analyses of test materials

HEAT	YIELD STRENGTH MPa (ksi)	ULTIMATE TENSILE STRENGTH MPa (ksi)	Cr CONTENT %	Mo CONTENT %	Si CONTENT %	C CONTENT %	Mn CONTENT %	S CONTENT %	P CONTENT %
ASME (a)	207 (30) min	414 (60) to 586 (85)	1.88-2.62	0.85-1.15	0.50 max.	0.15 max	0.25-0.66	0.035 max	0.035 max
X6216	241 (35.0)	495 (71.8)	2.19	1.00	0.26	0.12	0.44	0.016	
36202	246 (35.7)	504 (73.0)	2.24	0.96	0.34	0.12	0.43	0.023	
72768	228 (33.0)	469 (68.0)	2.16	0.94	0.38	0.10	0.41	0.012	
56448 (b)	279 (40.4)	476 (69.1)	2.15	1.01	0.26	0.10 (c)	0.56	0.006	0.010

(a) American Society of Mechanical Engineers Specification, SA-387, grade 22.

(b) Ingot analysis by Cameron Iron Works.

(c) Analysis by Oak Ridge National Laboratory: 0.0754, 0.0733.

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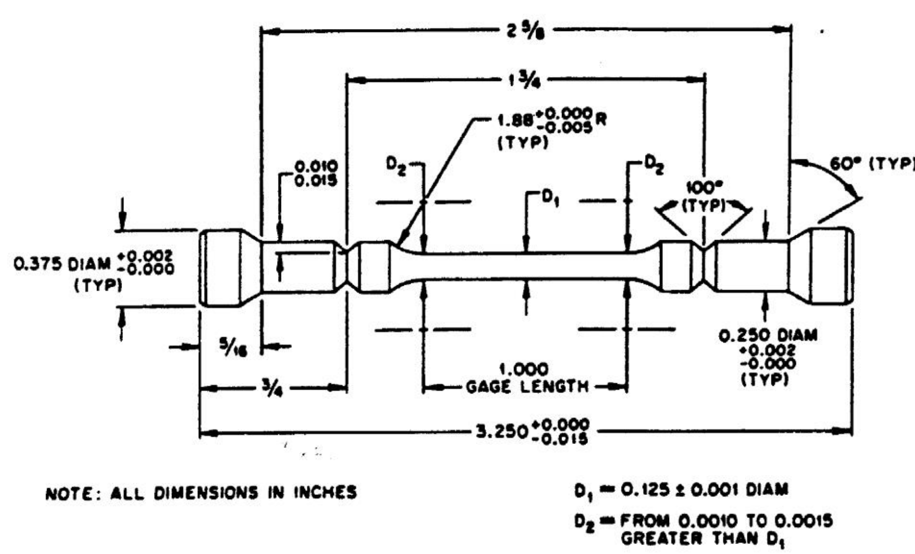

Fig. 1. Details of creep specimen. To convert dimensions to millimeters, multiply by 25.4.

Table 3. Creep data for heat 72768

TEST NO.	ENV (a)	STRESS MPa	STRESS ksi	TEMPERATURE °C	TEMPERATURE °F	T-1% (b) h	T-2% (c) h	T-5% (d) h	T-TERT (e) h	T-RUPT (f) h	MIN CREEP RATE %/h	LOAD STRAIN (g) %	CREEP STRAIN %	RED OF AREA %
16360	1	69	10.0	593	1099	971	2115	4435	1625	6698	0.00054		27.3	81.3
16882	2	103	14.9	593	1099	0.8	3	81	600	1337	0.0044	0.4	50.9	81.6
17377	2	103	14.9	593	1099	13	30	92	130	328	0.049	0.03	50.8	82.9
17495	2	69	10.0	649	1200	28	59	137	100	288	0.031		47.2	87
17947	2	206	29.9	482	900	186	402	860	600	2471	0.0044	0.72	41.3	78.9
18075	2	35	5.1	649	1200	2025	2400	2950	1800	4044	0.00002		48	71.4
18252	2	41	5.9	538	1000					122272D	0.0000016	0.04	0	10.3
18374	2	103	14.9	482	900					21668D	0.000035	0.03	1.2	0.64
18438	2	103	14.9	482	900					15425D				
18439	1	103	14.9	482	900					1266D	0.000015		2	
18446	2	21	3.0	649	1200	55000	94500	97000	91500	98665	0.0000065	0.05	5.2	19.5
18508	2	41	5.9	538	1000					97304D			0.8	
18859	1	103	14.9	538	1000	800	1900	5900	17800	18740D	0.00052	0	13.7	
18860	2	69	10.0	538	1000	67500	100000		50000	117120D	0.0000069	0.03	>2.5	
18862	2	21	3.0	649	1200	12000	17200			13085D	0.000041	0	2.2	3.6
19789	1	41	5.9	538	1000					12925D	0.000021		0.6	
19792	1	35	5.1	649	1200	1007	1763	3740	1250	4245	0.00066		16.9	76
19793	1	21	3.0	649	1200	2840	4825		4400	5794D	0.00008		3	
19796	1	21	3.0	649	1200	1850	5800	20900	28200	28627	0.0002	0.02	107	53.9
19945	1	41	5.9	538	1000	62000			75000	126746D	0.0000035	0.12	>1.7	14.1
22752	1	48	7.0	649	1200	345	540	920	290	1149	0.0017		25	86.7
22758	1	103	14.9	593	1099	20	28	87	180	358	0.05	0.73	48.5	83.1
22823	1	206	29.9	482	900	775	1385	2810	1750	6773	0.0014	0.85	30.5	79.6
23073	1	138	20.0	593	1099	0.6	1.6	6.5	26	38.3	0.71	0.05	54.2	85.3
23074	1	138	20.0	538	1000	27	60	200	600	1063	0.021		49.3	83.4
23340	2	69	10.0	593	1099	1550	2860	4680	2600	6441	0.00061	0.03	31.5	81.8
23621	2	69	10.0	593	1099	1220	2700	5200	3500	8761	0.0006		37	78.2
23624	2	103	14.9	538	1000	900	2200	6900	8300	14943	0.00065		24.1	57.5
23758	2	69	10.0	593	1099	750	1650	3300	2300	4899	0.00098	0.07	31.2	79.7
23825	2	172	24.9	482	900	1050	2080	5200	6000	14281	0.00095	0.11	42.8	74.1
24317	1	138	20.0	482	900	8000	16750	46000	30000	38442D	0.00012		10.9	
25030	2	172	24.9	482	900	1700	2150	3700	1750	8093	0.00028		37.1	82.2
25033	2	35	5.1	649	1200	2450	3500	4750	2100	5688	0.00021		24.3	77.7

(a) 1 = air environment; 2 = controlled-impurity He environment.
(b) Time in hours to reach 1% strain.
(c) Time in hours to reach 2% strain.
(d) Time in hours to reach 5% strain.
(e) Time to tertiary creep based on 0.2% strain offset.
(f) Time to rupture. "D" indicates that test was discontinued prior to failure.
(g) N denotes a slightly negative reading.

Table 4. Creep data for heat X6216

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
15023	2	69	10.0	593	1099	3000	4950	7350	3750	9660	0.00024	0.08	38.9	77
15045	2	69	10.0	593	1099					3186D		0.15	2.8	
15046	2	103	14.9	538	1000	1086	2777	7640	8000	14957	0.00061	0.05	38.2	75.8
15047	2	69	10.0	593	1099	2990	4553	6510	3150	7784	0.00025	0.1	26.6	63.3
17333	2	138	20.0	593	1099	5	11	34	42	90	0.13	N	42.1	86.6
17334	2	103	14.9	593	1099	39	105	306	365	793	0.014	0.02	44.5	80.6
17494	2	207	30.0	482	900	300	750	2000	2300	4895	0.0023	0.17	30.3	77.5
17864	2	69	10.0	649	1200	167	248	370	140	513	0.0039	N	29.1	
17876	1	69	10.0	593	1099	3700	7000	10750	7400	11717	0.00026	N	19.6	80.4
17918	2	138	20.0	538	1000	95	225	674	1050	2655	0.0067	0.09	38.9	75.5
22738	1	48	7.0	649	1200	535	775	1220	470	1496	0.0015	N	26.4	86.6
22766	1	103	14.9	593	1099	214	600	1630	1625	2291	0.0027	N	16	69.7
23103	1	103	14.9	538	1000	3500	29000	73500	69500	78644	0.000042	N	7.8	41.4
23360	1	172	24.9	482	900	8300	17200	46000	69000	71017	0.00011	0.63	26.6	74.4
23626	1	83	12.0	538	1000	80000				68754D	0.0000014	N	2.7	13.5
23653	2	172	24.9	482	900	4300	8800	20000	15800	24358D	0.00022	N	6.9	
23826	2	172	24.9	482	900	8000	17000	43500		59991D	0.00014	0.09	>4.7	
25029	2	172	24.9	482	900	8500	11900	18500	7000	19301D	0.000048	N	5.7	11.2

(a) 1 = air environment; 2 = controlled-impurity He environment.
(b) Time in hours to reach 1% strain.
(c) Time in hours to reach 2% strain.
(d) Time in hours to reach 5% strain.
(e) Time to tertiary creep based on 0.2% strain offset.
(f) Time to rupture. "D" indicates that test was discontinued prior to failure.
(g) N denotes a slightly negative reading.

Table 5. Creep data for heat 36202

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
15374	2	172	24.9	482	900	1500	2705	5200	2500	13509	0.00053	0.4	39.7	70.9
17849	1	172	24.9	482	900	1250	2900	8300	21000	28106	0.00006		35.5	64.6
25026	2	172	24.9	482	900	2200	5200	9700	2200	22225	0.00012	0.43	38.9	73.3
15373	2	207	30.0	482	900	349	787	1660	500	3494	0.0011	0.95	34.8	73.7
16263	1	207	30.0	482	900	204	620	1800	2030	6611	0.0025	0.25	45.1	71.1
18222	2	241	35.0	482	900	50	200	670	675	1796	0.006	0.2	32.3	74.7
22822	1	241	35.0	482	900	112	345	925	840	2250	0.0044	0.46	33.1	72
23625	1	83	12.0	538	1000	6000	24000	69000	60000	75325D	0.000036	N	5.7	21.2
15369	2	103	14.9	538	1000	842	2047	6144	6800	15232	0.00075	0.07	41.7	62.3
16264	1	103	14.9	538	1000	1150	2800	11050	15500	22172	0.00023	0	24.5	
18149	2	138	20.0	538	1000	65	170	475	820	1717	0.0098	0.15	40.5	75.2
22240	1	138	20.0	538	1000	110	305	980	1625	3114	0.0042		25.4	59.1
23067	1	138	20	538	1000	90	230	670	1150	2255	0.0072		39.1	73.7
22765	1	69	10	593	1100	650	2700	6200	4800	8980	0.00052		16.2	60.6
16883	2	103	15	593	1100	17	48	144	188	436	0.032		46.8	83
22759	1	103	15	593	1100	40	110	307	400	759	0.015	0.01	34.9	71.7
25028	1	35	5	649	1200	1950	3700	4980	3300	5096	0.00041	0.16	18.6	84.5
25967	1	35	5	649	1200	755	3700		3600	3935D	0.00048	30	2.2	30
22757	1	48	7	649	1200	770	1040	1600	1000	1848	0.000029		19.3	
17948	2	69	10	649	1200	47	7	204	115	361	0.018		34.6	84.9

(a) 1 = air environment, 2 = controlled-impurity He environment, and 3 = inert gas.
(b) Time in hours to reach 1% strain.
(c) Time in hours to reach 2% strain.
(d) Time in hours to reach 5% strain.
(e) Time to tertiary creep based on 0.2% strain offset.
(f) Time to rupture. "D" indicates that test was discontinued prior to failure.
(g) N denotes a slightly negative reading.

Table 6. Creep data for heat 56448

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
23853	2	35	5.1	649	1200	2000	2175	2450	1950	3050	0.00034	0.51	62.1	89.1
23856	2	172	24.9	482	900	2600	3750	6100	2250	13008	0.00016	0.8	38	87
24188	2	207	30.0	482	900	1600	2500	3890	2100	6338	0.00049	0.48	34.2	83.9
24190	2	69	10.0	593	1099	6600	10600	13900	8000	15488	0.000086		9.57	7.81
24191	2	103	14.9	538	1000	4700	9600	16700	9800	23434	0.00018		25.9	77.3
24193	1	172	24.9	482	900	2800	4450	9000	3000	20059	0.00024	0.13	31.1	87.9
24194	1	103	14.9	538	1000	3500	7700	19400	18400	23529	0.00015	0.00015	20.2	82.7
24213	1	69	10.0	593	1099	7000	9300	14100	7500	15434	0.00011	0.15	26.8	82.4
24218	1	172	24.9	482	900	2400	4000	8100	3000	21574	0.00039	0.19	34	82.3
24320	1	207	30.0	482	900	35	70	185	150	383	0.027	0.92	35.4	84.8
24325	1	138	20.0	538	1000	50	140	365	600	1320	0.013	0.38	48.7	86.3
24328	1	48	7.0	649	1200	810	970	1490	340	1564	0.0012		17.8	91.2
24333	1	83	12.0	538	1000	4750	18500	53500	52000	67492D	0.000073		5.9	23.2
24335	1	138	20.0	482	900	8500	17000	58000		67750D	0.00012		4.2	12.3
24336	1	55	8.0	649	1200	490	680	970	460	1169	0.0018		25.6	93.1
24343	1	103	14.9	593	1099	30	55	127		1594D	0.00041			
24595	2	207	30.0	482	900	400	720	1340	700	2834	0.0025	0.54	25.4	90.2
24597	2	190	27.6	482	900	950	1530	2670	1150	5678	0.092		38.1	87.1
24598	2	86	12.5	593	1099	1500	2140	3200	1350	3684	0.00048	0.65	18.2	82.3
24601	2	138	20.0	482	900	390	790	2160	5500	10511	0.0018		49.1	88.8
24604	2	121	17.6	538	1000	200	380	1170	2100	3679	0.0038	0.2	44.1	89.5
24780	2	28	4.1	649	1200	2400	2870	3680	2100	5090	0.00013	0.15	46.7	87.9
24787	2	69	10.0	649	1200	350	413	505	312	608	0.0001	34.8	89.4	
24794	2	138	20.0	482	900	16000				33594D	0.000059	0.03	>1.3	
25013	1	103	14.9	593	1099	10	40	125	292	513	0.036		42.2	85.3
25016	2	83	12.0	538	1000	5000	30000			39948D	0.00009		2.4	10.2
25018	2	69	10.0	538	1000	2100				36372D	0.000018		>2.0	
25019	1	69	10.0	538	1000					52027D	0.000014		1.8	9.2
25020	1	21	3.0	649	1200	3000	4400		2100	11432	0.000075		11.8	88.2
25023	1	21	3.0	649	1200	9600	13750		13550	15040D	0.00012		>3.8	
25024	2	172	24.9	482	900					3862D	0.0055		>0.7	
25025	2	35	5.1	649	1200					3615D	0.00011		>1.1	
25027	2	103	14.9	538	1000	900	2300	6700	7800	11915	0.00053		38	85.2
25031	2	89	10.0	593	1099	8200	8800	9750	7700	10794	0.000055	0.03	35.1	86
25034	1	207	30.0	482	900	35	85	225	225	615	0.02	1.12	39.2	82.3
25498	1	193	28.0	482	900	220	420	880	500	2553	0.0044	0.32	40.3	85.2
25521	2	172	24.9	482	900	2100	2900	4550	2200	9447	0.00032		36.5	84.1
25522	2	34	4.9	649	1200	7500	7650	8500	7200	10161	0.00013		31.6	69.1
25715	1	172	24.9	482	900	360	800	1980	3950	6947	0.0025	0.2	35.8	86.1
25963	1	35	5.1	649	1200	4750	5800		5150	6138	0.00012	0.03	17.2	89

(a) 1 = air environment; 2 = controlled-impurity He environment.
(b) Time in hours to reach 1% strain.
(c) Time in hours to reach 2% strain.
(d) Time in hours to reach 5% strain.
(e) Time to tertiary creep based on 0.2% strain offset.
(f) Time to rupture. "D" indicates that test was discontinued prior to failure.
(g) N denotes a slightly negative reading.

Another variable to be dealt with was the influence of environment on mechanical properties. The creep data were divided into the sets shown in Table 7 for analysis.

5. ANALYTICAL METHOD

One of the main goals in analyzing creep data for design strength purposes is that the data be represented by some well-behaved function that allows extrapolation from common measurement times of about 20,000 h to design times of 100,000 to 300,000 h. One of the newer methods for performing such analyses is the Minimum Commitment Method (MCM) developed by Manson[6] and modified by Pepe.[7] Pepe analyzed a large set of Alloy 800H rupture data by this and several other methods and concluded that the MCM was preferred.

The MCM equation is as follows:

$$\log t + \left[R_1(T - Tm) + R_2\left(\frac{1}{T} - \frac{1}{Tm}\right)\right] =$$

$$B + C \log S + DS + ES^2 \; . \qquad (1)$$

This equation contains variables of temperature (T, °R); stress (S, ksi); and time (t, h). A mean temperature (T_m, °R) appears in the equation and is simply the arithmetic average of the temperature range of the data set. The analysis determines the constants R_1, R_2, B, C, D, and E. Values of B and C are determined for each heat of material, and average values are determined for the entire data set.

The specific form of the MCM used was that described and made available to us by Pepe.[8] The data set was prepared and analyzed by the program disk made available by Pepe. This analysis gave values of the constants including average and lot values of B and C. The average values of B and C and the other constants were used in the above equation to calculate stress-time correlations for various temperatures. The minimum stress was determined by decreasing the logarithm (base 10) of the average stress by 1.65 times the lot standard deviation. Isothermal plots were constructed of time versus average and minimum stress to rupture. Individual data points from the data set were plotted on the appropriate isothermal plot. Values for the average or minimum rupture stress at any time and temperature can be read from the isothermal plots.

Table 7. Sets analyzed by Minimum Commitment Method and statistical parameters indicating how well model fit each set

SET	1% STRAIN	TERTIARY CREEP	RUPTURE
AIR & HELIUM	102 / 490021 / 0.7407 / 0.5170	93 / 822465 / 0.7641 / 0.3872	82 / 814590 / 0.8176 / 0.2940
AIR	49 / 244606 / 0.8144 / 0.4618	45 / 533578 / 0.7128 / 0.4860	37 / 408537 / 0.7773 / 0.3617
HELIUM	53 / 245415 / 0.6771 / 0.5731	48 / 288887 / 0.8374 / 0.2953	45 / 406053 / 0.8681 / 0.2391

NO. POINTS / TEST HOURS IN SET / R SQUARED (CORRELATION COEFFICIENT) / S.E.E. (LUMPED STANDARD ERROR OF ESTIMATE).

6. EXAMINATION OF DATA TO DETERMINE POSSIBLE ENVIRONMENTAL EFFECT

The data set for each creep property and each environment contains about 50 points totaling 250,000 to 400,000 h (see Table 7). Each set contains data from only four heats, and the data spread is rather large. The statistical data in Table 7 for R^2* and the S.E.E.† show that the data fit the model progressively better for the times to 1% strain, tertiary creep, and rupture, respectively.

Figure 2 shows the information developed concerning the effect of environment on the time to 1% strain at 593°C (1100°F). The continuous lines represent the average and minimum strengths obtained by the MCM analysis of the data from air and helium environments obtained over the temperature range of 482 to 649°C (900 to 1200°F). The lines from the MCM analysis are approximately the same up to 10,000 h where the extrapolations vary due to the scarcity of points at the longer times. The individual data points obtained in air and helium at 593°C (1100°F) are shown in Fig. 2. The solid points were obtained in a helium environment, and the open points were obtained in an air environment. These data points fail to show any consistent effect of environment.

A similar composite plot is shown in Fig. 3 for rupture data obtained at 593°C (1100°F) in air and helium environments. The two bands determined by the MCM for the average and minimum rupture strengths over the temperature range of 482 to 649°C (900 to 1200°F) are about the same for the two environments up to 100,000 h. The data points obtained in the two environments at 593°C fail to indicate any clear effect of environment. Hence, we conclude that the creep properties of the Cr-Mo steel over the temperature range of 482 to 649°C (900 to 1200°F) are equivalent in the two environments investigated.

7. ANALYSIS OF THE ENTIRE DATA SET

Since test environment was concluded not to be an important variable, all test data were grouped together (see Table 8) for analysis. Since the three properties—1% creep, tertiary creep, and rupture—are important, the data set shown in Table 8 was analyzed as

*R^2 is the correlation coefficient.

†S.E.E. is the lumped standard error of estimate.

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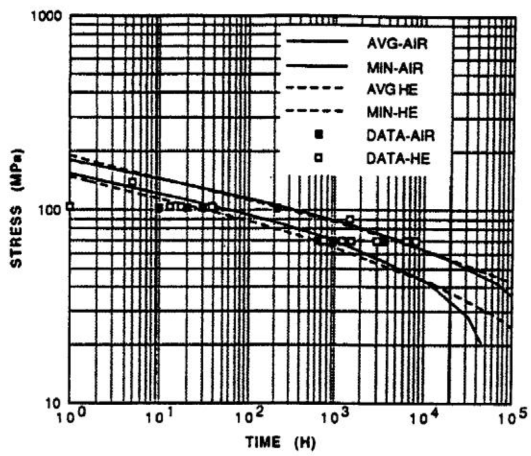

Fig. 2. Cr-Mo in air and He, 1% strain, 593°C; lines for Minimum Commitment Method analysis and points are data.

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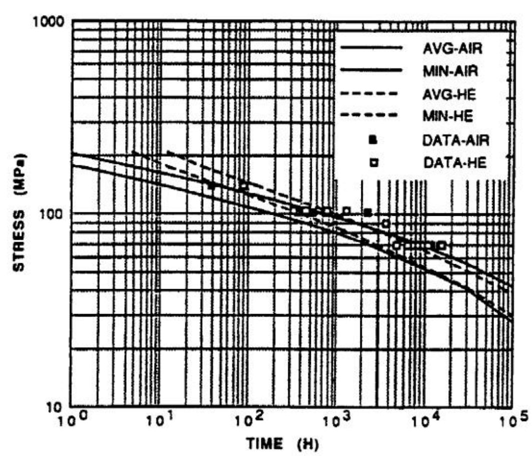

Fig. 3. Cr-Mo in air and He, rupture, 593°C; lines for Minimum Commitment Method analysis and points are data.

Table 8. Data set for 2.25 Cr-1 Mo steel creep analysis

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
15023	2	69	10.0	593	1099	3000	4950	7350	3750	9660	0.00024	0.08	38.9	77
15045	2	69	10.0	593	1099					3186D		0.15	2.8	
15046	2	103	14.9	538	1000	1086	2777	7640	8000	14957	0.00061	0.05	38.2	75.8
15047	2	69	10.0	593	1099	2990	4553	6510	3150	7784	0.00025	0.1	26.6	63.3
15369	2	103	14.9	538	1000	842	2047	6144	6800	15232	0.00075	0.07	41.7	62.3
15373	2	207	30.0	482	900	349	787	1660	500	3494	0.0011	0.95	34.8	73.7
15374	2	172	24.9	482	900	1500	2705	5200	2500	13509	0.00053	0.4	39.7	70.9
16263	1	207	30.0	482	900	204	620	1800	2030	6611	0.0025	0.25	45.1	71.1
16264	1	103	14.9	538	1000	1150	2800	11050	15500	22172	0.00023	0	24.5	
16360	1	69	10.0	593	1099	971	2115	4435	1625	6698	0.00054		27.3	81.3
16882	2	103	14.9	593	1099	0.8	3	81	600	1337	0.0044	0.4	50.9	81.6
16883	2	103	14.9	593	1099	17	48	144	188	436	0.032		46.8	83
17333	2	138	20.0	593	1099	5	11	34	42	90	0.13	N	42.1	86.6
17334	2	103	14.9	593	1099	39	105	306	365	793	0.014	0.02	44.5	80.6
17377	2	103	14.9	593	1099	13	30	92	130	328	0.049	0.03	50.8	82.9
17494	2	207	30.0	482	900	300	750	2000	2300	4895	0.0023	0.17	30.3	77.5
17495	2	69	10.0	649	1200	28	59	137	100	288	0.031		47.2	87
17849	1	172	24.9	482	900	1250	2900	8300	21000	28106	0.00006		35.5	64.6
17864	2	69	10.0	649	1200	167	248	370	140	513	0.0039	N	29.1	
17876	1	69	10.0	593	1099	3700	7000	10750	7400	11717	0.00025	N	19.6	80.4
17916	2	138	20.0	538	1000	95	225	674	1050	2655	0.0067	0.09	38.9	75.5
17947	2	206	29.9	482	900	186	402	860	600	2471	0.0044	0.72	41.3	78.9
17948	2	69	10.0	649	1200	47	7	204	115	361	0.018		34.6	84.9
18075	2	35	5.1	649	1200	2025	2400	2950	1800	4044	0.00002		46	71.4
18149	2	138	20.0	538	1000	65	170	475	820	1717	0.0098	0.15	40.5	75.2
18222	2	241	35.0	482	900	50	200	670	675	1796	0.006	0.2	32.3	74.7
18252	2	41	5.9	538	1000					122272D	0.0000016	0.04	0	10.3
18374	2	103	14.9	482	900					21668D	0.000035	0.03	1.2	0.64
18438	2	103	14.9	482	900					15425D				
18439	1	103	14.9	482	900					1266D	0.000015		2	
18446	2	21	3.0	649	1200	55000	94500	97000	91500	98665	0.0000065	0.05	5.2	19.5
18508	2	41	5.9	538	1000					97304D			0.8	
18859	1	103	14.9	538	1000	800	1900	5900	17800	18740D	0.00052	0	13.7	
18860	2	69	10.0	538	1000	67500	100000		50000	117120D	0.0000069	0.03	>2.5	
18862	2	21	3.0	649	1200	12000	17200			13085D	0.000041	0	2.2	3.6
19789	1	41	5.9	538	1000					12925D	0.000021		0.6	
19792	1	35	5.1	649	1200	1007	1763	3740	1250	4245	0.00066		16.9	76
19793	1	21	3.0	649	1200	2840	4825		4400	5794D	0.00008		3	
19796	1	21	3.0	649	1200	1850	5800	20900	28200	28627	0.0002	0.02	107	53.9
19945	1	41	5.9	538	1000	62000			75000	126746D	0.0000035	0.12	>1.7	14.1

Table 8. (continued)

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
22240	1	138	20.0	538	1000	110	305	980	1625	3114	0.0042		25.4	59.1
22738	1	48	7.0	649	1200	535	775	1220	470	1496	0.0015	N	26.4	86.6
22752	1	48	7.0	649	1200	345	540	920	290	1149	0.0017		25	86.7
22757	1	48	7.0	649	1200	770	1040	1600	1000	1848	0.000029		19.3	
22758	1	103	14.9	593	1099	20	28	87	180	358	0.05	0.73	48.5	83.1
22759	1	103	14.9	593	1099	40	110	307	400	759	0.015	0.01	34.9	71.7
22765	1	69	10.0	593	1099	650	2700	6200	4800	8980	0.00052		16.2	60.6
22766	1	103	14.9	593	1099	214	600	1630	1625	2291	0.0027	N	16	69.7
22822	1	241	35.0	482	900	112	345	925	840	2250	0.0044	0.46	33.1	72
22823	1	206	29.9	482	900	775	1385	2810	1750	6773	0.0014	0.85	30.5	79.6
23067	1	138	20.0	538	1000	90	230	670	1150	2255	0.0072		39.1	73.7
23073	1	138	20.0	593	1099	0.6	1.6	6.5	26	38.3	0.71	0.05	54.2	85.3
23074	1	138	20.0	538	1000	27	60	200	600	1063	0.021		49.3	83.4
23103	1	103	14.9	538	1000	3500	29000	73500	69500	78644	0.000042	N	7.8	41.4
23340	2	69	10.0	593	1099	1550	2860	4680	2600	6441	0.00061	0.03	31.5	81.8
23360	1	172	24.9	482	900	8300	17200	46000	69000	71017	0.00011	0.63	26.6	74.4
23621	2	69	10.0	593	1099	1220	2700	5200	3500	8761	0.0006		37	78.2
23624	2	103	14.9	538	1000	900	2200	6900	8300	14943	0.00065		24.1	57.5
23625	1	83	12.0	538	1000	6000	24000	69000	60000	75325D	0.000036	N	5.7	21.2
23626	1	83	12.0	538	1000	80000				68754D	0.0000014	N	2.7	13.5
23653	2	172	24.9	482	900	4300	8800	20000	15800	24358D	0.00022	N	6.9	
23758	2	69	10.0	593	1099	750	1650	3300	2300	4899	0.00098	0.07	31.2	79.7
23825	2	172	24.9	482	900	1050	2060	5200	6000	14281	0.00095	0.11	42.8	74.1
23826	2	172	24.9	482	900	8000	17000	43500		59991D	0.00014	0.09	>4.7	
23853	2	35	5.1	649	1200	2000	2175	2450	1950	3050	0.00034	0.51	62.1	89.1
23856	2	172	24.9	482	900	2600	3750	6100	2250	13008	0.00016	0.8	38	87
24188	2	207	30.0	482	900	1600	2500	3890	2100	6338	0.00049	0.48	34.2	83.9
24190	2	69	10.0	593	1099	6600	10600	13900	8000	15488	0.000086		9.57	7.81
24191	2	103	14.9	538	1000	4700	9600	16700	9800	23434	0.00018		25.9	77.3
24193	1	172	24.9	482	900	2800	4450	9000	3000	20059	0.00024	0.13	31.1	87.9
24194	1	103	14.9	538	1000	3500	7700	19400	16400	23529	0.00015	0.00015	20.2	82.7
24213	1	69	10.0	593	1099	7000	9300	14100	7500	15434	0.00011	0.15	26.8	82.4
24218	1	172	24.9	482	900	2400	4000	8100	3000	21574	0.00039	0.19	34	82.3
24317	1	138	20.0	482	900	8000	16750	46000	30000	38442D	0.00012		10.9	
24320	1	207	30.0	482	900	35	70	185	150	383	0.027	0.92	35.4	84.8
24325	1	138	20.0	538	1000	50	140	365	600	1320	0.013	0.38	48.7	88.3
24328	1	48	7.0	649	1200	610	970	1490	340	1564	0.0012		17.8	91.2
24333	1	83	12.0	538	1000	4750	18500	53500	52000	67492D	0.000073		5.9	23.2
24335	1	138	20.0	482	900	8500	17000	58000		67750D	0.00012		4.2	12.3
24336	1	55	8.0	649	1200	490	680	970	460	1169	0.0018		25.6	93.1
24343	1	103	14.9	593	1099	30	55	127		1594D	0.00041			
24595	2	207	30.0	482	900	400	720	1340	700	2834	0.0025	0.54	25.4	90.2

Table 8. (continued)

TEST NO.	ENV (a)	STRESS	STRESS	TEMPERATURE	TEMPERATURE	T-1% (b)	T-2% (c)	T-5% (d)	T-TERT (e)	T-RUPT (f)	MIN CREEP RATE	LOAD STRAIN (g)	CREEP STRAIN	RED OF AREA
		MPa	ksi	°C	°F	h	h	h	h	h	%/h	%	%	%
24597	2	190	27.6	482	900	950	1530	2670	1150	5676	0.092		38.1	87.1
24598	2	86	12.5	593	1099	1500	2140	3200	1350	3664	0.00048	0.65	18.2	82.3
24601	2	138	20.0	482	900	390	790	2160	5500	10511	0.0018		49.1	88.8
24604	2	121	17.6	538	1000	200	380	1170	2100	3679	0.0038	0.2	44.1	89.5
24780	2	28	4.1	649	1200	2400	2870	3680	2100	5090	0.00013	0.15	46.7	67.9
24787	2	69	10.0	649	1200	350	413	505	312	608	0.0001	34.8	89.4	
24794	2	138	20.0	482	900	16000				33594D	0.000059	0.03	>1.3	
25013	1	103	14.9	593	1099	10	40	-125	292	513	0.036		42.2	85.3
25016	2	83	12.0	538	1000	5000	30000			39948D	0.00009		2.4	10.2
25018	2	69	10.0	538	1000	2100				36372D	0.000018		>2.0	
25019	1	69	10.0	538	1000					52027D	0.000014		1.6	9.2
25020	1	21	3.0	649	1200	3000	4400		2100	11432	0.000075		11.8	88.2
25023	1	21	3.0	649	1200	9600	13750		13550	15040D	0.00012		>3.8	
25024	2	172	24.9	482	900					3862D	0.0055		>0.7	
25025	2	35	5.1	649	1200					3615D	0.00011		>1.1	
25026	2	172	24.9	482	900	2200	5200	9700	2200	22225	0.00012	0.43	38.9	73.3
25027	2	103	14.9	538	1000	900	2300	6700	7800	11915	0.00053		38	85.2
25028	1	35	5.1	649	1200	1950	3700	4980	3300	5096	0.00041	0.16	18.6	84.5
25029	2	172	24.9	482	900	8500	11900	18500	7000	19301D	0.000046	N	5.7	11.2
25030	2	172	24.9	482	900	1700	2150	3700	1750	8093	0.00028		37.1	82.2
25031	2	69	10.0	593	1099	8200	8800	9750	7700	10794	0.000055	0.03	35.1	86
25033	3	35	5.1	649	1200	2450	3500	4750	2100	5688	0.00021		24.3	77.7
25034	1	207	30.0	482	900	35	85	225	225	615	0.02	1.12	39.2	82.3
25498	1	193	28.0	482	900	220	420	880	500	2553	0.0044	0.32	40.3	85.2
25521	2	172	24.9	482	900	2100	2900	4550	2200	9447	0.00032		36.5	84.1
25522	2	34	4.9	649	1200	7500	7650	8500	7200	10161	0.00013		31.6	69.1
25715	1	172	24.9	482	900	360	800	1980	3950	6947	0.0025	0.2	35.8	86.1
25963	1	35	5.1	649	1200	4750	5800		5150	6138	0.00012	0.03	17.2	89
25967	1	35	5.1	649	1200	755	3700		3600	3935D	0.00048		2.2	

(a) 1 = air environment, 2 = controlled-impurity He environment, and 3 = inert gas.
(b) Time in hours to reach 1% strain.
(c) Time in hours to reach 2% strain.
(d) Time in hours to reach 5% strain.
(e) Time to tertiary creep based on 0.2% strain offset.
(f) Time to rupture. "D" indicates that test was discontinued prior to failure.
(g) N denotes a slightly negative reading.

three sets (see Table 7). A set of plots for rupture is shown in Figs. 4 through 8. The continuous lines are for the average and minimum properties determined from the MCM analysis using all the rupture data in Table 8. The individual data points from the data set are shown for each temperature. These isothermal plots were used to determine the minimum rupture stresses associated with various times and temperatures.

Similar analyses were performed for tertiary creep and 1% strain. The plots were constructed and appropriate values taken from the plots. The values taken from the plots are shown in Table 9. The rules for the high-temperature Code Case N-47 specify that the least of 100% of the stress associated with 1% strain, 80% of that associated with tertiary creep, and 67% of that associated with rupture be used to determine the design stress, S_t.[9] All of these criteria deal with the minimum stress which is defined as the average stress minus 1.65 times the standard deviation. The results in Figs. 9, 10, 11, and 12 for times of 10,000, 30,000, 100,000, and 300,000 h, respectively, and in Table 9 show that the stress associated with tertiary creep controls through 510°C (950°F), and the stress associated with 1% strain controls at higher temperatures.

The present data set only involves 4 heats of material, and, although some of the test times are in excess of 100,000 h, this data set is too limited in scope to be a basis for determining Code Case N-47 design stresses. However, it is interesting to see where the results of this limited analysis fall with respect to the N-47 design stresses. This comparison is made in Table 10. The agreement between the design stresses obtained in the Oak Ridge National Laboratory (ORNL) analysis and those in N-47 were good up to 538°C (1000°F), but at higher temperatures, the design stresses obtained by the ORNL analysis are lower than those in N-47.

Materials people at the Gulf General Atomic Company in 1975 considered the mechanical properties of 2.25 Cr-1 Mo steel and their agreement with the values in ASME Code Case 1592, which was a predecessor to the present Code Case N-47.[10] They found that the time-dependent stress intensity, S_t, was controlled by 100% of the minimum stress for 1% strain for times up to 100 h at 538 through 649°C (1000 through 1200°F). At all other conditions, the design stress was controlled by two-thirds the stress to rupture. Based on their analysis of the data, the Gulf General Atomics Company concluded that the expected minimum rupture values for this material in Code Case 1592 should be reduced 10%. These revised values are tabulated in their working document. These changes were not made, and the values of the minimum rupture stress presently tabulated in Code Case N-47 are the same as those in its predecessor, Case 1592.

ORNL-DWG 93-12852

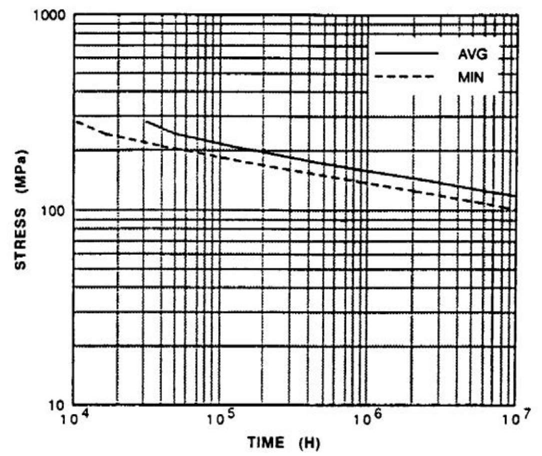

Fig. 4. Rupture properties of Cr-Mo steel at 427°C; estimated by Minimum Commitment Method.

ORNL-DWG 93-12853

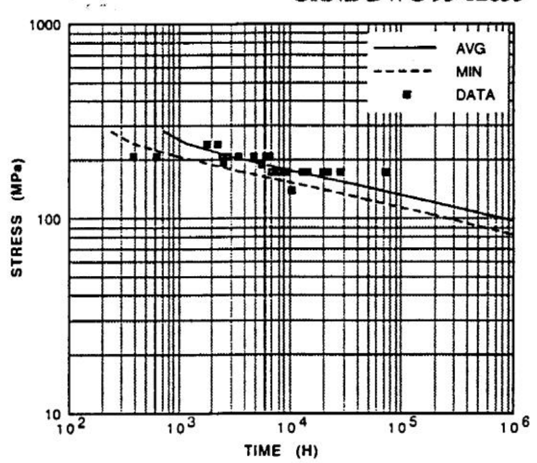

Fig. 5. Rupture properties of Cr-Mo steels at 482°C; lines are Minimum Commitment Method analysis and points are data.

ORNL-DWG 93-12854

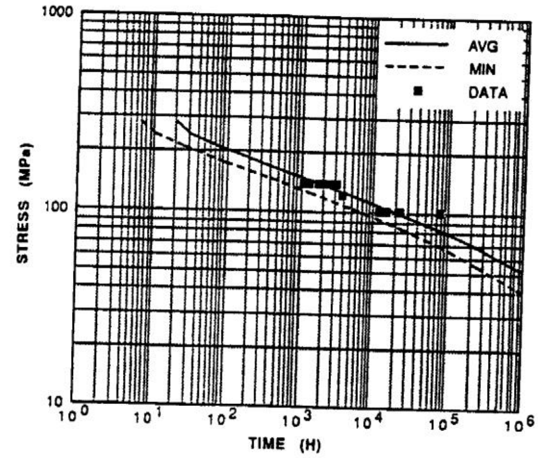

Fig. 6. Rupture properties of Cr-Mo steel at 538°C; lines are Minimum Commitment Method analysis and points are data.

ORNL-DWG 93-12855

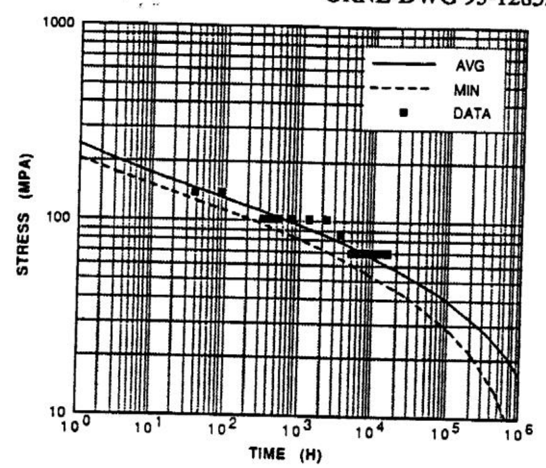

Fig. 7. Rupture properties of Cr-Mo steel at 593°C; lines are Minimum Commitment Method analysis and points are data.

ORNL-DWG 93-12856

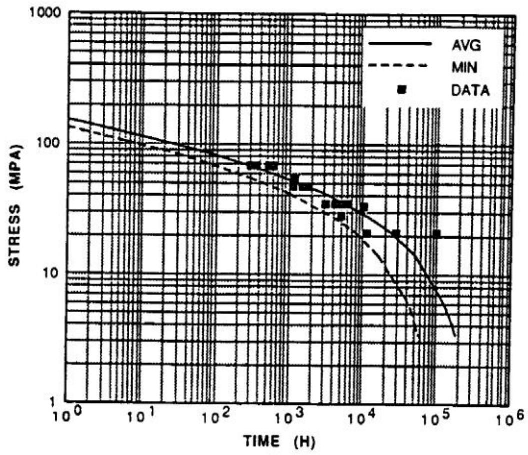

Fig. 8. Rupture properties of Cr-Mo steel at 649°C; lines are Minimum Commitment Method analysis and points are data.

Table 9. Determination of S_t for Cr-Mo steel using three code criteria (100% of the stress to produce 1% strain, 80% of the stress to cause tertiary creep, and 66.7% of the stress to cause rupture)

TEMPERATURE	0.667*	0.667*	0.667*	0.667*	0.8*	0.8*	0.8*	0.8*	1*	1*	1*	1*	St-1E4 h	St-3E4 h	St-1E5 h	St-3E5 h
	10,000-h RUPT	30,000-h RUPT	100,000-h RUPT	300,000-h RUPT	10,000-h TERT	30,000-h TERT	100,000-h TERT	300,000-h TERT	1% IN 10,000 h	1% IN 30,000 h	1% IN 100,000 h	1% IN 300,000 h				
°C (°F)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)	MPa (ksi)
427 (800)			122 (17.7)	106 (15.3)	149 (21.6)	127 (18.4)	110 (16.0)	94 (13.6)			183 (26.5)	162 (23.5)		127 (18.4)	110 (16.0)	94 (13.6)
455 (850)	124 (18.0)	110 (16.0)	101 (14.7)	85 (12.3)	124 (18.0)	109 (15.7)	92 (13.4)	79 (11.4)	138 (20.0)		133 (19.3)	121 (17.5)	124 (18.0)	109 (15.7)	92 (13.4)	79 (11.4)
482 (900)	101 (14.6)	88 (12.7)	76 (11.0)	64 (9.3)	99 (14.4)	88 (12.8)	72 (10.4)	61 (8.8)	114 (16.6)	100 (14.5)	86 (12.5)	79 (11.5)	101 (14.6)	88 (12.8)	72 (10.4)	61 (8.8)
510 (950)	82 (12.0)	71 (10.3)	60 (8.7)	50(7.3)	83 (12.0)	70 (10.1)	55 (8.0)	46 (6.6)	90.0 (13.0)	75 (10.9)	62 (9.0)	51 (7.4)	82 (12.0)	70 (10.1)	55 (8.0)	46 (6.6)
538 (1000)	64 (9.3)	55 (8.0)	43 (6.3)	35 (5.1)	63 (9.2)	50 (7.2)	39 (5.6)	30 (4.4)	59 (8.6)	48 (7.0)	37 (5.4)	23 (3.3)	59 (8.6)	48 (7.0)	37 (5.4)	23 (3.3)
566 (1050)	49 (7.2)	41 (6.0)	32 (4.7)	24 (3.5)	46 (6.6)	35 (5.0)	27 (3.9)	19 (2.8)	41 (6.0)	32 (4.6)	25 (3.6)		41 (6.0)	32 (4.6)	25 (3.6)	
593 (1100)	37 (5.3)	28 (4.0)	19 (2.7)	12 (1.8)	32 (4.7)	23 (3.3)	15 (2.2)	9.0 (1.3)	26 (3.8)	17 (2.5)	11 (1.6)		26 (3.8)	17 (2.5)	11 (1.6)	
621 (1150)	25 (3.7)	17 (2.4)	7.6 (1.1)	4.8 (0.7)	21 (3.0)	14 (2.0)	8.9 (1.2)		10 (1.5)	3.5 (0.5)			10 (1.5)	3.5 (0.5)		
649 (1200)	12 (1.8)	5.5 (0.8)			9.7 (1.4)	4.8 (0.7)	2.1 (0.3)									

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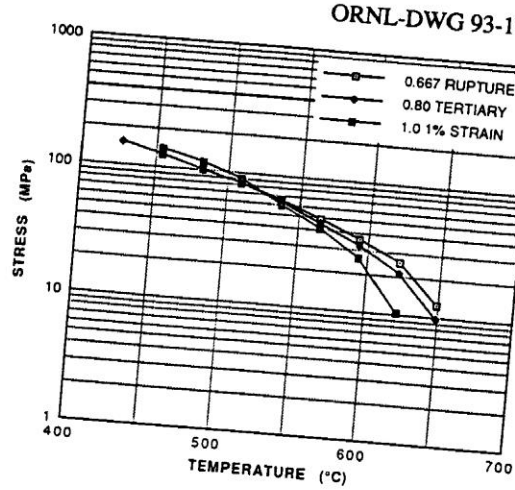

Fig. 9. Data for determining S_t for 10,000 h.

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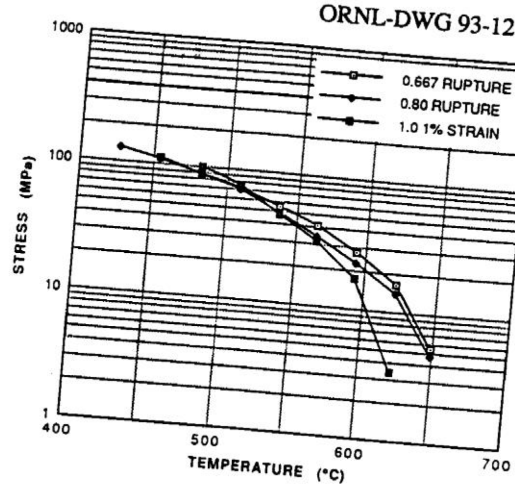

Fig. 10. Data for determining S_t for 30,000 h.

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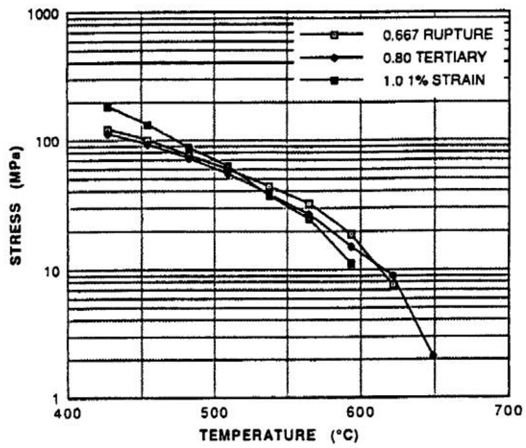

Fig. 11. Data for determining S_t for 100,000 h.

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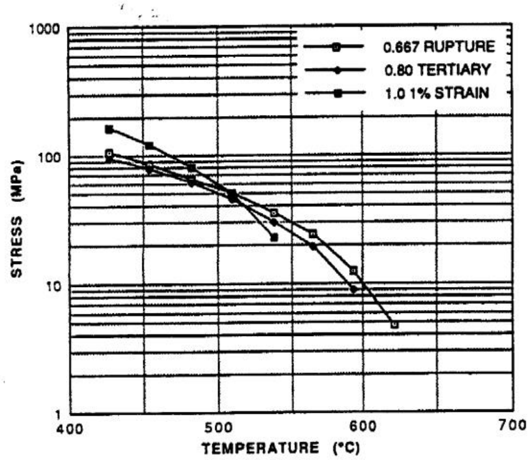

Fig. 12. Data for determining S_t for 300,000 h.

Table 10. Comparison of S_t obtained from Oak Ridge National Laboratory data and that in Code Case N-47

TEMPERATURE	10,000 h, ORNL	10,000 h, N-47	10,000 h, DIF(a)	30,000 h, ORNL	30,000 h, N-47	30,000 h, DIF(a)
°C	MPa	MPa	%	MPa	MPa	%
427	148.9	158.6	6.1	126.8	141.3	10.2
454	124.1	126.2	1.6	108.9	112.4	3.1
482	99.3	99.3	0.0	88.2	86.2	-2.4
510	82.7	77.9	-6.2	69.6	66.9	-4.1
538	59.3	60.0	1.1	48.3	51.7	6.7
566	41.4	46.2	10.4	31.7	39.3	19.3
593	26.2	34.5	24.0	17.2	28.3	39.0
621	10.3			3.4		

100,000 h, ORNL	100,000 h, N-47	100,000 h DIF(a)	300,000 h, ORNL	300,000 h, N-47	300,000 h DIF(a)
MPa	MPa	%	MPa	MPa	%
110.3	124.1	11.1	93.8	111.0	15.5
92.4	96.5	4.3	78.6	84.8	7.3
71.7	75.1	4.6	60.7	66.2	8.3
55.2	57.9	4.8	45.5	50.3	9.6
37.2	43.4	14.3	22.8	35.8	36.5
24.8	32.4	23.4		27.6	
11.0	22.8	51.5		18.6	

(a) DIF = (N-47-ORNL)/N-47*100.

Booker et al.[11] analyzed a data set of rupture data consisting of 563 points obtained over the temperature range of 454 to 600°C. These data were analyzed on the basis of isothermal plots, and values were obtained for the minimum rupture stress. The minimum rupture stresses are compared in Table 11 for Code Case N-47, the present ORNL analysis, and the Booker et al. analysis. The rupture stress values for 10,000 h are in good agreement for all three analyses. For 100,000 h, all three analyses agree well at 427°C. At 482 and 538°C (900 and 1000°F), the agreement is good between the present ORNL and N-47 values, but Booker's values are significantly lower. At 593°C (1100°F), the disagreement of the three analyses is significant with the present ORNL value being the lowest and the N-47 value being the highest.

8. INFLUENCE OF PRETEST AGING

Since the microstructure is partially bainite, which contains finely dispersed carbides, it would be expected that these fine carbides would coarsen with time and the material become weaker. Since this would be a thermally activated process, the rate of weakening would be dependent upon temperature. The required tensile properties of SA 336, grade F-22a, are a minimum yield strength of 207 MPa (30 ksi) and an ultimate tensile strength of 414 to 586 MPa (60 to 85 ksi).

The tensile properties of several samples were determined in two conditions: (1) isothermally annealed and (2) isothermally annealed plus pretest aged. The aging conditions and the tensile test results are summarized in Table 12. Aging at 593 to 649°C (1100 or 1200°F) decreased the yield strength of some of the samples below the specified minimum value of 207 MPa (30 ksi).

Several specimens were aged prior to creep testing. The test results for these samples are given in Table 13. The second column in Table 13 has a one-digit code for the aging condition, and the meaning of this digit is given in Table 14. The aging conditions were quite varied, so it is not possible to do any detailed analysis on the creep data for aged samples in Table 13. Figures 13 through 16 show the points for the preaged samples on the MCM rupture lines obtained by analyzing the data set in Table 8. In general, the rupture strengths of the pretest aged samples fall short of the minimum strength of the material tested in the as isothermally annealed condition.

Table 11. Comparison of minimum rupture stresses from these sources

TEMPERATURE	10,000 h	10,000 h	10,000 h	100,000 h	100,000 h	100,000 h
	ORNL	BOOKER	N-47	ORNL	BOOKER	N-47
°C (°F)	MPa	MPa	MPa	MPa	MPa	MPa
427 (800)		254	238	183	181	186
455 (850)	186			151		
482 (900)	151	144	149	114	99	113
510 (950)	123			90		
538 (1000)	96	91	90	64	56	65
566 (1050)	73			48		
593 (1100)	55	48	52	28	30	34
621 (1150)	37			11		
649 (1200)	18					

Table 12. Tensile properties of 2.25 Cr-1 Mo steel at 25°C before and after aging

Heat	Aging conditions			Yield strength		Ultimate tensile strength		Elongation (%)		Reduction in area (%)
	Temperature (°C)	Environment	Time (h)	(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
36202	NA	NA	NA	246	35.7	504	73.0	24.0	14.1	71.8
36202	593	HTGR-He	10,000	236	34.2	506	73.4	24.3	16.0	69.7
36202	593	HTGR-He	20,500	212	30.8	474	68.8	24.4	18.1	70.9
36202	593	HTGR-He	34,000	190	27.5	481	69.7	25.4	17.2	70.5
X6216	NA	NA	NA	241	35.0	495	71.8	14.1	23.6	71.6
X6216	593	HTGR-He	10,000	195	28.3	476	69.1	16.0	24.1	71.6
X6216	593	HTGR-He	20,500	212	30.7	455	66.0	17.3	24.3	72.9
X6216	593	HTGR-He	34,000	197	28.6	474	68.8	16.3	23.8	70.2
X6216	649	HTGR-He	24,500	167	24.2	385	55.9	21.2	30.4	81.3
72768	NA	NA	NA	228	33.0	469	68.0	15.0	25.3	75.0
72768	593	HTGR-He	10,000	195	28.3	476	69.1	16.0	24.1	71.6
72768	593	HTGR-He	20,500	212	30.7	455	66.0	17.3	24.3	72.9
72768	593	HTGR-He	34,500	178	25.8	470	68.2	17.6	25.2	71.8
56448	NA	NA	NA	279	40.4	476	69.1	15.8	24.4	76.9
56448	671	Ar	522	251	36.4	443	64.2	18.9	27.4	80.0
56448	671	Na	522	203	29.4	410	59.4	20.1	29.5	84.2
56448	671	Ar	4,000	245	35.6	406	58.9	20.9	29.9	71.6
56448	671	Na	4,000	167	24.2	370	53.6	26.5	35.5	78.9
56448	649	HTGR-He	13,000	157	22.7	374	54.2	23.2	32.6	79.3

Table 13. Creep test results for pretest aged specimens

TEST NO.	AGING(a)	ENV(b)	STRESS MPa	STRESS ksi	TEMPERATURE °C	TEMPERATURE °F	T-1%(c) h	T-2%(d) h	T-5%(e) h	T-T(f) h	T-R(g) h	MCR(h) %/h	LOAD STR(i) %	CREEP STR %	RED OF AREA %	HEAT
24196	6	2	172	24.9	482	900	120	225	420	230	1223	0.0082	0.66	43.3	85.3	56448
24201	7	2	172	24.9	482	900	280	425	775	770	2232	0.0073		45.2	86.4	56448
24215	7	2	172	24.9	482	900	135	220	425	230	1175	0.0086	0.15	44.1	84.4	56448
24334	8	2	172	24.9	482	900	10	400	881	520	1535	0.001	2.15	31.8	87.1	56448
24341	9	2	172	24.9	482	900	160	260	460	200	1149	0.0048	0.03	36.7	86.1	56448
24605	9	2	172	24.9	482	900	42	85	152	100	368	0.024	0.94	40.6	82.3	56448
24599	6	2	138	20.0	482	900	150	450	1550	4400	8662	0.0025	0.17	54	85.5	56448
24586	9	2	138	20.0	482	900	700	1250	2510	1200	4838	0.00078	0.45	46.5	87.7	56448
24612	9	2	138	20.0	482	900	410	640	1210	450	4024	0.0018	0.5	51	86.2	56448
24781	8	2	121	17.6	482	900	4200	9700	13800	9200	25840D	0.00012		>12.0		56448
24192	6	2	103	14.9	538	1000	60	130	360	740	1535	0.013	0.05	49.5	85.4	56448
24209	7	2	103	14.9	538	1000	100	300	1000	2000	3584	0.0045	0.06	46.6	87.6	56448
24348	8	2	103	14.9	538	1000	860	980	1240	800	2023	0.0005	0.59	40.6	89.2	56448
24798	8	2	103	14.9	538	1000	150	200	350	660	1198	0.019	0.12	56.2	86.3	56448
24587	9	2	103	14.9	538	1000	138	274	710	700	1831	0.0084		52.4	86.9	56448
24793	9	2	103	14.9	538	1000	45	95	260	800	1385	0.018	0.13	56.3	88	56448
24788	6	2	83	12.0	538	1000	490	1280	4200	5600	12419D	0.032		>29.5		56448
24610	7	2	83	12.0	538	1000	1950	5100	13100		30955D	0.00036		>10.3		56448
24592	8	2	83	12.0	538	1000	360	555	1165	210	1447D	0.0075		6.32	7.49	56448
24603	9	2	83	12.0	538	1000	400	800	2000	4500	8815	0.0023		55	87.3	56448
24790	9	2	83	12.0	538	1000	200	450	1600	8200	13202	0.0013		49	90.9	56448
24189	1	2	103	14.9	593	1099	15	80	260	295	623	0.016	N	30.4	79.2	X6216
24214	2	2	103	14.9	593	1099	27	80	250	280	584	0.017	N	34.8	85.5	X6216
25017	4	2	103	14.9	593	1099		10	38	200	411	0.00031		40	79.2	X6216
24806	5	2	103	14.9	593	1099	2	7	23	52	92	0.18		46.1	84.8	X6216
24803	5	2	103	14.9	593	1099	3	8	25	80	115	0.18	0.08	50.2	85.7	36202
24206	2	2	103	14.9	593	1099	2.5	10	29	82	135	0.16		73.2	86.2	36202
23855	1	2	103	14.9	593	1099	20	45	142	280	438	0.033	0.4	37.4	79.1	36202
23851	1	2	103	14.9	593	1099					166			41.2	89.7	72768
24212	2	2	103	14.9	593	1099	2	5	14	52	73	0.33	0.23	53.8	88.9	72768
24802	5	2	103	14.9	593	1099	2	5	19	65	96	0.22	0.18	50.5	88.9	72768
24346	6	2	103	14.9	593	1099	5	11	21	13	57.3	0.17		40.2	90.3	56448
25021	4	2	69	10.0	593	1099	630	1200	2610	2000	4311	0.0017		25.9	78.8	X6216
25022	4	2	69	10.0	593	1099	39	660	1300	600	2364	0.0025	0.16	30	82.7	X6216
24197	6	2	69	10.0	593	1099	225	500	1240	1600	2823	0.0039	0.32	34.5	80.2	56448
24611	7	2	69	10.0	593	1099	4000	5950	7550	5700	8570	0.00029	N	30.3	84.5	56448
24345	8	2	69	10.0	593	1099	35	71	170	330	600	0.03		46.1	85.2	56448
24581	9	2	69	10.0	593	1099	90	160	390	600	1330	0.013	0.31	57.9	90.4	56448
24791	7	2	55	8.0	593	1099	10000	13300	16700	8000	26283D	0.00003		>9.2		56448
24609	8	2	55	8.0	593	1099	545	880	1730	550	4647	0.0014		53.6	88.9	56448
24777	9	2	55	8.0	593	1099	650	1270	2800	5000	9375	0.001	1.45	36.7	84.3	56448
24606	6	2	49	7.1	649	1200	150	210	303	175	474	0.006		57	89	56448
24602	7	2	49	7.1	649	1200	2700	2900	3250	2750	3457	0.00043		27.6	90.9	56448
24779	9	2	49	7.1	649	1200	55	115	295	390	743	0.017	0.004	61.5	93.8	56448
25015	10	2	49	7.1	649	1200	100	118	168	100	299	0.005		62.7	79.6	56448
25509	3	2	35	5.1	649	1200	2250	3150	4700	2300	5881	0.00048	0.14	11.9	27.5	X6216

Table 13. (continued)

24208	6	2	35	5.1	649	1200	2620	3100	3870	2350	4622	0.00035	0.06	28.1	72.4	56448
24216	7	2	35	5.1	649	1200	4600	5500	6120	3600	6488	0.000077	0.83	33.4	86.7	56448
24340	8	2	35	5.1	649	1200	180	300	640	600	1630	0.00066		56.6	85.6	56448
24590	9	2	35	5.1	649	1200	1600	2000	2575	1600	3430	0.00046		39.6	82.6	56448
24600	9	2	35	5.1	649	1200	1580	2500	3220	2000	4221	0.00044		59.2	87.8	56448
24778	8	2	28	4.1	649	1200	2600	2700	2970		3588		0.01	62.7	90.4	56448
25511	3	2	21	3.0	649	1200	8800	22000			31261D	0.0001	0.05	>3.1		X6216
24801	8	2	21	3.0	649	1200	230	500	2200	3750	6610	0.0013	0.13	38.4	71.9	56448
25014	8	2	21	3.0	649	1200	2260	3190	5000	1900	11770	0.0003		32.7	43.2	56448
24792	9	2	21	3.0	649	1200	8000			6850	10583D	0.000025	0.12	>1.9		56448

(a) See Table 13 for aging treatments.
(b) Environment, 1 = air and 2 = controlled-impurity helium.
(c) Time to 1% strain.
(d) Time to 2% strain.
(e) Time to 5% strain.
(f) Time to tertiary creep based on 0.2% strain offset.
(g) Time to rupture. "D" means that test was discontinued prior to rupture.
(h) MCR = minimum creep rate in %/h.
(i) "N" means that loading strain was slightly negative.

Table 14. Legend for aging treatments

1.	Aged 10,000 h at 593°C in He
2.	Aged 20,000 h at 593°C in He
3.	Aged 27,500 h at 649°C in He
4.	Aged 26,300 h at 593°C in He
5.	Aged 34,000 h at 593°C in He
6.	Aged 522 h at 671°C in Na
7.	Aged 522 h at 671°C in Ar
8.	Aged 4,000 h at 671°C in Na
9.	Aged 4,000 h at 671°C in Ar
10.	Aged 13,000 h at 649°C in He

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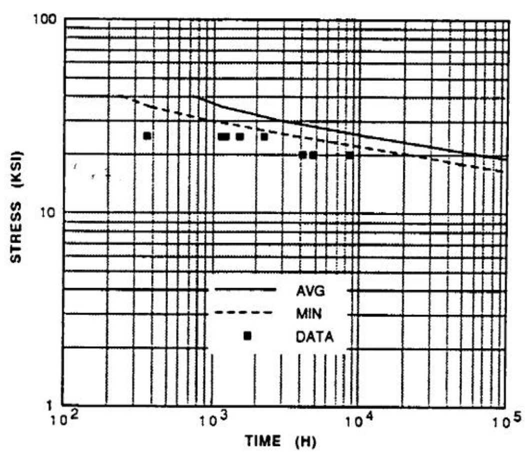

Fig. 13. Rupture properties of Cr-Mo steel at 428°C, unaged (lines by Minimum Commitment Method analysis) and aged (points).

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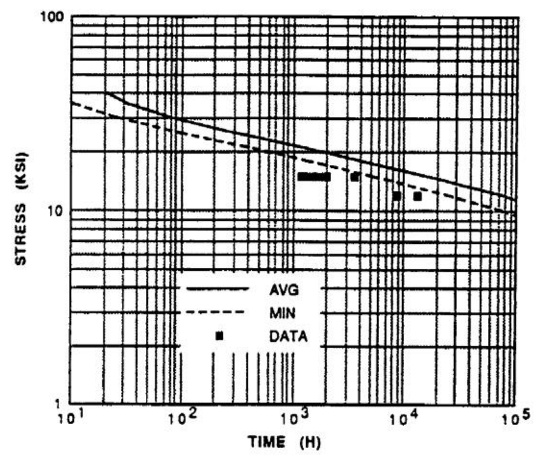

Fig. 14. Rupture properties of Cr-Mo steel at 538°C, unaged (lines obtained by Minimum Commitment Method) and aged (points).

ORNL-DWG 93-12863

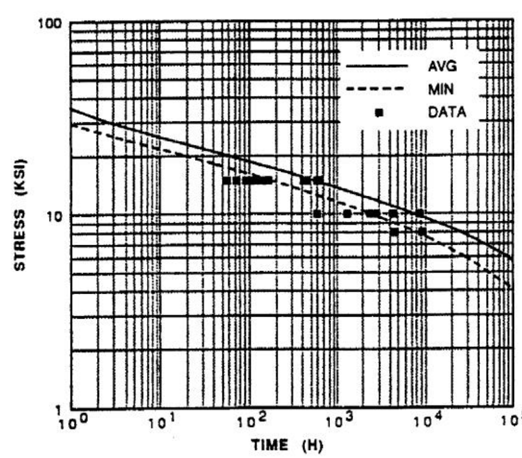

Fig. 15. Rupture properties of Cr-Mo steel at 593°C, unaged (lines obtained by Minimum Commitment Method analysis) and aged (points).

ORNL-DWG 93-12864

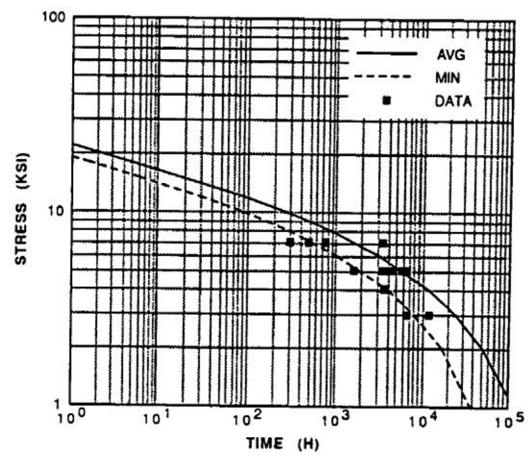

Fig. 16. Rupture properties of Cr-Mo steel at 649°C, unaged (lines obtained by Minimum Commitment Method analysis) and aged (points).

9. CONCLUSIONS

1. The MCM was found to work well for 2.25 Cr-1 Mo steel in that the data were fit well by the correlations, and extrapolations of the correlations to reasonable times appeared reasonable.
2. Analysis of creep test results in air and helium by the MCM did not reveal any effect of environment to times of about 100,000 h on the test results.
3. The ORNL creep data set consisting of the results from four heats was analyzed by the MCM using the analytical methods on Code Case N-47. The values obtained from the rather limited ORNL data set were lower than those from N-47 at 538 through 649°C (1000 through 1200°F).
4. Room-temperature tensile tests of preaged specimens revealed that extended aging of some heats at 593 and 649°C (1100 and 1200°F) decreased the yield strength below the 30 ksi minimum value specified by ASME for this material.
5. The data were not sufficient to obtain quantitative values, but pretest aged specimens generally had lower creep strength than isothermally annealed material.

10. ACKNOWLEDGMENTS

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