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Analysis of Elevated-Temperature Tensile and Creep Properties of Normalized and Tempered 2¼ Cr-1 Mo Steel

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ANALYSIS OF ELEVATED-TEMPERATURE TENSILE AND CREEP PROPERTIES OF NORMALIZED AND TEMPERED 2 1/4 Cr-1 Mo STEEL

M. K. Booker, B.L.P. Booker, and R. W. Swindeman

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ANALYSIS OF ELEVATED-TEMPERATURE TENSILE AND CREEP PROPERTIES OF NORMALIZED AND TEMPERED 2 1/4 Cr-1 Mo STEEL*

M. K. Booker, B.L.P. Booker, and R. W. Swindeman

ABSTRACT

The ferritic 2 1/4 Cr-1 Mo steel is an important construction material for elevated-temperature applications worldwide. It is of particular interest for coal conversion pressure vessels. We collected tensile and creep data for normalized and tempered 2 1/4 Cr-1 Mo steel from American, Japanese, British, French, and German sources. These included creep data obtained at temperatures from 427 to 600°C (800–1112°F) and tensile data from room temperature to 550°C (1022°F). Properties examined included yield strength, ultimate tensile strength, 10^5-h creep-rupture strength, and 10^{-5}%/h creep strength. These are the properties used in setting allowable stresses for Section VIII, Division 1, of the *ASME Boiler and Pressure Vessel Code*. The data were analyzed by using lot-centered regression approaches that yielded expressions for the variations in the above properties with loading condition, as well as accounting for lot-to-lot variations in properties.

We found no indications of systematic differences in any of the properties examined for data from the different countries. However, the estimated allowable stresses from this investigation fell up to 10% below those currently given for this material in the ASME Code. Several possible reasons were cited for the differences, and we concluded that our results are not overly conservative. On the other hand, there is no direct evidence that the current code allowable stresses are insufficiently conservative, since those stresses rely on factors (such as service experience) other than experimental data.

INTRODUCTION

The ferritic 2 1/4 Cr-1 Mo steel is an important construction material for elevated-temperature applications worldwide. It is of

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particular interest for coal conversion pressure vessels. This report describes an analysis of available creep and tensile data for normalized and tempered 2 1/4 Cr-1 Mo steel performed to obtain an estimate of allowable stresses by the rules established for Section VIII, Division 1, of the *ASME Boiler and Pressure Vessel Code*. The analyses were performed by using the lot-centered regression techniques that were shown[1] to be applicable to such problems in an earlier analysis of data for type 321H stainless steel. The results of this investigation provide estimates of appropriate ASME allowable stresses for the particular subset of material examined.

ALLOWABLE STRESS CRITERIA

The allowable stress, *S*, in Section VIII, Division 1, of the ASME Code is defined for a ferritic steel as the lowest of the following stress values at a given temperature:

1. one-fourth of the specified minimum tensile strength at room temperature,
2. one-fourth of the tensile strength at temperature,
3. two-thirds of the specified minimum yield strength at room temperature,
4. two-thirds of the yield strength at temperature,
5. 100% of the average stress for a creep rate of 0.01%/1000 h,
6. 67% of the average stress for rupture in 100,000 h, and
7. 80% of the minimum stress for rupture in 100,000 h.

It should be noted that "tensile strength at temperature" in item 2 above is defined at 110% of the value obtained for that temperature from a trend curve normalized to the minimum specified strength at room temperature, while "yield strength at temperature" is defined as 100% of such a value from an analogous trend curve for that property.

DATA

The data used in this evaluation were derived from an international variety of sources, including Japanese,[2–4] German,[5] French,[6] British,[7] and

American[8–11] data. The primary criteria used for selection of lots* of material for inclusion in the data base were that the room-temperature yield strength for that lot be above 310 MPa (45 ksi) and that the room-temperature ultimate tensile strength (UTS) lie in the range 517 to 620 MPa (75–90 ksi). However, in the case of creep data, data from several lots of material with a UTS in the range 620 to 655 MPa (90–95 ksi) were included because the data were particularly extensive. Tables 1 and 2 summarize the data available from the various countries, and Appendix B provides a full listing of data used as well as available characterization of the various lots of material for which data were obtained. Note that, although Table 1 shows a very extensive creep-rupture data set, the available data for minimum creep rate were very sparse, consisting of 55 data for four lots of material, all from American sources. In all creep data analyses, tests at temperatures above 600°C or with lives less than 10 h were excluded, since we intended to estimate allowable stresses only to about 550°C. Deletion of data at temperatures above 600°C prevents the results from being biased by those data.

*A lot is defined as a particular product form of a particular heat of material in a given heat-treatment condition. Often a heat is represented by only one lot.

Table 1. Summary of creep-rupture data sets used

National origin	Number of lots	Number of data	Temperature range (°C)	Longest rupture life (h)
France	7	78	500–600	8,911
Great Britain	6	23	500–600	5,121
Japan	26	228	450–600	85,901
United States	8	79	427–566	8,227
West Germany	6	67	500–600	39,606
TOTAL	53	475	427–600	85,901

Table 2. Summary of tensile data sets used

National origin	Number of lots	Number of data	Temperature range (°C)
Great Britain	19	118	20–500
Japan	9	90	22–550
United States	15	94	22–538
TOTAL	43	302	20–550

ANALYTICAL APPROACH

The analyses of both tensile and creep strength data in this investigation are based on the application of lot-centered regression techniques. Booker and Booker[1] detail the development of such techniques for applications to these types of data, and Appendix A contains a step-by-step summary of the methods.

CREEP DATA ANALYSIS

Initial analysis of the data was performed by a generalized regression treatment[12] of lot-centered data, as used in the previous analysis[1] of the data for type 321H stainless steel. In this step, all data were treated together as a single population, regardless of strength level, grade, deoxidation, heat treatment conditions, etc. It should be noted, however, that the lot-centered approach preserves the individuality of each lot, so that lots of differing strength can be combined with some degree of flexibility.

We found the available creep-rupture data to be well represented by

$$\log t_r = C_h - 3.656 \log \sigma - 0.02564T - 1.052 \times 10^{-5} T\sigma \;, \qquad (1)$$

where

t_r = rupture life, h;

σ = stress, MPa (1 ksi = 6.895 MPa); and

T = temperature, K.

All logarithms used in this report are base 10. The parameter C_h is a "lot constant" that reflects the relative strengths of different lots of material, assuming that the stress and temperature dependence is the same for all lots. (Examination of isothermal individual lot residual plots showed this assumption to be a good one.) The average value of C_h was 33.41. Equation (1) yielded a coefficient of determination (R^2) of 91.7% when fit to 475 data for 54 lots of material. The "within-lot" variance, V_w (in log t_r), for this fit was 0.0532, and the "between-lot" variance, V_B, was 0.0667. Figures 1 through 10 illustrate the fit of this equation compared with data for individual lots.

The minimum creep rate data were not judged to be sufficient to obtain reliable results from a detailed analysis. Therefore, to obtain the best possible estimates of creep strength, the creep rate data were normalized to the corresponding creep rupture data by the method of Monkman and Grant.[13] Figure 11 illustrates this relationship, which is given by

$$\dot{e}_m = 3.6 t_r^{-1.0} \ . \qquad (2)$$

Thus, Eqs. (1) and (2) may be used together to yield predictions for minimum creep rate as a function of stress, temperature, and lot-to-lot variations in strength. Note that Fig. 11 contains considerable scatter, especially for one set of data at 454°C for which the creep rates in long-term tests are considerably below the values that would be predicted by Eq. (2). This phenomenon could be due to the nonclassical shapes of the creep curves observed[10] for this lot of material. In light of the limited amount of available creep rate data, the line in Fig. 11 was drawn in a fashion that provides a good description of most of the data and that is conservative (in terms of allowable stress estimation) for the remaining data.

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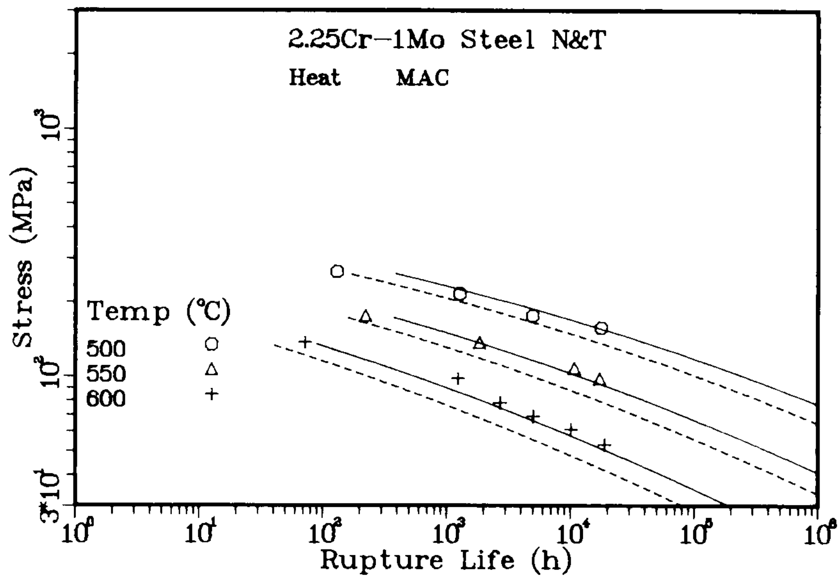

Fig. 1. Comparison of experimental data and predicted creep-rupture behavior for heat MAC of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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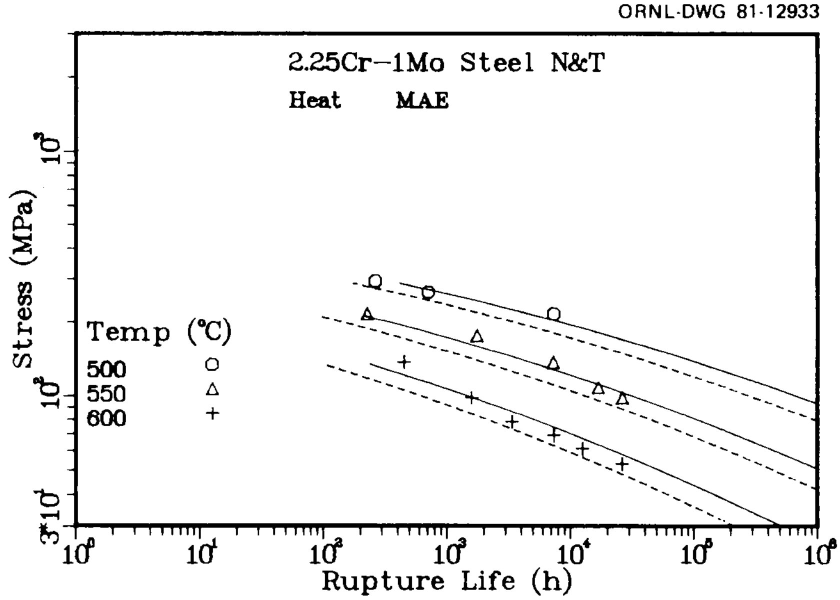

Fig. 2. Comparison of experimental data and predicted creep-rupture behavior for heat MAE of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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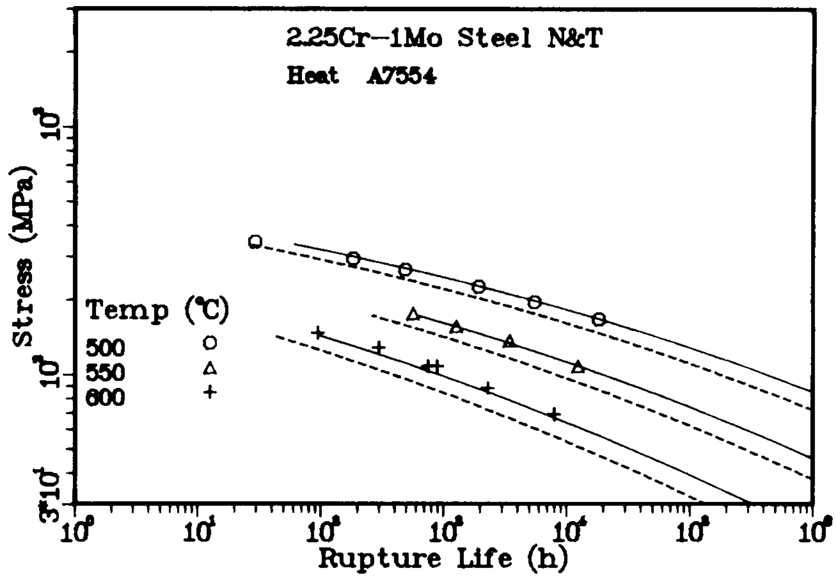

Fig. 3. Comparison of experimental data and predicted creep-rupture behavior for heat A7554 of normalized and tempered 2 1/4 Cr–1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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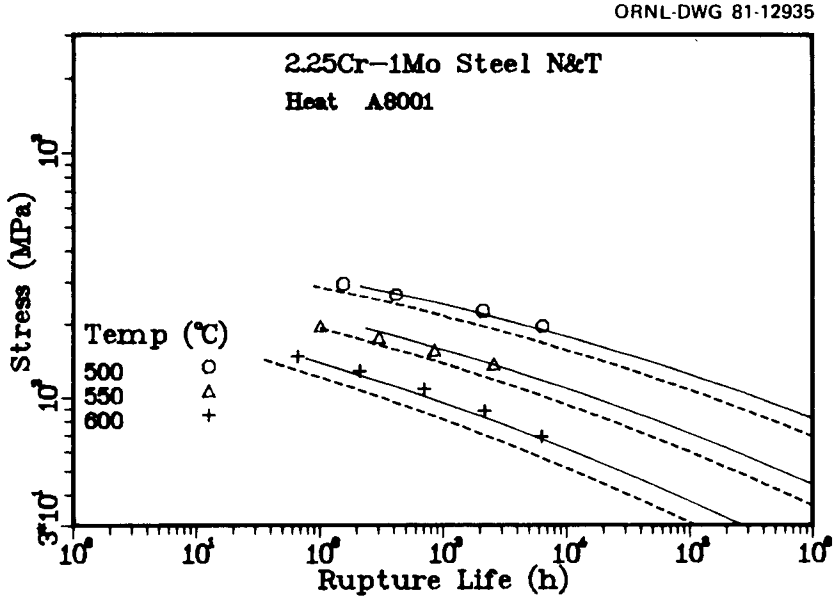

Fig. 4. Comparison of experimental data and predicted creep-rupture behavior for heat A8001 of normalized and tempered 2 1/4 Cr–1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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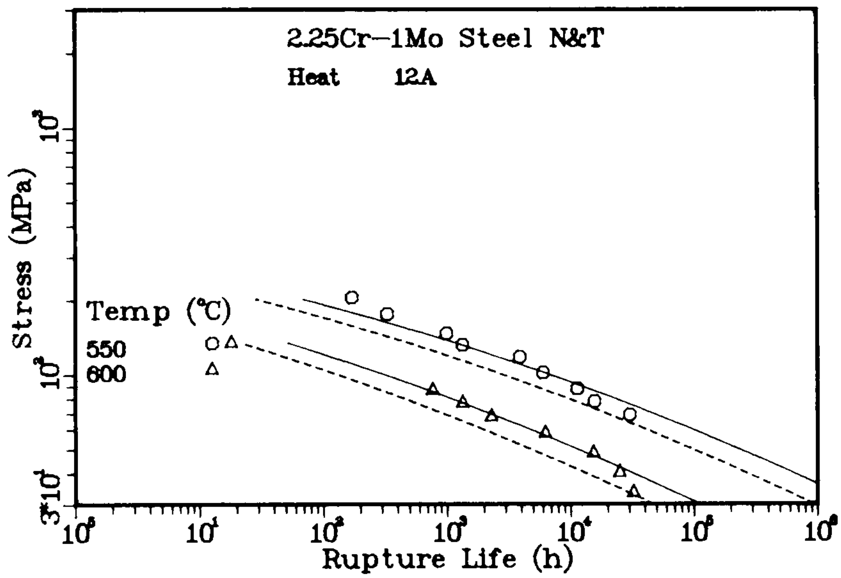

Fig. 5. Comparison of experimental data and predicted creep-rupture behavior for heat 12A of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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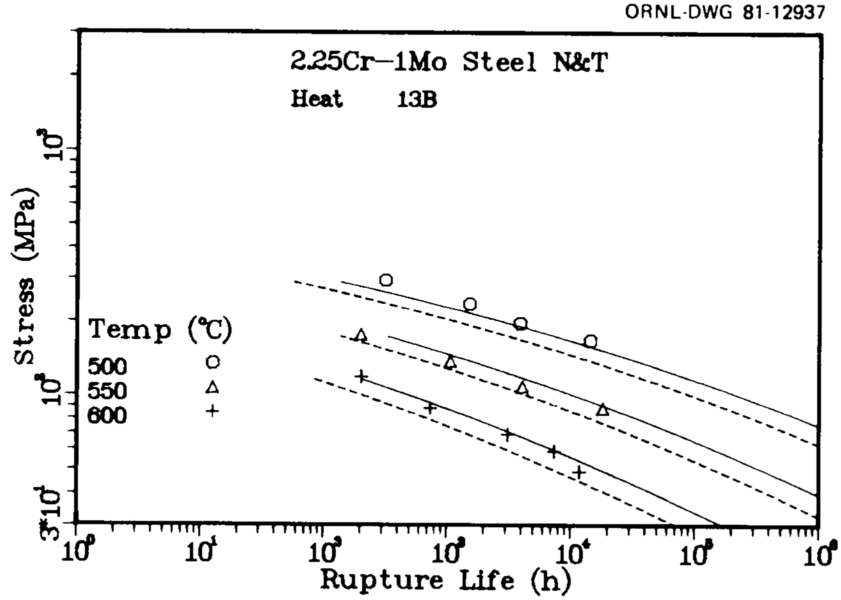

Fig. 6. Comparison of experimental data and predicted creep-rupture behavior for heat 13B of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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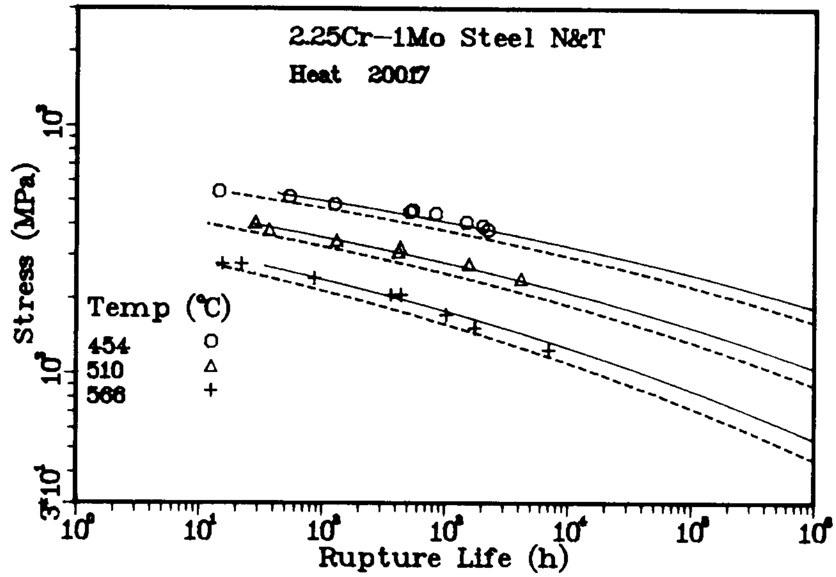

Fig. 7. Comparison of experimental data and predicted creep-rupture behavior for heat 20017 of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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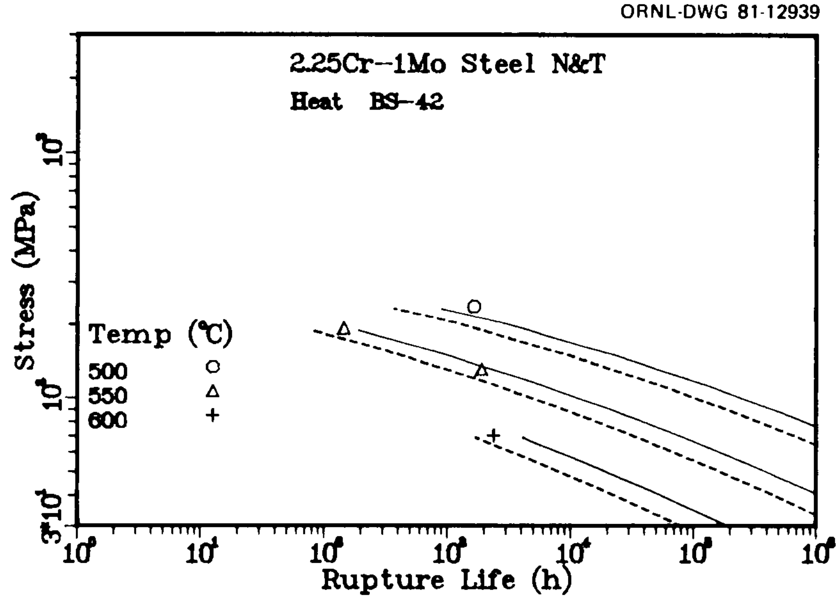

Fig. 8. Comparison of experimental data and predicted creep-rupture behavior for heat BS-42 of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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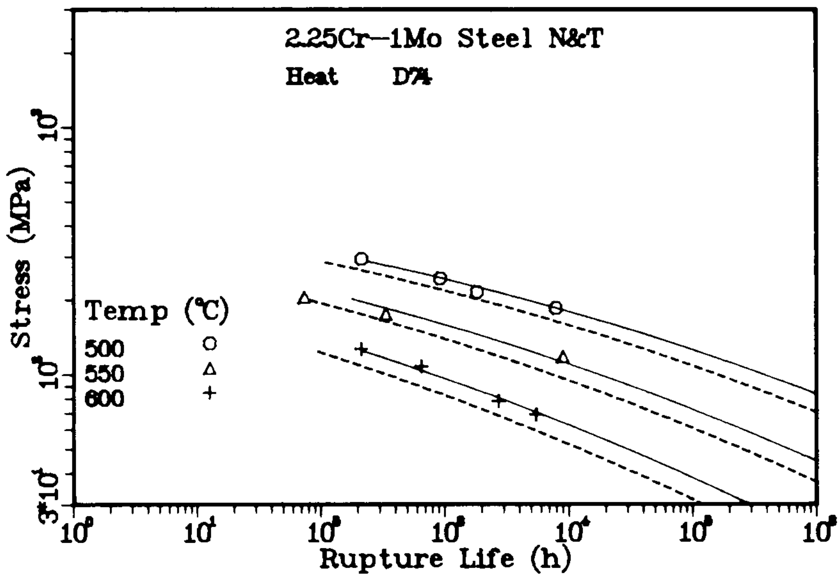

Fig. 9. Comparison of experimental data and predicted creep-rupture behavior for heat D74 of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

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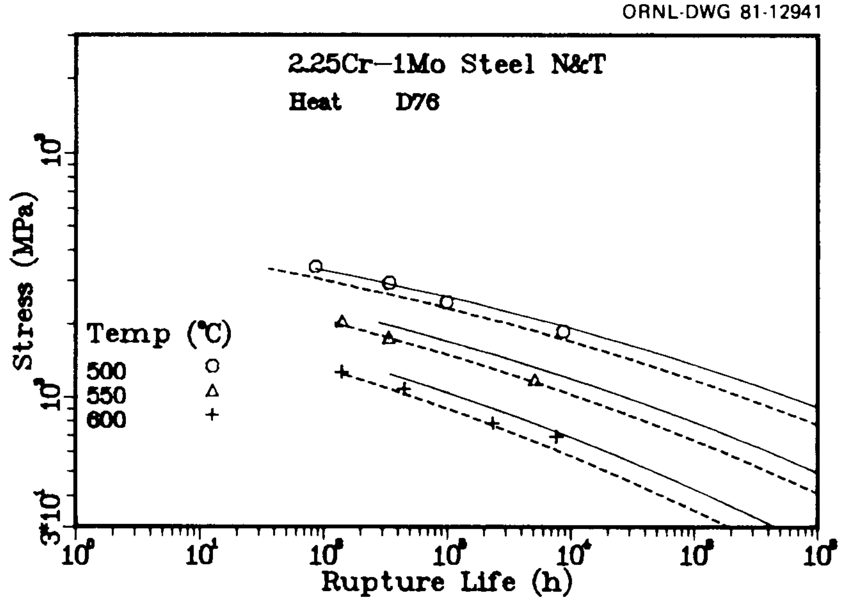

Fig. 10. Comparison of experimental data and predicted creep-rupture behavior for heat D76 of normalized and tempered 2 1/4 Cr-1 Mo steel. Solid lines represent average predicted behavior for this lot; dashed lines represent average minus 1.65 within-lot standard errors.

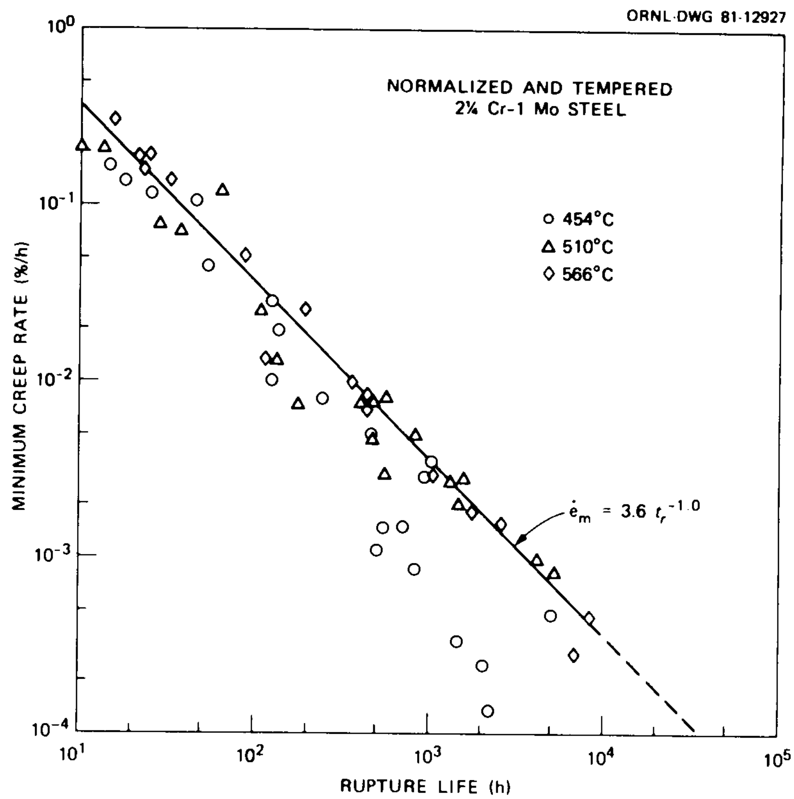

Fig. 11. Relationship between rupture life and minimum creep rate for normalized and tempered 2 1/4 Cr-1 Mo steel (four lots).

Figure 12 illustrates the relationship between the lot constant from Eq. (1) (and thus the creep rupture strength) and room-temperature UTS for individual lots. Creep strength tends to increase slightly with UTS, especially at the higher UTS levels, but the correlation is too weak to warrant estimation of different allowable stress levels for different UTS levels.

Figure 13 compares the lot constants for individual lots on the basis of national origin. Although some variations from country to country are seen, given the number of lots for which data are available (and given the ability of lot-centered regression to deal with strength variations) no reason is apparent why the data from different countries cannot be combined. The ASME normally has not used data from sources outside the U.S. in establishing allowable stresses. However, in the present case, addition of the foreign data makes a very important and substantial contribution to the available data base. Moreover, the U.S. data fall

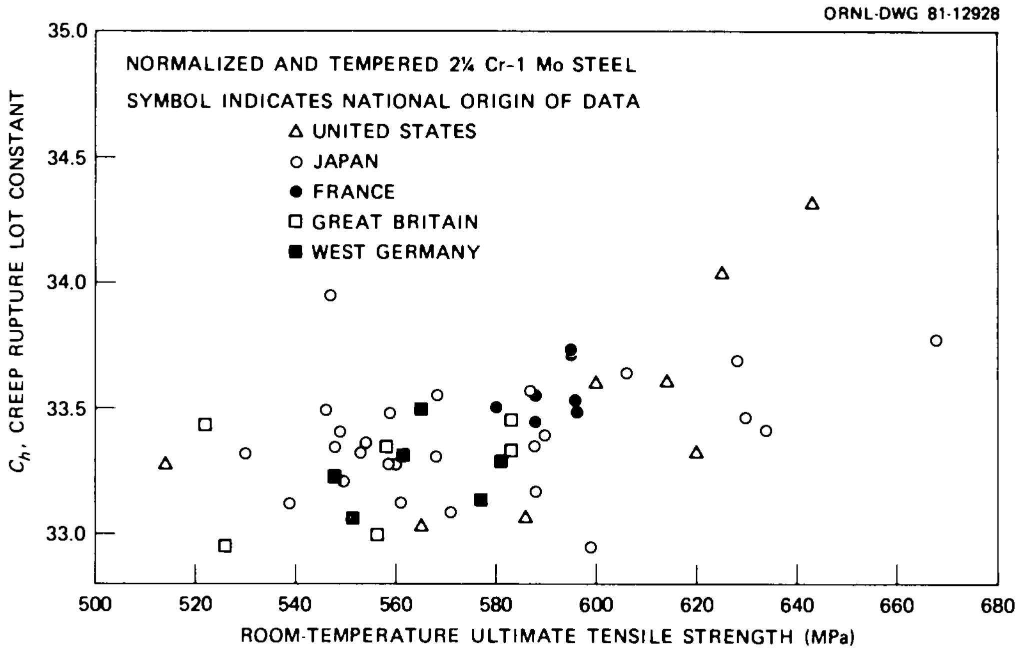

Fig. 12. Relationship between room-temperature ultimate tensile strength and creep-rupture lot constant for normalized and tempered 2 1/4 Cr-1 Mo steel.

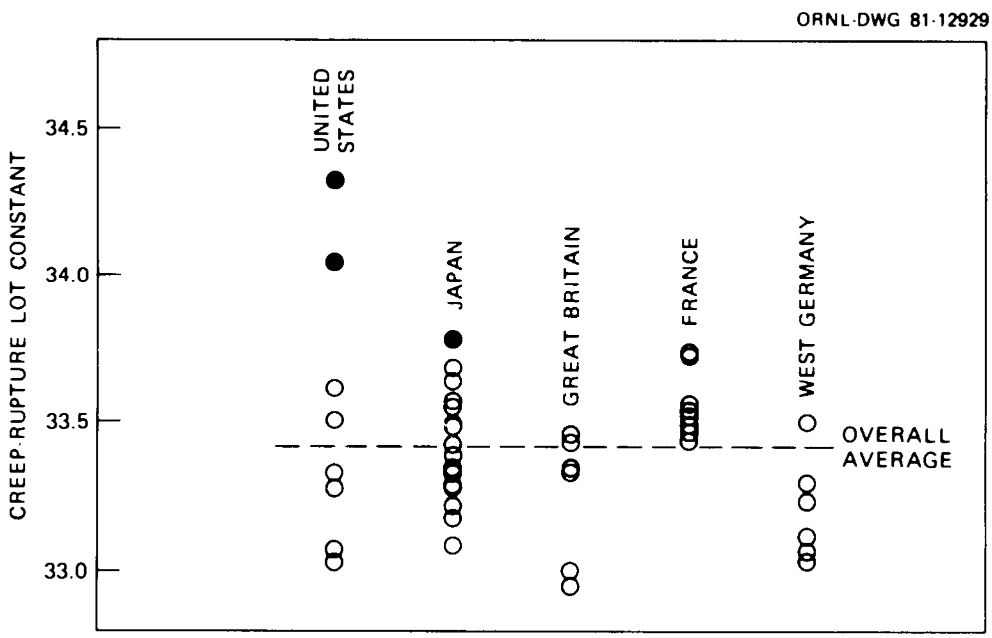

Fig. 13. Comparison of creep-rupture lot constants obtained from data of various national origins. Solid points indicate lots with room temperature UTS greater than 620 MPa.

approximately in the midrange of all the data, so the foreign data introduce no apparent bias toward either higher or lower allowable stresses. It appears advisable, then, to use the complete data base [as described by Eqs. (1) and (2)] for the estimation of allowable stresses. Table 3 summarizes the predicted creep-rupture and creep strengths needed for such estimation.

Table 3. Estimated creep and creep-rupture strengths of normalized and tempered 2 1/4 Cr-1 Mo steel

Temperature		10^5-h Creep-rupture strength, MPa (ksi)				10^{-5}%/h Average creep strength	
(°C)	(°F)	Average[a]	Minimum[b]	0.67 × Average	0.8 × Minimum	(MPa)	(ksi)
427	800	240 (34.7)	200 (29.1)	160 (23.2)	160 (23.3)	201	29.2
454	850	189 (27.4)	155 (22.5)	127 (18.4)	124 (18.0)	156	22.6
482	900	145 (21.0)	117 (16.9)	97 (14.0)	94 (13.5)	117	17.0
510	950	108 (15.7)	85 (12.4)	72 (10.5)	68 (9.9)	86	12.5
538	1000	79 (11.5)	61 (8.8)	53 (7.7)	49 (7.0)	61	8.9
566	1050	56 (8.2)	42 (6.2)	38 (5.5)	34 (5.0)	43	6.2

[a]Estimated from average lot constant.

[b]Estimated from a "minimum" lot constant given by the average minus 1.65 $\sqrt{V_B + V_w}$.

TENSILE DATA ANALYSIS

The available yield and tensile strength data were analyzed by lot-centered regression analysis of log strength as a function of temperature. This approach is very similar to the commonly used "ratio technique,"[14] and both methods involve the same assumptions[1] about the relative behavior of different heats (i.e., that plots of log strength against temperature for different heats are parallel). The advantages of the lot-centered regression technique are (1) more efficient use of available data, (2) less emphasis on room-temperature strength, and (3) greater ease of implementation by computer analysis.

The yield strength data summarized in Table 2 were described in this procedure by

$$\log \sigma_y = C_h - 6.435 \times 10^{-4}T + 1.948 \times 10^{-6}T^2 - 2.382 \times 10^{-9}T^3 \quad , \qquad (3)$$

where σ_y = 0.2% offset yield strength (MPa) and T = temperature (°C). Again C_h is a lot constant, now with an average value of 2.621, and R^2 = 81.6% for the fit to 302 data from 43 lots of material. The "between-lot" variance, V_B, was 0.00395 and "within-lot" variance, V_w, was 0.000422.

The ultimate tensile strength data were described by

$$\log \sigma_u = C_h - 1.102 \times 10^{-3}T + 4.704 \times 10^{-6}T^2 - 6.084 \times 10^{-9}T^3 , \quad (4)$$

where σ_u is the ultimate tensile strength and the other parameters are as in Eq. (3). The average value of C_h was 2.780, and R^2 = 88.4% for the fit to the same 302 data; V_B was 0.000706 and V_w was 0.000267.

Figures 14 and 15 illustrate the fits of the above equations to the overall data sets for these two properties, and Fig. 16 compares the

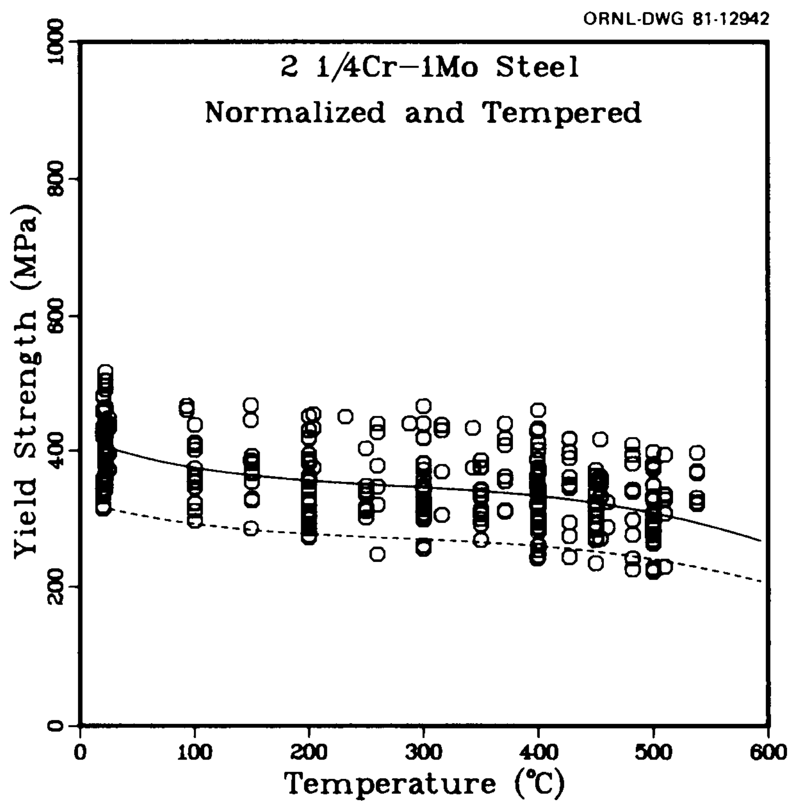

Fig. 14. Comparison of experimental data and predicted yield strength values. Solid lines represent average predicted behavior; dashed lines represent average minus 1.65 within-lot standard errors.

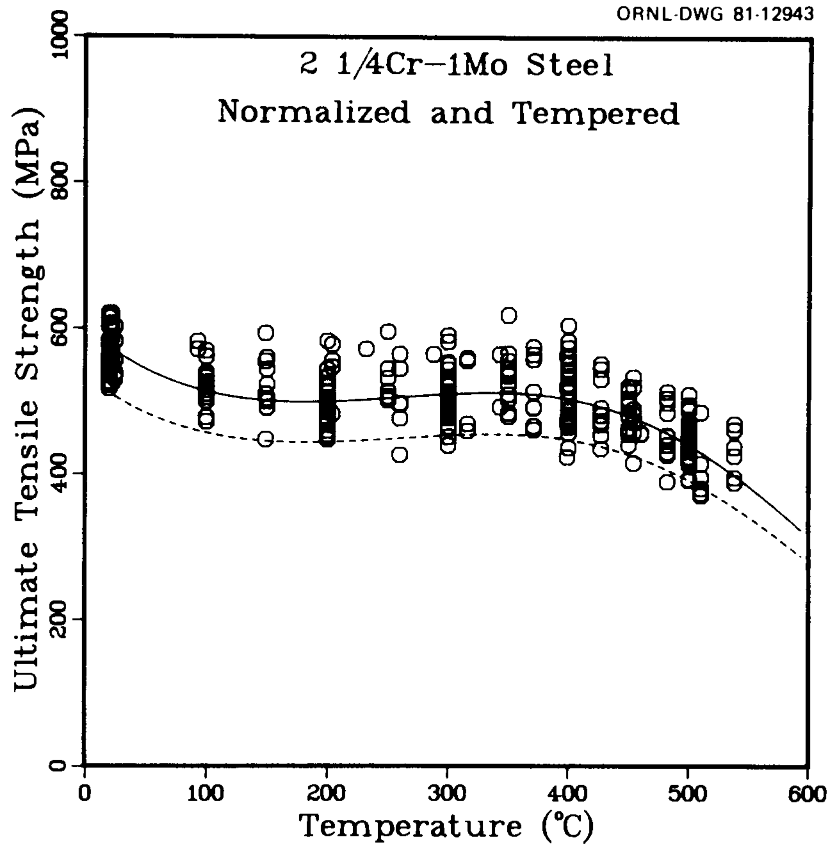

Fig. 15. Comparison of experimental data and predicted ultimate tensile strength values. Solid lines represent average predicted behavior; dashed lines represent average minus 1.65 within-lot standard errors.

individual lot constants obtained for the lots of various national origins. Again there is no apparent reason why the data from different countries should not be combined.

Table 4 summarizes the predicted yield and ultimate tensile strength values from the above analysis, both in terms of average behavior and in terms of "minimum" behavior. In this case, "minimum" is determined by normalizing the equations (though appropriate choice of lot constant) to the specification room-temperature values: 310 MPa (45 ksi) for yield strength and 517 MPa (75 ksi) for ultimate tensile strength.

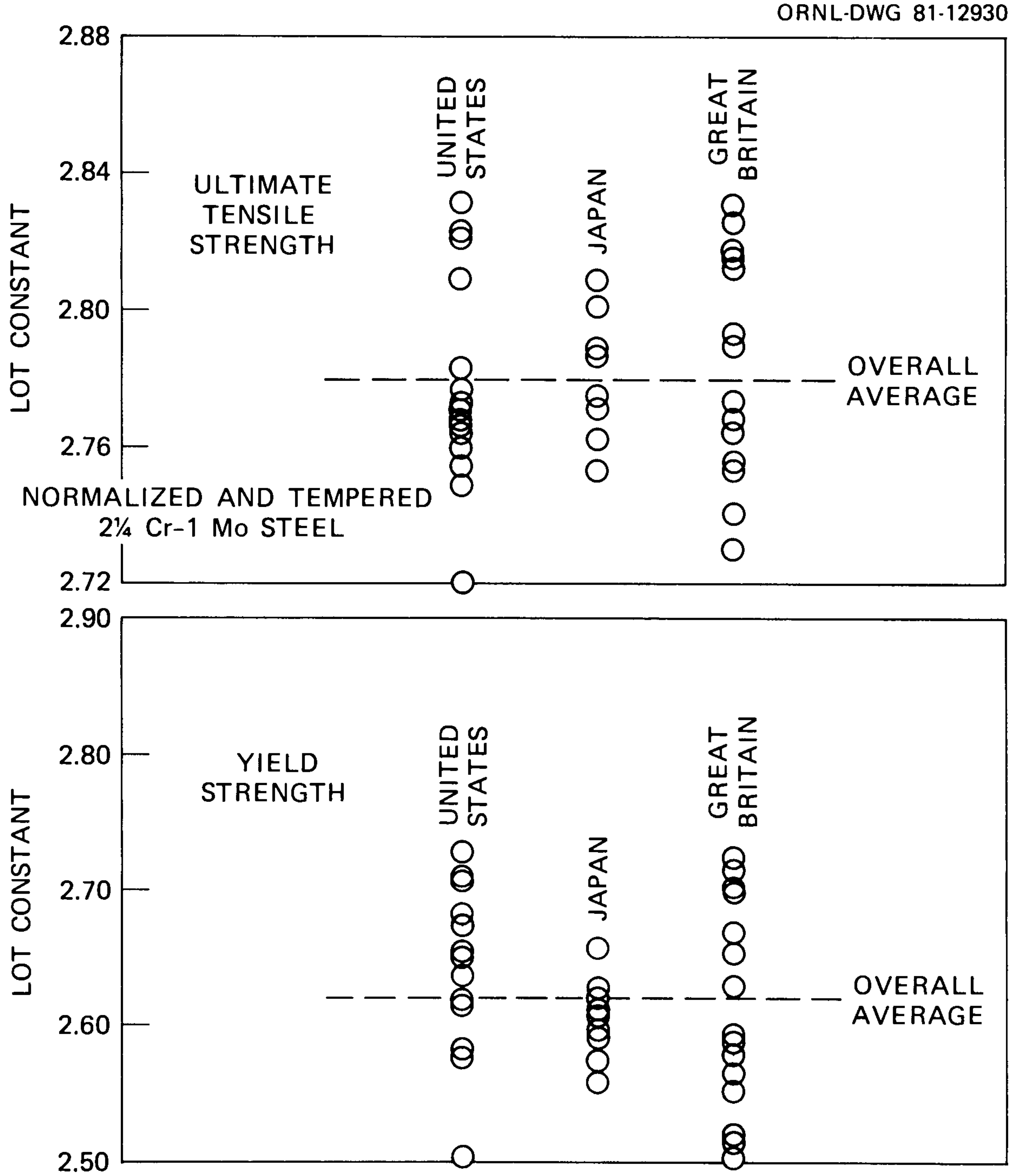

Fig. 16. Comparison of yield and ultimate tensile strength lot constants obtained from data of various national origins.

Table 4. Predicted values of yield and ultimate tensile strengths for normalized and tempered 2 1/4 Cr-1 Mo steel

Temperature		Yield strength, MPa (ksi)			Ultimate tensile strength, MPa (ksi)		
(°C)	(°F)	Average[a]	Minimum[b]	(2/3) × Minimum	Average[a]	Minimum[b]	1.1 × minimum/4
24	75	404 (58.6)	310 (45.0)	207 (30.0)	570 (82.7)	517 (75.0)	142 (20.6)
38	100	397 (57.6)	305 (44.2)	203 (29.4)	555 (80.5)	503 (73.0)	138 (20.0)
93	200	376 (54.5)	288 (41.8)	192 (27.8)	516 (74.8)	468 (67.9)	129 (18.7)
149	300	363 (52.6)	278 (40.3)	185 (26.8)	501 (72.7)	454 (65.8)	125 (18.1)
204	400	355 (51.5)	272 (39.4)	181 (26.2)	500 (72.5)	454 (65.8)	125 (18.1)
260	500	349 (50.6)	268 (38.9)	179 (26.0)	506 (73.4)	459 (66.6)	126 (18.3)[c]
316	600	344 (49.9)	264 (38.3)	176 (25.5)	512 (74.2)	464 (67.3)	128 (18.6)[c]
371	700	338 (49.0)	259 (37.6)	173 (25.1)	510 (74.0)	462 (67.0)	127 (18.4)[c]
427	800	328 (47.6)	252 (36.5)	168 (24.4)	493 (71.5)	447 (64.8)	123 (17.8)
454	850	321 (46.6)	246 (35.7)	164 (23.8)	478 (69.3)	434 (62.9)	119 (17.2)
482	900	314 (45.5)	241 (35.0)	161 (23.4)	457 (66.3)	414 (60.0)	114 (16.5)
510	950	304 (44.1)	233 (33.8)	155 (22.5)	430 (62.4)	390 (56.6)	107 (15.5)
538	1000	293 (42.5)	225 (32.6)	150 (21.8)	399 (57.9)	362 (52.5)	100 (14.5)
566	1050	281 (40.8)	216 (31.3)	144 (20.9)	363 (52.6)	329 (47.7)	90 (13.0)

[a]Estimated from average lot constant.

[b]Estimated by adjusting lot constant to yield specified minimum value at room temperature.

[c]Although these values in the range 260 to 371°C (500–700°F) exceed that at 204°C (400°F), current ASME practice does not allow one to take advantage of such a strength increase with temperature. Thus for allowable stress estimation these values were set at 125 MPa (18.1 ksi).

ALLOWABLE STRESSES

Table 5 compares the allowable stresses estimated by the rules described above from results given in Tables 3 and 4 with the allowable stresses currently given in ASME Code Section VIII, Division 1 (Table UCS-23) for 2 1/4 Cr-1 Mo plate material (SA-387). The Class 1 designation refers to material with room-temperature specified yield and tensile strengths of 207 MPa (30 ksi) and 414 MPa (60 ksi). The stresses for this material (usually annealed) are shown for comparison only. The

Table 5. Estimated allowable design stress values for normalized and tempered 2 1/4 Cr-1 Mo steel

Temperature		Allowable stress value, MPa (ksi)			
		Current ASME Code Section VIII, Division 1 for SA-387, Grade 22		Analysis[a]	Controlling criterion[b]
(°C)	(°F)	Class 1	Class 2		
24	75	103 (15.0)		129 (18.7)	1
38	100	103 (15.0)		129 (18.7)	1
93	200	103 (15.0)		129 (18.7)	1
149	300	103 (15.0)		125 (18.1)	2
204	400	103 (15.0)		125 (18.1)	2
260	500	103 (15.0)		125 (18.1)	2
316	600	103 (15.0)		125 (18.1)	2
371	700	103 (15.0)	118 (17.2)	125 (18.1)	2
427	800	103 (15.0)	116 (16.9)	123 (17.8)	2
454	850	99 (14.4)	113 (16.4)	119 (17.2)	2
482	900	90 (13.1)	109 (15.8)	94 (13.6)	3
510	950	76 (11.0)	76 (11.0)	68 (9.9)	3
538	1000	54 (7.8)	52 (7.6)	49 (7.1)	3
566	1050	40 (5.8)	40 (5.8)	34 (4.9)	3

[a]Estimated from our analysis. Note, however, that allowable stresses can only be established by the appropriate ASME Code bodies and that factors other than data (such as service experience) can influence those values.

[b]1 = one-fourth of the room-temperature ultimate tensile strength.

2 = 1.1 × one-fourth of the ultimate tensile strength at temperature.

3 = 80% of the minimum stress for rupture in 100,000 h.

Class 2 material more closely resembles that used here, having the same specified minimum room-temperature tensile properties, but the specification for that material does not include the 620 MPa (90 ksi) upper limit on room-temperature ultimate tensile strength.

The "allowable stresses" estimated in the current analysis (only the appropriate ASME Code bodies can actually set allowable stresses, of course) are controlled by the room-temperature tensile strength up to 93°C (200°F), by the ultimate tensile strength at temperature from 149 to 454°C (300–850°F), and by the minimum stress for rupture in 100,000 h from 482 to 566°C (900–1050°F). The temperature range limitations of the current data base did not allow estimation of allowable stresses at higher temperatures.

Section VIII, Division 1 of the Code does not tabulate allowable stresses for Class 2 material below 371°C (700°F). The stresses estimated from the current data base fall somewhat above those given in the Code for Class 1 material in this range, as expected. In the temperature range 371 through 454°C (700–850°F), where our estimates are still controlled by tensile properties, they exceed those given in the Code for both Class 1 and 2 material. However, for temperatures from 482 to 566°C (900–1050°F), where our estimates are controlled by creep-rupture properties, they fall below the Code values for Class 2 material in every case. In the range 510 to 566°C (950–1050°F), our values also fall below the Code values for Class 1 material (which in fact equal or exceed the values for Class 2 material in this range).

Several reasons can be postulated for the differences between our estimated allowable stress values and those currently given in the Code. These include the following.

1. The ASME Code bodies responsible for setting allowable stresses give consideration (rightfully) to factors (such as service experience) other than test data when determining the levels of those stresses. Conceivably, such information was used in establishing the values for this material (or at least can be used to justify those values now after several years of use). Details concerning use of such information are not immediately available, however, and it is beyond the scope of our analysis

to seek them out. (Our purpose is not to question the Code values. We merely seek to obtain the most accurate possible analysis of the best available set of test data.)

2. The ASME Code generally excludes foreign data from consideration in setting allowable stresses. Therefore, our use of data from several countries could have biased our results. Comparisons such as that shown in Fig. 13, however, seem to indicate that no such bias exists.

3. Since the material specifications employed for setting allowable stresses for the Code included no upper limit on strength their stresses for Class 2 material could have been increased (relative to the present estimate) by the influence of very strong (in terms of room-temperature tensile properties) lots of material. Again, however, no information regarding this possibility is currently available. Still, the fact that allowable stresses for Class 2 material are equal to or below those for Class 1 material seems to indicate that such an effect would not be large if it existed at all. As for the Class 1 (annealed) material, another recent study[15] has indicated that such material in the temperature range 500 to 600°C may exhibit long-term rupture strength that is superior to that of Class 2 (normalized and tempered) material.

4. The Code generally defines minimum in terms of average minus 1.65 "standard deviations" in log stress. The present method is similar in concept, except that minimum behavior is predicted by using an offset of 1.65 standard errors ($V_B + V_W$) in log time. The current definition of standard error is felt to be more meaningful than the "standard deviation" used by ASME, since the present definition recognizes directly that variability occurs both from within-lot and between-lot sources and partitions the variance accordingly, whereas the definition used by ASME does not. The ASME definition implies a constant ratio between minimum and average stress for a given rupture life, so that the ratio of minimum to average rupture life for a given stress typically increases at higher temperatures. Our method implies a constant ratio of minimum to average rupture life for a given stress, so that the ratio of minimum to average stress for a given rupture life typically decreases at higher temperatures. As a result, the present method becomes more and more conservative relative to the Code method as temperatures increase. Part of the difference

between the Code values for allowable stress and our estimates can be traced to this source. However, as can be seen from Table 3, our estimates would still be below the Code values under some conditions even if they were based on average behavior only.

5. Because the Code values were set several years ago, and because no foreign data were employed, the data base used in setting the Code stresses was considerably smaller than that used here, and the longest rupture times available for that analysis were far shorter than those available in our analysis. Moreover, the analysis techniques available at the time of the Code analysis were certainly less sophisticated than those used here. Thus, our estimates may actually be simply more accurate than those given in the Code. Service experience based on the Code stresses has apparently been good, however, so there is no immediate indication that those stresses are nonconservative. Still, the possibility that better data bases and more modern analytical techniques can result in changes in allowable stress estimates made from test data only is emphasized by Table 6. Here, the Code Section VIII, Division 1 allowable stress values and our estimated values are compared with 80% of the minimum stress to rupture in 10^5 h for Class 1 material as given in Code Case N-47 to Section III of the ASME Code. The Code Case N-47 analysis was

Table 6. Comparison of allowable stress criteria for 2 1/4 Cr-1 Mo steel from four sources

Temperature		Allowable stress, MPa (ksi)			
		Current ASME Code Section VIII, Division 1 allowable stresses for SA-387, Grade 22		80% of Minimum stress to rupture	
(°C)	(°F)	Class 1	Class 2	From ASME Code Case Case N-47[a]	From present analysis
482	900	90 (13.1)	109 (15.8)	90 (13.1)	94 (13.6)
510	950	76 (11.0)	76 (11.0)	70 (10.1)	68 (9.9)
538	1000	54 (7.8)	52 (7.6)	52 (7.5)	49 (7.1)
566	1050	40 (5.8)	40 (5.8)	39 (5.6)	34 (4.9)

[a]For material comparable to Class 1 from Section VIII, Division 1.

taken directly from Smith[8] and was performed more recently than the Section VIII analysis, presumably with a better data base. The N-47 values also fall below the corresponding (Class 1) Section VIII values in the temperature range 510 to 566°C (950–1050°F).

In conclusion, we see no reason to believe that the results of our analysis are overly conservative, even though our estimated allowable stress values fall below those currently given in Section VIII, Division 1 of the ASME Code for either Class 1 or 2 SA-387 Grade 22 material in the creep range.

SUMMARY AND CONCLUSIONS

Available data for normalized and tempered 2 1/4 Cr-1 Mo steel were collected from American, Japanese, British, French, and German sources. The primary selection criteria for including data from a given lot of material in the collection were that the room-temperature yield strength exceed 310 MPa (45 ksi) and that the room-temperature ultimate tensile strength be in the range 517 to 620 MPa (75–90 ksi). Creep data obtained at temperatures from 427 to 600°C (800–1112°F) were included, and tensile data from room temperature to 550°C (1022°F) were used. Properties examined included yield strength, ultimate tensile strength, 10^5-h creep rupture strength, and 10^{-5}%/h creep strength, because these are the properties used in setting allowable stresses for Section VIII, Division 1 of the *ASME Boiler and Pressure Vessel Code*. The data were analyzed by using lot-centered regression approaches that yielded analytical expressions for the variations in the various properties and as well accounted for lot-to-lot variations in properties. Specific conclusions from these analyses follow.

1. Systematic differences in properties for data from the five different countries were not clearly indicated for any of the properties examined.

2. Creep-rupture strength appeared to be only weakly correlated with room-temperature ultimate tensile strength, and then only in the upper range of the tensile strengths examined.

3. Our estimated allowable stresses were controlled by ultimate tensile strength in the range from room temperature through 454°C (850°F) and by creep-rupture strength from 482 to 566°C (900–1050°F). The data used were not felt to be appropriate for estimating allowables stresses at higher temperatures.

4. The estimated allowable stresses obtained from our analysis fell slightly below those currently given in Section VIII, Division 1 of the Code for either annealed or normalized and tempered 2 1/4 Cr-1 Mo steel. Several possible reasons were cited for the differences, and we concluded that our results are not overly conservative. On the other hand, there is no direct evidence that the current Code allowable stresses are insufficiently conservative, since those stresses rely on factors (such as service experience) in addition to experimental data. Analysis of experimental data alone indicates that consideration should be given to lowering the Code allowable stresses, but these additional factors (which were not considered in this investigation) may indicate otherwise.

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Appendix A

LOT-CENTERED REGRESSION ANALYSIS

Tensile Data

Yield and tensile strength are often expressed as simple polynomial functions of temperature:

$$\hat{S} = \sum_{i=0}^{N} b_i T^i \ , \tag{A1}$$

where

$\hat{S}$ = the predicted yield or tensile strength,

T = temperature, and

b_i = constants whose values are estimated by regression or other techniques.

In essence, the ratio technique involves an implicit assumption that different heats display parallel curves of log strength versus temperature. As a first step toward implementing this assumption in a direct data fit, Eq. (A1) can be rewritten as

$$\widehat{\log S} = \sum_{i=0}^{N} b'_i T^i \ . \tag{A2}$$

This equation is not equivalent to Eq. (A1) but would be expected to describe the data equally well.

Next, one employs a technique of centering the data for each lot, as has been reported for creep data by Sjodahl.[1] The equation thus becomes

$$\widehat{\log S_{hj}} - \overline{\log S_h} = \sum_{i=1}^{N} b'_i \left(T^i_{hj} - \overline{T^i_h} \right) \ , \tag{A3}$$

where the barred symbols represent average values of each variable for each lot. The index i again refers to the power of temperature, j refers to the particular test, and h refers to the particular lot. Equation (A3) can be arranged as

$$\widehat{\log S_{hj}} = \overline{\log S_h} + \sum_{i=1}^{N} b_i' T_{hj}^i - \sum_{i=1}^{N} b_i' \overline{T_h^i} \, , \qquad \text{(A4)}$$

or as

$$\widehat{\log S_{hj}} = \left(\overline{\log S_h} - \sum_{i=1}^{N} b_i' \overline{T_h^i} \right) + \sum_{i=1}^{N} b_i' T_{hj}^i \, . \qquad \text{(A5)}$$

Note that the quantity in parentheses is a constant (C_h) for a given lot. The other term on the right side of the equation is a function of temperature but not of lot. Thus, a fit of Eq. (A3) to the available data will yield for the different lots predictions that are parallel in log S versus T but have different intercept values. These intercept values are determined by a regression fit to all data, not merely by the room-temperature strength as in the ratio technique. In fact, lots for which no room-temperature data at all are available can be included in the lot-centered analysis. Such lots would, of course, have to be excluded from the ratio analysis. Note that since each lot has its own intercept, no explicit intercept term is required in the model in Eq. (A3).

If the assumption of log S versus T parallelism is not met, plots of strength ratio against temperature emphasize effects that cause the lack of parallelism. Likewise, residual plots of $(\log S - \widehat{\log S})$ against T from the above regression technique will point up such effects (log S is the log observed strength, $\widehat{\log S}$ is the log predicted strength). The regression technique can be used to determine a statistically defined average or minimum curve (see below), or these predictions can be keyed to room-temperature values as in the ratio technique. Thus, the technique presented here includes all the advantages of the ratio technique but avoids its major disadvantages. However, this technique is suited only to computer analysis — not to manual analysis.

Creep Data

First assume that the logarithm of rupture life ($\log t_r$)* has been chosen as the dependent variable for the analysis. Label $\log t_r$ as Y. Now assume that Y can be expressed as a linear function (in the regression sense) of terms involving stress (σ) and temperature (T). Label these terms as X_i. In general form we thus have

$$\hat{Y}_K = \sum_{i=0}^{N} a_i X_{iK} , \tag{A6}$$

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

As the next step, each variable (Y and all X) is "lot centered," and the equation becomes

$$\hat{Y}_{Kh} - \overline{Y}_h = \sum_{i=1}^{N} a_i'(X_{iKh} - \overline{X}_{ih}) , \tag{A7}$$

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

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*The debate that has sometimes arisen over this choice is not central to the results obtained and will not be discussed here. The authors frankly do not feel that there is any legitimate question over the choice of dependent variable in this context.

$$\hat{Y}_{Kh} = \overline{Y}_h - \sum_{i=1}^{N} \hat{a_i}\overline{X}_{ih} + \sum_{i=1}^{N} \hat{a_i} X_{iKh} \; . \qquad \text{(A8)}$$

The quantity $\hat{Y}_h - \sum_{i=1}^{N} \hat{a_i}\overline{X}_{ih}$ is a constant for a given heat and replaces the intercept term a_0 in the uncentered analysis. Thus, each lot will have a different intercept term, but all other coefficients $\hat{a_i}$ will be common to all lots. (There is no separate $\hat{a_0}$ term, because it would be superfluous.)

Lot centering the data involves no complicated mathematics and can be done by anyone who can add, subtract, and divide. However, for large data sets these simple operations can become quite tedious, and the centering is best done by computer. Implications of lot centering are also straightforward, although a first glance at Eq. (A8) can leave one lost in a maze of variables and subscripts.

As pointed out above, different lots are treated as having different intercept values, but all other equation constants are lot-independent. Thus, all lots vary similarly with the independent variable, but any two lots will always be separated by a constant increment in log t_r space. This assumption of parallelism may or may not be a good one in any given case.

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

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

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

The analyst makes several decisions along the way, but all actual computations are performed by machine. The final result is a single equation with perhaps three or four regression constants.

Calculation of Average and Minimum Strength by Regression on Lot-Centered Data

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

First, return to Eq. (A7),

$$\hat{Y}_{Kh} - \overline{Y}_h = \sum_{i=1}^{N} a_i'(X_{iKh} - \overline{X}_{ih}) \ . \tag{A7}$$

Here the barred variables represent simple arithmetic average values for a given lot of index h. The index i refers to the term in the model and K to the particular datum within lot h. Equation (A7) is fit to the data as written, with $Y_{Kh} - \overline{Y}_h$ as the dependent variable, where Y_{Kh} is the experimental value of log t_r. However, because $\overline{Y}_h$ is a known constant for a given lot, all the error in prediction is in the estimation of $\hat{Y}_{Kh}$. Thus, when Eq. (A7) is fit to data by least squares and the a_i' are determined, the total "error" in fitting the model can be described by a residual sum of squares RSS, given by

$$\text{RSS} = \sum_{h=1}^{H} \sum_{K=1}^{M} (\hat{Y}_{Kh} - Y_{Kh})^2 \ . \tag{A9}$$

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

$$df = n - N - H \ , \tag{A10}$$

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

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

$$V_w = \text{RSS}/df \ . \tag{A11}$$

Equation (A7) can now be transformed to Eq. (A8),

$$\hat{Y}_{Kh} = \overline{Y}_h - \sum_{i=1}^{N} a_i' \overline{X}_{ih} + \sum_{i=1}^{N} a_i' X_{iKh} \tag{A8}$$

or

$$\hat{Y}_{Kh} = C_h + \sum_{i=1}^{N} a_i' X_{ikH} \, , \tag{A12}$$

where the differences in behavior of different lots are now explicitly defined in terms of the lot constants C_h, where

$$C_h = \overline{Y}_h - \sum_{i=1}^{N} a_i' \overline{X}_{ih} \, . \tag{A13}$$

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

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

A possible solution comes from the work of Mandel and Paule,[3] who studied variations in behavior caused by measurements of chemical variables at different laboratories. After Sjodahl,[1] we extrapolate Mandel's lab-to-lab variation results to our lot-to-lot variation data. Following this approach, we find that the C_h for each lot should be given a weight w_h of

$$w_h = k_h/(k_h\lambda + 1) \ , \tag{A14}$$

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

$$\overline{C}_h = \sum_{h=1}^{H} C_h w_h / \sum_{h=1}^{H} w_h \ . \tag{A15}$$

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

Mandel and Paule[3] present an iterative technique, which does indeed result in a solution for both $\overline{C}_h$ and V_B. Our experiment is that results are obtained typically after only three or four iterations. Sjodahl[1] has reported similar quick convergence to a solution. The result is probably the most fairly weighted estimate of average behavior obtainable by any technique proposed to this point.

Note also that by the direct separation of the variability into its two components V_B and V_w, this method also yields better estimates of error than could be obtained by estimates of error that are a mixture of within-lot and between-lot variability, with no clear meaning. Because variance estimation is central to the estimation of any statistical limit, regression on lot-centered data thus also opens the way for superior techniques to estimate these limits.

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Appendix B

DATA LISTING

This appendix presents computer printouts of the following:

Characterization of Lots of 2 1/4 Cr-1 Mo Steel

Chemical Composition of Lots of 2 1/4 Cr-1 Mo Steel

Tensile Data

Creep Data

CHARACTERIZATION OF LOTS OF 2 1/4CR-1MO STEEL

LOT	*HEAT TREATMENT	PRODUCT FORM	PRODUCT SIZE (MM)	SOURCE CODE
075	N(925C,0.5H),T(775C,0.5H)	TUBE	3680DX23	IRSID-FRA
12A	N(930C,2H),T(750C,2H)	ROUND	25	ISI97,131
12B	N(1030C,2H),T(750C,2H)	ROUND	25	ISI97,131
13B	N(950C,30MIN)AC,T(750C,2H)AC	SQUARE	20X20	ISI97,131
20	N(940C,20MIN),T(750C,40MIN)			ISI97,131
2C	N(910C,20MIN),T(750C,1H)	SQUARE	20	ISI97,131
35E2135	N(920C,6H),T(700C,8H),FC+PWHT	FORGING	200	JSW
40K205	N(920C),T(750C)	PLATE	48	JSW
40K210	N(920C),T(750C)	PLATE	48	JSW
40K220	N(920C),T(750C)	PLATE	48	JSW
43K830	920C,10H,675C,16H,675C,16H	FORGING	187	JSW
44K2158	N(920C,1.5H),T(730C,1.5H)	PLATE	25	JSW
45K2436	920C,8H,660,8H,620,62H,695,27H	PLATE	166	JSW
45K2643	900C,8H,660,9H,620,62H,695,27H	PLATE	166	JSW
45K2653	910C,8H,660,7H,620,62H,695,27H	PLATE	166	JSW
45K3088H	930C,5H,630C,2H,665C,30H	FORGING	200	JSW
6D165	920C,7H,650,7H,620,62H,685,27H	PLATE	163	JSW
7A	N(975C,5H),T(760C,12H)	TUBE	3550DX40	ISI97,131
A7095	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
A7554	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
A7959	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
A8001	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
BS-104		FORGING		BSCC
BS-105	N(950C),T(700C)	FORGING		BSCC
BS-109	N(1025C),T(675C)	BAR	25	BSCC
BS-113	N(1025C),T(675C)	FORG.BLOOM		BSCC
BS-116	N(1025C),T(675C)	FORGED HDR		BSCC

* T=TEMPERED; N=NORMALIZED; FC=FURNACE COOLED;
AC=AIR COOLED; PWHT=POSTWELD HEAT TREATMENT

CHARACTERIZATION OF LOTS OF 2 1/4CR-1MO STEEL

LOT	*HEAT TREATMENT	PRODUCT FORM	PRODUCT SIZE (MM)	SOURCE CODE
BS-123	N(900/960C),T(700C)	TUBE	0-10	BSCC
BS-124	N(900/960C),T(700C)	TUBE	0-10	BSCC
BS-138	N(900/960C),T(690C)	TUBE	25.5	BSCC
BS-139	N(900/960C),T(690C)	TUBE	25.5	BSCC
BS-142	N(960C),T(690C)	TUBE	50.7	BSCC
BS-155	N(950C,1H),T(680C,2H)	BAR	22	BSCC
BS-158	N(9506,1H),T(680C,2H)	BAR	19	BSCC
BS-162	N(950C,1H),T(680C,2H)	BAR	19	BSCC
BS-25	N(920/950C),T(750C)	TUBE	7.6	BSCC
BS-31	N(940C),T(700C,4H)	TUBE	104	BSCC
BS-38	N(920/950C),T(750C)	TUBE	7.5	BSCC
BS-41	N(920/950C),T(750C)	TUBE	8.7	BSCC
BS-42	N(920/950C),T(750C)	TUBE	9.5	BSCC
BS-48	N(920/950C),T(750C)	TUBE	7	BSCC
BS-50	N(1020C),T(675C,14H)	TUBE	38.1	BSCC
D73718	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
D73967	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
D73992	N(920C,10MIN),T(720C,45MIN)	TUBE	600D X 8	SUMITOMO
D74	N(925C,0.5H),T(775C,0.5H)	TUBE	2730D X 18	IRSID-FRA
D76	N(925C,0.5H),T(775C,0.5H)	TUBE		IRSID-FRA
D77	N(925C,0.5H),T(775C,0.5H)	TUBE		IRSID-FRA
D78	N(925C,0.5H),T(775C,0.5H)	TUBE		IRSID-FRA
D79	N(925C,0.5H),T(775C,0.5H)	TUBE		IRSID-FRA
D80	N(925C,0.5H),T(775C,0.5H)	TUBE		IRSID-FRA
F63	N(980C),T(725C,4H)	TUBE FORG.		IRSID-FRA
KB-151	N(927C,1H),AC,T(704C,1H)	ROD	22	ORNL-4922
MAB	930C,1H,AC+740C,2H,AC+700C,4	PLATE	72	NRIM 11A

* T=TEMPERED; N=NORMALIZED; FC=FURNACE COOLED;
AC=AIR COOLED; PWHT=POSTWELD HEAT TREATMENT

CHARACTERIZATION OF LOTS OF 2 1/4CR-1MO STEEL

LOT	*HEAT TREATMENT	PRODUCT FORM	PRODUCT SIZE (MM)	SOURCE CODE
MAC	930C,1H,AC+740C,2H,AC+700C,4	PLATE	100	NRIM 11A
MAD	930C,1H,AC+750C,2H,AC+700C,2.5	PLATE	62	NRIM 11A
MAE	920C,3.5H,AC+720C,5H,AC+710C,5	PLATE	63	NRIM 11A
MAF	920C,6H,AC+740C,8H,AC+720C,8H	PLATE	108	NRIM 11A
P-108	N(940C),T(704C)	PLATE	51	DS6S2
P-11	N(927C),T(718C),T(690C)	PLATE	105	DS6S2
P-12	N(927C),T(718C),T(690C)	PLATE	105	DS6S2
P-15E	Q(954C),A(718C)	PLATE	102	DS6S2
P-25	N(954C),T(704C)	PLATE	152	DS6S2
P-27	N(927C),T(704C)	PLATE	159	DS6S2
P-28	N(954C),T(704C)	PLATE	159	DS6S2
P-31A	N(954C),T(738C)	PLATE	159	DS6S2
P-31B	N(954C),T(771C)	PLATE	159	DS6S2
P-42	Q(968C),T(571C),T(690C,15H)	PLATE	190	DS6S2
P-45	Q(954C),T(732C)	PLATE	190	DS6S2
P-51	Q(954C),T(704C)	PLATE		DS6S2
P-9A	N(940C),T(677C)	PLATE	25	DS6S2
P-9B	N(940C),T(704C)	PLATE	25	DS6S2
PR20205A	920C,6H,650C,6H,690C,25H	PLATE	20	JSW
PR20205B	920C,6H,650C,6H,690C,25H	PLATE	20	JSW
PR20205C	920C,6H,650C,6H,690C,25H	PLATE	20	JSW
SH/FR	920C,10H,660C,7H,690C,24H	FORGING	149	JSW

* T=TEMPERED; N=NORMALIZED; FC=FURNACE COOLED;
AC=AIR COOLED; PWHT=POSTWELD HEAT TREATMENT

CHEMICAL COMPOSITION OF LOTS OF 2 1/4CR-1MO STEEL
CONTENT, WT. %

LOT	C	MN	P	S	SI	CR	NI	MO	CU	AL	N
13B	.10	.45	.013	.015	.35	2.37	.007	1.04	.13		
20	.11	.48	.021	.01	.25	2.43		.98			
--BAR--											
BS-109	.12	.48	.010	.023	.27	2.10	.32	1.01			
BS-155	.11	.47	.012	.016	.13	2.38	.19	.97	.10		
BS-158	.09	.43	.015	.034	.14	2.26	.18	.94	.15		
BS-162	.09	.53	.012	.018	.16	2.29	.26	.95	.14		
--FORGED BLM--											
BS-113	.12	.47	.013	.020	.20	2.44	.18	.90	.11		
--FORGED HDR--											
BS-116	.12	.47	.012	.018	.25	2.38	.15	.90	.11		
--FORGING--											
35E213	.14	.50	.013	.007	.28	2.37		1.05			
5											
43K830	.15	.56	.014	.013	.28	2.37		1.01			
45K308	.13	.49	.009	.006	.26	2.31		.96			
8H											
BS-104	.13	.38	.022	.026	.20	2.29	.09	1.08	.09		
BS-105	.15	.51	.019	.025	.28	2.37	.22	1.06	.10		
SH/FR	.14	.54	.013	.009	.14	2.48		1.04			
--PLATE--											
40K205	.11	.42	.019	.011	.25	2.12		.98			
40K210	.11	.46	.015	.016	.27	2.12		.97			
40K220	.13	.48	.013	.015	.26	2.18		.96			
44K215	.09	.58	.013	.011	.22	2.12		.90			
8											
45K243	.15	.53	.010	.007	.28	2.30	.28	1.00			
6											
45K264	.15	.56	.010	.007	.28	2.35	.28	1.02			
3											
45K265	.15	.58	.007	.008	.29	2.33		1.02			
3											
6D165	.14	.56	.010	.007	.22	2.28		1.00			
MAB	.12	.48	.013	.006	.26	2.00	.08	.96	.08	.014	.0096
MAC	.12	.48	.015	.007	.29	.220	.05	.99	.07	.017	.0095
MAD	.13	.44	.017	.010	.30	2.37	.09	.91	.05	.017	.0108
MAE	.15	.61	.015	.015	.27	2.35	.32	.96	.02	.012	.0086
MAF	.15	.63	.015	.016	.18	2.23	.24	.97	.20	.010	.0083
P-108	.14	.41	.010	.022	.24	2.48		.98			
P-11	.12	.41	.010	.017	.21	2.18		.95			
P-12	.13	.42	.017	.020	.27	2.29		.91			
P-15E	.15	.40	.013	.020	.32	2.39	.23	.96	.25	.018	
P-25	.14	.47	.007	.015	.40	2.40		1.02			
P-27	.13	.43	.008	.015	.34	2.38	.22	1.08			
P-28	.12	.45			.40	2.25		1.00			
P-31A	.14	.54			.42	2.44	.23	1.02			
P-31B	.14	.54			.42	2.44	.23	1.02			
--PLATE--											
P-42	.12	.43	.010	.018	.26	2.34	.20	.98			
P-45	.14	.51	.013	.016	.27	2.27		.96			
P-51	.14	.42	.010	.022	.15	2.21		.92			
P-9A	.13	.57	.010	.020	.19	2.42		.90			
P-9B	.13	.57	.010	.020	.19	2.42		.90			
PR2020	.16	.51	.014	.019	.24	2.40		.97			
5A											
PR2020	.16	.61	.016	.021	.30	2.40		.97			
5B											
PR2020	.16	.73	.011	.017	.47	2.40		1.00			
5C											
--ROD--											
KB-151	.12	.44	.0096	.015	.40	2.20	.21	.91			
--ROUND--											
12A	.11	.54			.25	2.52		1.05			
12B	.11	.54			.25	2.52		1.05			
--SQUARE--											
2C	.12	.45	.013	.011	.56	2.39		.89			.008

CHEMICAL COMPOSITION OF LOTS OF 2 1/4CR-1MO STEEL
CONTENT, WT. %

LOT	C	MN	P	S	SI	CR	NI	MO	CU	AL	N
--TUBE--											
075	.10	.475	.013	.018	.36	3.30	.10	.965	.135		
7A	.15	.57	.018	.016	.41	2.31	<.15	1.09	.16		.009
A7095	.10	.47	.018	.012	.36	2.16		.92	.12	.002	.0106
--TUBE--											
A7554	.12	.50	.019	.012	.40	2.10		.91	.09	.002	.0112
A7959	.14	.50	.020	.008	.33	2.30		.99	.10	.001	.0126
A8001	.11	.49	.022	.010	.35	2.01		.91	.10	.003	.0100
BS-123	.12	.53	.019	.018	.21	2.28	.13	.99	.19		
BS-124	.11	.45	.018	.012	.16	2.05	.11	1.02	.15		
BS-138	.13	.53	.018	.015	.16	2.08	.14	1.03	.09		
BS-139	.16	.59	.018	.011	.25	2.26	.06	1.01	.09		
BS-142	.15	.52	.024	.023	.18	1.05		1.05			
BS-25	.08	.46	.014	.013	.31	2.28	.19	.98	.13		
BS-31	.12	.52	.028	.036	.24	2.24	.29	1.07	.15		
BS-38	.11	.53	.013	.017	.30	2.30	.16	1.03	.13		
BS-41	.11	.53	.020	.014	.30	2.24	.24	.96	.10		
BS-42	.11	.45	.011	.017	.20	2.40	.18	.97	.12		
BS-48	.12	.52	.016	.012	.35	2.27	.22	1.02	.16		
BS-50	.10	.45	.020	.020	.26	2.28	.23	1.02	.11		
D73718	.11	.51	.011	.008	.42	2.17		.95	.10	.002	.0098
D73967	.11	.43	.012	.007	.44	2.12		.99	.10	.002	.0116
D73992	.11	.48	.010	.007	.36	2.26		.94	.09		.0106
D74	.075	.39	.013	.012	.365	2.02	.14	.945	.085		
D76	.075	.42	.012	.011	.395	2.39	.10	.96	.120		
D77	.095	.41	.012	.015	.33	2.30	.08	1.00	.120		
D78	.105	.445	.012	.011	.41	2.25	.08	.87	.105		
D79	.095	.475	.014	.014	.425	2.15	.085	1.04	.115		
D80	.105	.46	.013	.012	.42	2.08	.085	1.01	.110		
--TUBE FRGNG--											
F63	.12	.45	.016	.006	.20	2.38		.91			

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
MAB	22.	392.0	559.0	27.00	78.00
MAB	100.	353.0	500.0	26.00	79.00
MAB	200.	343.0	470.0	23.00	78.00
MAB	300.	382.0	490.0	19.00	75.00
MAB	400.	343.0	470.0	21.00	74.00
MAB	450.	314.0	441.0	21.00	75.00
MAB	500.	294.0	392.0	28.00	78.00
MAC	22.	441.0	588.0	23.00	76.00
MAC	100.	412.0	539.0	22.00	77.00
MAC	200.	382.0	500.0	20.00	76.00
MAC	300.	372.0	480.0	18.00	75.00
MAC	400.	372.0	480.0	18.00	71.00
MAC	450.	353.0	461.0	20.00	74.00
MAC	500.	333.0	421.0	22.00	77.00
MAF	22.	363.0	549.0	27.00	70.00
MAF	100.	353.0	510.0	26.00	73.00
MAF	200.	343.0	490.0	24.00	71.00
MAF	300.	343.0	490.0	20.00	66.00
MAF	400.	333.0	490.0	20.00	62.00
MAF	450.	314.0	461.0	21.00	63.00
MAF	500.	294.0	392.0	24.00	67.00
P-11	22.	343.0	523.0	30.00	75.00
P-11	149.	285.0	448.0	28.00	79.00
P-11	260.	247.0	427.0	29.00	78.00
P-11	399.	241.0	424.0	25.00	74.00
P-11	427.	243.0	436.0	24.00	70.00
P-11	454.	416.0	416.0	25.00	71.00
P-11	482.	225.0	390.0	26.00	76.00
P-11	510.	229.0	374.0	29.00	79.00
P-12	22.	462.0	586.0	30.00	75.00
P-12	149.	385.0	510.0	24.00	72.00
P-12	260.	378.0	496.0	22.00	65.00
P-12	343.	375.0	493.0	22.00	69.00
P-12	399.	349.0	472.0	22.00	69.00
P-12	427.	361.0	469.0	22.00	69.00
P-12	454.	358.0	458.0	22.00	71.00
P-12	482.	343.0	431.0	23.00	73.00
P-12	510.	336.0	415.0	24.00	74.00
P-25	25.	372.0	530.0	29.00	
P-25	316.	305.0	470.0	23.00	73.00
P-25	371.	311.0	492.0		72.00
P-25	427.	274.0	470.0	24.00	72.00
P-25	482.	298.0	454.0	24.00	76.00
P-27	149.	467.0	594.0	22.00	70.00
P-27	204.	454.0	578.0	21.00	71.00
P-27	232.	450.0	572.0	20.00	70.00
P-27	260.	440.0	565.0	21.00	69.00
P-27	288.	440.0	565.0	21.00	68.00

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
P-27	316.	430.0	556.0	21.00	71.00
P-27	343.	434.0	565.0	20.00	66.00
P-27	371.	440.0	575.0	20.00	66.00
P-27	399.	429.0	563.0	20.00	66.00
P-27	427.	417.0	545.0	21.00	68.00
P-27	454.	417.0	534.0	21.00	64.00
P-27	482.	409.0	499.0	23.00	72.00
P-27	510.	394.0	486.0	23.00	75.00
P-27	538.	397.0	462.0	24.00	76.00
P-28	25.	434.0	538.0	26.00	73.00
P-28	371.	312.0	467.0	21.00	70.00
P-42	22.	490.0	615.0	24.00	66.00
P-42	427.	398.0	482.0	19.50	65.00
P-42	538.	367.0	389.0	22.50	65.00
P-45	22.	496.0	620.0	29.00	76.00
P-45	93.	466.0	582.0	29.00	78.00
P-45	204.	454.0	556.0	25.00	75.00
P-45	316.	438.0	560.0	22.00	72.00
P-45	371.	408.0	558.0	23.00	69.00
P-45	427.	389.0	531.0	23.00	72.00
P-45	482.	381.0	505.0	24.00	73.00
P-45	538.	331.0	438.0	28.00	76.00
P-51	22.	418.0	565.0	28.00	72.00
P-51	204.	375.0	483.0	23.00	71.00
P-51	316.	369.0	460.0	21.00	69.00
P-51	371.	362.0	462.0	21.00	66.00
P-51	427.	350.0	454.0	21.00	68.00
P-51	482.	339.0	427.0	21.00	69.00
P-51	538.	324.0	396.0	24.00	72.00
P-9A	22.	516.0	620.0	28.00	72.00
P-9A	399.	387.0	472.0	21.00	73.00
P-9A	454.	350.0	473.0	22.00	71.00
P-9A	510.	328.0	396.0	26.00	76.00
P-9B	22.	464.0	597.0	29.00	72.00
P-9B	399.	321.0	474.0	23.00	68.00
P-9B	454.	332.0	483.0	24.00	71.00
P-9B	510.	307.0	371.0	30.00	76.00
A7095	22.	379.0	559.0	34.00	75.00
A7095	100.	355.0	523.0	31.70	79.80
A7095	150.	327.0	500.0	30.70	78.20
A7095	200.	324.0	496.0	27.30	76.60
A7095	250.	316.0	507.0	25.00	76.60
A7095	300.	327.0	526.0	20.00	73.30
A7095	350.	331.0	540.0	23.30	71.60
A7095	400.	304.0	523.0	25.70	69.80
A7095	450.	303.0	497.0	28.70	73.30
A7095	500.	307.0	457.0	30.00	76.60
A7554	22.	412.0	587.0	31.30	75.00

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
A7554	100.	401.0	561.0	27.70	79.80
A7554	150.	381.0	544.0	30.70	78.20
A7554	200.	362.0	533.0	25.00	76.60
A7554	250.	348.0	545.0	25.00	76.60
A7554	300.	346.0	551.0	22.30	71.60
A7554	350.	334.0	566.0	24.30	71.60
A7554	400.	335.0	551.0	25.70	69.70
A7554	450.	324.0	515.0	29.00	73.30
A7554	500.	308.0	461.0	32.00	78.20
A8001	22.	386.0	546.0	33.70	76.60
A8001	100.	361.0	515.0	30.00	79.80
A8001	150.	354.0	504.0	31.30	78.20
A8001	200.	341.0	498.0	28.30	78.20
A8001	250.	335.0	514.0	22.70	75.00
A8001	300.	316.0	531.0	21.00	73.30
A8001	350.	313.0	545.0	24.30	71.60
A8001	400.	299.0	524.0	26.70	71.60
A8001	450.	292.0	497.0	27.70	73.30
A8001	500.	276.0	453.0	31.30	76.60
BS-25	20.	332.0	526.0	30.00	
BS-25	200.	275.0	449.0	26.00	
BS-25	300.	255.0	452.0	26.00	
BS-25	400.	245.0	466.0	26.00	
BS-25	500.	227.0	419.0	29.00	
BS-31	20.	460.0	583.0	24.00	
BS-31	200.	419.0	520.0	20.00	
BS-31	300.	418.0	514.0	21.00	
BS-31	400.	401.0	514.0	18.00	
BS-31	500.	376.0	457.0	24.00	
BS-38	20.	357.0	556.0	26.00	
BS-38	200.	299.0	477.0	26.00	
BS-38	300.	306.0	478.0	24.00	
BS-38	400.	294.0	488.0	24.00	
BS-38	500.	277.0	445.0	25.00	
BS-42	20.	314.0	558.0	27.00	
BS-42	200.	324.0	489.0	25.00	
BS-42	300.	329.0	510.0	20.00	
BS-42	400.	332.0	544.0	21.00	
BS-42	500.	327.0	496.0	24.00	
BS-48	20.	318.0	522.0	27.00	
BS-48	200.	272.0	512.0	22.00	
BS-48	300.	255.0	591.0	17.00	
BS-48	400.	260.0	605.0	21.00	
BS-48	500.	263.0	510.0	24.00	
BS-50	20.	457.0	560.0	21.00	
BS-50	200.	430.0	505.0	19.00	
BS-50	300.	419.0	494.0	18.00	
BS-50	400.	412.0	502.0	20.00	

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
BS-50	500.	373.0	432.0	21.00	
P-10B	22.	503.0	570.0	27.00	73.00
P-10B	399.	362.0	520.0	22.00	69.00
P-10B	454.	356.0	490.0	20.00	65.00
P-10B	510.	334.0	381.0	25.00	78.00
P-15E	25.	448.0	602.0	29.00	71.00
P-15E	454.	361.0	520.0	23.00	63.00
P-15E	482.	341.0	485.0	23.00	65.00
P-15E	538.	321.0	426.0	25.00	70.00
P-31A	25.	439.0	582.0	26.00	72.00
P-31A	260.	347.0	498.0	25.00	70.00
P-31A	371.	355.0	514.0	22.00	65.00
P-31A	427.	345.0	492.0	23.00	65.00
P-31A	460.	324.0	456.0	23.00	71.00
P-31A	482.	241.0	453.0	24.00	71.00
P-31B	25.	396.0	556.0	29.00	72.00
P-31B	260.	320.0	477.0	27.00	71.00
P-31B	371.	310.0	493.0	26.00	65.00
P-31B	427.	294.0	474.0	23.00	62.00
P-31B	460.	287.0	457.0	26.00	66.00
P-31B	482.	276.0	441.0	25.00	70.00
P-32B	22.	490.0	606.0	25.00	63.00
P-32B	93.	460.0	571.0	23.00	63.00
P-32B	149.	445.0	555.0	21.00	60.00
P-32B	204.	433.0	547.0	21.00	59.00
P-32B	260.	427.0	545.0	21.00	60.00
P-32B	316.	438.0	557.0	18.00	57.00
P-32B	371.	418.0	565.0	20.00	56.00
P-32B	427.	418.0	552.0	18.00	53.00
P-32B	482.	394.0	514.0	17.00	58.00
P-32B	538.	370.0	470.0	18.00	59.00
BS-104	20.	430.0	577.0	14.00	
BS-104	100.	408.0	526.0		
BS-104	200.	394.0	489.0		
BS-104	300.	381.0	480.0		
BS-104	350.	386.0	480.0		
BS-104	400.	375.0	477.0		
BS-104	450.	372.0	456.0		
BS-104	500.	349.0	416.0		
BS-105	20.	434.0	583.0	22.00	
BS-105	100.	409.0	536.0	18.00	
BS-105	200.	387.0	500.0	17.00	
BS-105	300.	381.0	486.0	15.00	
BS-105	350.	376.0	485.0	14.00	
BS-105	400.	368.0	477.0	14.00	
BS-105	450.	363.0	464.0	15.00	
BS-105	500.	349.0	414.0	16.00	
BS-109	20.	421.0	620.0	26.00	

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
BS-109	150.	392.0	560.0	22.00	
BS-109	250.	403.0	596.0	21.00	
BS-109	350.	375.0	619.0	25.00	
BS-109	400.	346.0	574.0	25.00	
BS-109	450.	338.0	521.0	28.00	
BS-113	20.	426.0	572.0	21.00	
BS-113	150.	368.0	491.0	18.00	
BS-113	200.	354.0	472.0	17.00	
BS-113	300.	357.0	464.0		
BS-113	400.	338.0	457.0	15.00	
BS-116	20.	343.0	542.0		
BS-116	200.	289.0	448.0	17.00	
BS-116	300.	304.0	440.0	15.00	
BS-116	400.	287.0	437.0	15.00	
BS-116	500.	266.0	394.0	18.00	
BS-123	20.	344.0	517.0	27.00	
BS-123	200.	328.0	451.0	22.00	
BS-123	300.	344.0	502.0	17.00	
BS-123	400.	318.0	523.0	13.00	
BS-123	500.	285.0	466.0	14.00	
BS-124	20.	480.0	617.0	20.00	
BS-124	200.	418.0	544.0	18.00	
BS-124	300.	440.0	528.0	13.00	
BS-124	400.	433.0	553.0	15.00	
BS-124	500.	398.0	489.0	15.00	
BS-138	20.	339.0	620.0	22.00	
BS-138	200.	307.0	544.0	19.00	
BS-138	300.	298.0	554.0	16.00	
BS-138	400.	281.0	560.0	20.00	
BS-138	500.	268.0	473.0		
BS-139	20.	350.0	602.0	28.00	
BS-139	200.	323.0	524.0		
BS-139	300.	318.0	521.0	22.00	
BS-139	400.	321.0	523.0	22.00	
BS-139	500.	285.0	435.0	28.00	
BS-142	20.	481.0	614.0	23.00	
BS-142	100.	438.0	569.0	20.00	
BS-142	200.	451.0	583.0	16.00	
BS-142	300.	466.0	582.0	14.00	
BS-142	400.	460.0	583.0	10.00	
BS-142	500.	381.0	492.0	16.00	
BS-155	20.	358.0	547.0	26.00	
BS-155	100.	296.0	478.0	28.00	
BS-155	200.	321.0	489.0	24.00	
BS-155	300.	314.0	491.0	20.00	
BS-155	350.	341.0	503.0	17.00	
BS-155	400.	281.0	478.0	20.00	
BS-155	450.	321.0	483.0	21.00	

2 1/4CR-1MO STEEL
TENSILE DATA

LOT NUMBER	TEMPERATURE (C)	YIELD STRENGTH (MPA)	ULTIMATE TENSILE STRENGTH (MPA)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
BS-155	500.	293.0	434.0	22.00	
BS-158	20.	357.0	535.0	28.00	
BS-158	100.	311.0	472.0	28.00	
BS-158	200.	285.0	454.0	24.00	
BS-158	300.	260.0	466.0	21.00	
BS-158	350.	268.0	480.0	20.00	
BS-158	400.	253.0	472.0	19.00	
BS-158	450.	234.0	461.0	22.00	
BS-158	500.	222.0	424.0	24.00	
BS-162	100.	322.0	478.0	27.00	
BS-162	200.	307.0	460.0	27.00	
BS-162	300.	321.0	497.0	21.00	
BS-162	350.	306.0	510.0	20.00	
BS-162	400.	260.0	478.0	20.00	
BS-162	450.	268.0	460.0	23.00	
BS-162	500.	290.0	449.0	21.00	
D73718	22.	355.0	548.0	36.00	76.60
D73718	100.	323.0	505.0	32.70	81.20
D73718	150.	326.0	492.0	30.00	79.80
D73718	200.	311.0	486.0	28.70	79.80
D73718	250.	301.0	502.0	26.70	78.20
D73718	300.	299.0	508.0	23.30	75.00
D73718	350.	291.0	524.0	25.70	73.30
D73718	400.	284.0	514.0	25.70	69.80
D73718	450.	272.0	481.0	29.70	75.00
D73718	500.	263.0	441.0	33.00	78.20
D73967	22.	364.0	553.0	35.00	76.60
D73967	100.	346.0	522.0	31.00	81.20
D73967	150.	329.0	504.0	30.00	79.80
D73967	200.	322.0	499.0	28.30	78.20
D73967	250.	311.0	505.0	25.00	76.60
D73967	300.	307.0	523.0	23.00	75.00
D73967	350.	299.0	536.0	24.30	73.30
D73967	400.	284.0	525.0	26.70	69.80
D73967	450.	284.0	498.0	28.70	73.30
D73967	500.	276.0	454.0	31.70	78.20
D73992	22.	401.0	568.0	33.70	75.00
D73992	100.	374.0	532.0	30.70	76.60
D73992	150.	366.0	523.0	29.00	78.20
D73992	200.	359.0	523.0	25.00	76.60
D73992	250.	341.0	532.0	22.70	75.00
D73992	300.	347.0	544.0	20.70	71.60
D73992	350.	343.0	556.0	23.30	69.80
D73992	400.	332.0	535.0	23.30	69.80
D73992	450.	305.0	504.0	28.00	71.60
D73992	500.	304.0	464.0	28.00	78.20

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
20	500	196.0	5236.		16.50	85.00
20	500	216.0	5376.		18.60	88.00
20	500	245.0	1980.		13.60	83.00
20	550	98.0	14316.		17.00	90.00
20	550	118.0	3686.		19.60	87.00
20	550	147.0	795.		23.30	90.00
20	550	176.0	408.		22.80	87.00
2C	550	98.0	11734.		51.60	86.00
2C	550	137.0	544.		35.00	84.00
2C	550	216.0	114.		58.30	85.00
7A	500	157.0	4972.		57.40	78.90
7A	500	196.0	1064.		56.60	79.80
7A	500	246.0	250.		50.90	71.50
7A	500	309.0	41.		47.80	64.90
7A	500	344.0	14.		41.80	63.20
7A	550	98.0	6202.		61.00	80.40
7A	550	122.0	1864.		66.80	81.90
7A	550	157.0	346.		66.80	80.50
7A	550	196.0	146.		62.00	73.20
7A	575	78.0	6942.		58.10	83.30
7A	575	98.0	1446.		68.40	81.90
7A	575	122.0	558.		74.00	86.50
7A	575	157.0	122.		54.50	84.00
7A	575	245.0	10.		54.90	77.40
12A	550	69.0	30128.		59.70	76.30
12A	550	78.0	15612.		71.30	80.50
12A	550	88.0	11275.		63.10	83.40
12A	550	102.0	5978.		75.80	83.50
12A	550	118.0	3876.		68.00	68.70
12A	550	132.0	1335.		80.00	86.20
12A	550	147.0	993.		81.20	79.80
12A	550	176.0	329.		71.20	75.20
12A	550	206.0	170.		61.50	72.70
12A	600	34.0	32291.		57.80	83.40
12A	600	41.0	24868.		75.30	79.50
12A	600	49.0	15271.		64.00	78.90
12A	600	59.0	6229.		79.40	84.30
12A	600	69.0	2297.		81.30	86.80
12A	600	78.0	1341.		86.00	88.20
12A	600	88.0	766.		65.00	61.70
12A	600	137.0	18.		86.00	90.50
12B	550	83.0	16047.		71.20	80.00
12B	550	98.0	5765.		75.80	84.40
12B	550	118.0	3536.		80.30	86.00
12B	550	137.0	1558.		81.80	87.20
12B	550	157.0	656.		99.00	87.80
12B	550	176.0	231.		71.30	86.80
12B	600	36.0	39606.		44.40	74.20
12B	600	43.0	21482.		42.40	67.40
12B	600	49.0	17019.		52.10	72.10
12B	600	59.0	6344.		65.00	80.30
12B	600	69.0	2228.		80.40	87.00
12B	600	78.0	1273.		87.90	86.90
12B	600	88.0	908.		61.30	84.40
12B	600	137.0	18.		80.30	90.20

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
13B	500	167.0	14328.		23.00	84.60
13B	500	196.0	3888.		23.00	84.00
13B	500	235.0	1512.		19.50	83.70
13B	500	294.0	315.		14.00	78.00
13B	550	88.0	18144.		23.50	87.00
13B	550	108.0	4059.		31.00	86.30
13B	550	137.0	1056.		38.50	88.50
13B	550	176.0	200.		36.50	86.30
13B	600	49.0	11758.		17.00	87.00
13B	600	59.0	7392.		29.50	91.60
13B	600	69.0	3104.		36.00	92.20
13B	600	88.0	727.		49.00	91.00
13B	600	118.0	201.		37.00	89.10
D74	500	186.0	7820.			
D74	500	216.0	1801.			
D74	500	245.0	913.			
D74	500	294.0	211.			
D74	550	118.0	8911.			
D74	550	176.0	332.			
D74	550	206.0	73.			
D74	600	69.0	5422.			
D74	600	78.0	2699.			
D74	600	108.0	644.			
D74	600	127.0	210.			
D76	500	186.0	8672.			
D76	500	245.0	986.			
D76	500	294.0	340.			
D76	500	343.0	86.			
D76	550	118.0	5105.			
D76	550	176.0	336.			
D76	550	206.0	141.			
D76	600	69.0	7678.			
D76	600	78.0	2336.			
D76	600	108.0	448.			
D76	600	127.0	140.			
D77	500	225.0	3098.			
D77	500	294.0	548.			
D77	500	343.0	296.			
D77	500	392.0	47.			
D77	550	137.0	2793.			
D77	550	176.0	660.			
D77	550	235.0	55.			
D77	600	69.0	5668.			
D77	600	78.0	2959.			
D77	600	108.0	533.			
D77	600	127.0	274.			
D77	600	147.0	78.			
D78	500	176.0	5656.			
D78	500	196.0	4472.			
D78	500	245.0	1550.			
D78	500	294.0	409.			
D78	500	343.0	107.			
D78	550	108.0	6120.			
D78	550	118.0	3448.			
D78	550	147.0	916.			

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
D78	550	176.0	293.			
D78	550	206.0	94.			
D78	600	69.0	6342.			
D78	600	78.0	3163.			
D78	600	108.0	340.			
D78	600	127.0	105.			
D79	500	196.0	6106.			
D79	500	245.0	1478.			
D79	500	294.0	588.			
D79	500	343.0	189.			
D79	550	108.0	6636.			
D79	550	137.0	1525.			
D79	550	176.0	288.			
D79	550	206.0	105.			
D79	600	69.0	4239.			
D79	600	78.0	2560.			
D79	600	108.0	313.			
D79	600	127.0	100.			
D80	500	196.0	5461.			
D80	500	245.0	1451.			
D80	500	294.0	665.			
D80	500	343.0	191.			
D80	550	108.0	7440.			
D80	550	147.0	1043.			
D80	550	176.0	297.			
D80	550	206.0	148.			
D80	600	69.0	7718.			
D80	600	78.0	2973.			
D80	600	108.0	355.			
D80	600	127.0	98.			
F63	550	176.0	716.			
F63	550	196.0	304.			
F63	550	235.0	34.			
F63	600	88.0	3425.			
F63	600	108.0	958.			
F63	600	127.0	736.			
MAB	500	137.0	28837.		36.00	85.00
MAB	500	157.0	9734.		58.00	87.00
MAB	500	176.0	4333.		55.00	90.00
MAB	500	216.0	909.		38.00	65.00
MAB	500	265.0	104.		49.00	89.00
MAB	550	98.0	24661.		37.00	84.00
MAB	550	108.0	14197.		45.00	84.00
MAB	550	137.0	1322.		73.00	90.00
MAB	550	176.0	164.		49.00	89.00
MAB	600	53.0	16964.		36.00	90.00
MAB	600	61.0	9765.		38.00	90.00
MAB	600	69.0	5221.		56.00	91.00
MAB	600	78.0	2401.		47.00	91.00
MAB	600	98.0	909.		60.00	83.00
MAB	600	137.0	129.		65.00	90.00
MAC	500	157.0	17706.		32.00	87.00
MAC	500	176.0	4946.		37.00	86.00
MAC	500	216.0	1277.		34.00	84.00

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
MAC	500	265.0	130.		29.00	82.00
MAC	550	98.0	17124.		31.00	85.00
MAC	550	108.0	10741.		32.00	86.00
MAC	550	137.0	1845.		35.00	87.00
MAC	550	176.0	223.		44.00	88.00
MAC	600	53.0	18912.		45.00	88.00
MAC	600	61.0	10083.		36.00	89.00
MAC	600	69.0	5027.		52.00	92.00
MAC	600	78.0	2708.		38.00	90.00
MAC	600	98.0	1229.		41.00	88.00
MAC	600	137.0	72.		36.00	89.00
MAD	500	216.0	2804.		45.00	83.00
MAD	500	265.0	562.		32.00	82.00
MAD	500	294.0	168.		34.00	81.00
MAD	550	98.0	29944.		22.00	54.00
MAD	550	108.0	20015.		23.00	64.00
MAD	550	137.0	6627.		31.00	67.00
MAD	550	176.0	890.		34.00	80.00
MAD	550	216.0	159.		58.00	85.00
MAD	600	53.0	18313.		25.00	60.00
MAD	600	61.0	11382.		36.00	65.00
MAD	600	69.0	6222.		36.00	73.00
MAD	600	78.0	3371.		34.00	79.00
MAD	600	98.0	1610.		58.00	84.00
MAD	600	137.0	353.		41.00	80.00
MAE	500	216.0	7311.		39.00	71.00
MAE	500	265.0	701.		40.00	80.00
MAE	500	294.0	262.		34.00	77.00
MAE	550	98.0	26173.		29.00	55.00
MAE	550	108.0	16785.		24.00	62.00
MAE	550	137.0	7251.		21.00	48.00
MAE	550	176.0	1748.		31.00	59.00
MAE	550	216.0	225.		50.00	85.00
MAE	600	53.0	26175.		22.00	53.00
MAE	600	61.0	12501.		21.00	55.00
MAE	600	69.0	7308.		32.00	49.00
MAE	600	78.0	3355.		53.00	71.00
MAE	600	98.0	1579.		39.00	72.00
MAE	600	137.0	450.		46.00	61.00
MAF	500	157.0	14475.		40.00	82.00
MAF	500	176.0	6377.		48.00	82.00
MAF	500	216.0	1066.		50.00	80.00
MAF	500	265.0	265.		36.00	77.00
MAF	500	294.0	57.		29.00	74.00
MAF	550	98.0	24515.		48.00	82.00
MAF	550	108.0	13098.		39.00	83.00
MAF	550	137.0	1618.		50.00	85.00
MAF	550	176.0	267.		45.00	82.00
MAF	600	53.0	23523.		27.00	71.00
MAF	600	61.0	14367.		38.00	80.00
MAF	600	69.0	7635.		38.00	84.00
MAF	600	78.0	3827.		37.00	85.00
MAF	600	98.0	919.		53.00	88.00
MAF	600	137.0	83.		70.00	85.00
P-12	454	331.0	1010.	.360E-02		

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
P-12	454	352.0	482.	.520E-02		
P-12	454	379.0	124.	.282E-01		
P-12	454	400.0	46.	.11E+00		
P-12	454	420.0	26.	.12E+00		
P-12	482	269.0	1464.	.200E-02		
P-12	482	276.0	439.	.470E-02		
P-12	482	290.0	584.	.830E-02		
P-12	482	310.0	64.	.12E+00		
P-12	482	345.0	10.	.21E+00		
P-42	427	345.0	5059.	.470E-03	28.00	73.00
P-42	427	379.0	968.	.290E-02	29.00	72.00
P-42	482	241.0	5075.	.830E-03	35.00	68.00
P-42	482	276.0	1303.	.280E-02	37.00	74.00
P-42	538	172.0	8227.	.470E-03	23.00	48.00
P-42	538	241.0	115.	.360E-01	34.00	77.00
P-42	538	276.0	23.	.15E+00	34.00	75.00
P-45	427	414.0	1495.		18.00	78.00
P-45	427	483.0	32.		20.00	72.00
P-45	482	379.0	41.		18.00	77.00
20017	454	379.0	2218.	.133E-03	9.90	73.00
20017	454	393.0	2016.	.240E-03	9.80	69.70
20017	454	407.0	1484.	.330E-03	18.50	67.50
20017	454	441.0	831.	.860E-03	20.10	76.50
20017	454	448.0	513.	.110E-02	20.00	73.30
20017	454	455.0	542.	.150E-02	18.40	78.20
20017	454	482.0	125.	.100E-01	16.80	72.50
20017	454	517.0	54.	.450E-01	18.40	74.90
20017	454	544.0	14.	.17E+00	18.00	74.90
20017	510	241.0	4134.	.100E-02	19.40	40.70
20017	510	276.0	1559.	.290E-02	20.80	65.30
20017	510	310.0	416.	.750E-02	26.40	79.90
20017	510	324.0	428.	.800E-02	25.10	82.70
20017	510	345.0	130.	.130E-01	27.20	80.80
20017	510	379.0	37.	.700E-01	23.20	77.70
20017	510	407.0	29.	.770E-01	22.40	79.90
20017	566	124.0	6945.	.290E-03	7.00	24.30
20017	566	152.0	1747.	.185E-02	10.00	23.20
20017	566	172.0	1021.	.300E-02	15.20	39.10
20017	566	207.0	362.	.100E-01	15.70	37.80
20017	566	207.0	437.	.840E-02	14.80	42.40
20017	566	241.0	86.	.520E-01	22.10	74.40
20017	566	276.0	15.	.30E+00	21.00	84.90
20017	566	276.0	22.	.19E+00	23.10	84.50
6D165	450	260.0	8115.			
6D165	450	260.0	9239.			
A7095	500	196.0	4708.		46.70	80.00
A7095	500	226.0	1156.		51.70	83.30
A7095	500	265.0	301.		50.30	84.00
A7095	500	294.0	123.		46.70	81.90
A7095	550	137.0	3016.		33.30	70.60
A7095	550	156.0	1115.		44.70	79.10
A7095	550	176.0	410.		52.00	81.90
A7095	550	196.0	116.		80.30	86.00
A7095	600	69.0	4717.		22.30	70.30
A7095	600	88.0	2112.		36.70	78.50

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
A7095	600	108.0	750.		44.70	78.00
A7095	600	128.0	248.		40.70	78.60
A7095	600	147.0	99.		49.00	85.20
A7554	500	167.0	18230.		33.00	70.60
A7554	500	196.0	5446.		40.00	75.20
A7554	500	226.0	1918.		51.30	82.50
A7554	500	265.0	483.		48.40	83.00
A7554	500	294.0	182.		56.70	83.50
A7554	500	343.0	29.		41.00	82.80
A7554	550	108.0	12377.		18.30	54.00
A7554	550	137.0	3416.		46.30	70.00
A7554	550	156.0	1258.		60.00	78.50
A7554	550	176.0	563.		54.00	81.50
A7554	600	69.0	7958.		29.70	68.80
A7554	600	88.0	2282.		44.30	77.40
A7554	600	108.0	744.		47.80	77.90
A7554	600	108.0	884.		58.70	76.90
A7554	600	128.0	296.		49.70	78.60
A7554	600	147.0	94.		51.30	82.90
A8001	500	196.0	6367.		39.00	79.20
A8001	500	226.0	2100.		57.00	83.30
A8001	500	265.0	416.		46.00	82.30
A8001	500	294.0	154.		41.30	82.00
A8001	550	137.0	2574.		36.30	76.10
A8001	550	156.0	852.		61.00	82.00
A8001	550	176.0	302.		70.70	84.70
A8001	550	196.0	101.		55.70	86.80
A8001	600	69.0	6277.		15.30	66.30
A8001	600	88.0	2166.		40.70	76.30
A8001	600	108.0	701.		53.70	79.60
A8001	600	128.0	212.		55.70	84.30
A8001	600	147.0	66.		56.70	86.80
BS-25	500	239.0	262.		47.00	81.50
BS-25	550	131.0	1060.		44.40	82.40
BS-25	550	193.0	63.		62.30	84.60
BS-25	600	70.0	1685.		27.40	79.00
BS-31	500	239.0	968.		28.70	82.70
BS-31	550	131.0	2445.		31.70	77.40
BS-31	600	70.0	2562.		32.70	79.00
BS-38	500	239.0	420.		43.30	81.90
BS-38	550	131.0	1467.		41.20	83.30
BS-38	550	193.0	35.		48.70	87.60
BS-38	600	70.0	2097.		32.70	89.00
BS-41	500	239.0	5121.		33.20	75.70
BS-41	550	131.0	1472.		36.70	83.20
BS-41	550	193.0	215.		51.10	84.60
BS-41	600	70.0	1931.		29.30	89.10
BS-42	500	239.0	1650.		34.70	83.30
BS-42	550	131.0	1902.		39.40	86.40
BS-42	550	193.0	144.		37.60	85.50
BS-42	600	70.0	2389.		40.10	91.20
BS-48	500	239.0	3509.		48.40	74.60
BS-48	550	131.0	2226.		35.30	51.80
BS-48	550	193.0	369.		41.70	67.80

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
BS-48	600	70.0	888.		40.00	69.30
BS-50	500	239.0	75.		34.60	56.40
BS-50	550	131.0	7579.		7.40	28.60
BS-50	550	193.0	1023.		21.60	42.30
BS-50	600	70.0	2874.		35.20	87.50
MPC-1	427	414.0	621.			
MPC-1	482	276.0	2913.			
MPC-1	482	310.0	240.			
MPC-1	482	345.0	99.			
MPC-1	538	172.0	11006.			
MPC-1	538	207.0	468.			
MPC-1	538	241.0	94.			
MPC-2	427	345.0	7123.			
MPC-2	427	358.0	3137.			
MPC-2	427	379.0	960.			
MPC-2	482	207.0	5448.			
MPC-2	482	241.0	1531.			
MPC-2	482	276.0	688.			
MPC-2	482	345.0	50.			
MPC-2	538	138.0	4991.			
MPC-2	538	241.0	33.			
P-50A	427	345.0	2523.		14.50	75.00
P-50A	427	362.0	980.		15.50	76.00
P-50A	454	276.0	4025.		17.50	78.00
P-50A	454	310.0	879.		26.00	79.00
P-50A	454	362.0	82.		18.50	76.00
SH/FR	450	250.0	10698.			
SH/FR	450	250.0	14632.			
40K205	550	108.0	4322.			
40K205	550	123.0	2115.			
40K210	550	108.0	5792.			
40K210	550	122.0	2130.			
40K210	600	78.0	3901.			
40K220	600	78.0	1838.			
43K830	600	74.0	3176.			
D73718	500	196.0	3018.		55.70	82.40
D73718	500	226.0	860.		50.00	85.20
D73718	500	265.0	190.		51.00	84.40
D73718	500	294.0	85.		52.70	83.20
D73718	550	137.0	2515.		42.00	76.70
D73718	550	156.0	695.		43.70	82.80
D73718	550	176.0	267.		57.70	86.40
D73718	550	196.0	86.		58.30	86.90
D73718	600	69.0	4012.		21.00	70.40
D73718	600	88.0	1744.		44.70	78.50
D73718	600	108.0	663.		45.70	79.80
D73718	600	128.0	223.		54.70	82.90
D73718	600	147.0	52.		58.30	86.10
D73967	500	166.0	9667.		61.70	74.10
D73967	500	196.0	2782.		61.30	80.30
D73967	500	226.0	936.		62.00	84.40
D73967	500	265.0	227.		54.80	83.00
D73967	500	294.0	91.		36.00	83.30
D73967	500	343.0	20.		42.00	82.00
D73967	550	108.0	11124.		16.00	50.70

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
D73967	550	137.0	2132.		57.80	72.50
D73967	550	156.0	560.		36.30	70.30
D73967	550	176.0	261.		65.00	87.50
D73967	550	196.0	59.		67.50	84.80
D73967	600	69.0	6425.		22.70	64.10
D73967	600	88.0	2151.		46.70	61.70
D73967	600	108.0	616.		48.70	70.70
D73967	600	128.0	171.		59.00	79.10
D73967	600	147.0	51.		65.30	84.50
D73992	500	166.0	21607.		24.00	67.50
D73992	500	196.0	4795.		37.30	78.20
D73992	500	226.0	1834.		42.70	82.60
D73992	500	265.0	422.		36.00	83.70
D73992	500	294.0	162.		35.00	82.30
D73992	500	343.0	32.		32.70	79.80
D73992	500	392.0	13.		32.00	80.20
D73992	550	108.0	14517.		23.30	64.00
D73992	550	137.0	4283.		28.00	62.90
D73992	550	156.0	1609.		51.00	76.50
D73992	550	176.0	432.		54.20	82.20
D73992	550	196.0	125.		52.00	83.30
D73992	600	69.0	5579.		30.30	81.20
D73992	600	88.0	1846.		45.70	80.90
D73992	600	108.0	781.		49.00	80.40
D73992	600	128.0	299.		53.00	81.10
D73992	600	147.0	89.		49.00	82.20
KB-151	454	448.0	708.	.150E-02	19.30	82.10
KB-151	454	465.0	243.	.800E-02	19.20	80.90
KB-151	454	483.0	137.	.195E-01	22.00	77.00
KB-151	454	517.0	18.	.13E+00	23.90	76.50
KB-151	510	276.0	555.	.300E-02	34.00	82.50
KB-151	510	276.0	830.	.500E-02	28.40	78.80
KB-151	510	310.0	174.	.750E-02	31.60	84.90
KB-151	510	345.0	104.	.250E-01	28.00	72.90
KB-151	510	379.0	13.	.21E+00	26.80	79.10
KB-151	566	138.0	2520.	.160E-02	14.90	33.90
KB-151	566	172.0	436.	.700E-02	24.20	71.20
KB-151	566	207.0	195.	.260E-01	25.20	78.80
KB-151	566	241.0	25.	.19E+00	28.10	87.00
KB-151	566	241.0	32.	.14E+00	25.10	83.90
39E2135	450	343.0	12550.			
39E2135	550	147.0	1263.			
44K2158	600	69.0	6286.			
44K2158	600	78.0	4290.			
44K2158	600	98.0	1477.			
45K2436	500	199.0	1125.			
45K2436	550	110.0	3922.			
45K2436	600	82.0	1726.			
45K2643	500	199.0	1453.			
45K2643	600	82.0	1627.			
45K2653	450	302.0	1917.			
45K2653	500	199.0	3883.			
45K2653	550	151.0	2030.			
45K2653	600	82.0	2713.			
45K3088H	450	265.0	9217.			

2 1/4CR-1MO STEEL
CREEP DATA

LOT NUMBER	TEMPERATURE (C)	STRESS (MPA)	RUPTURE LIFE (H)	MINIMUM CREEP (%/H)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)
45K3088H	450	304.0	1842.			
45K3088H	500	216.0	1670.			
45K3088H	550	167.0	1228.			
PR20205A	450	265.0	1635.			
PR20205A	500	196.0	1210.			
PR20205A	550	118.0	1989.			
PR20205A	600	69.0	3713.			
PR20205B	450	265.0	2821.			
PR20205B	500	196.0	1696.			
PR20205B	550	118.0	2579.			
PR20205B	600	69.0	4044.			
PR20205C	450	265.0	5046.			
PR20205C	500	196.0	2113.			
PR20205C	550	118.0	3445.			
PR20205C	600	88.0	1137.			

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