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Addendum 1

Introduction

This addendum contains updated elastic and rupture stress data for materials based on WRC 541, 2nd Edition. Updated data is provided in SI and USC units for 9Cr-1Mo, TP304L, TP316L, TP317L, Alloy 800HT, and HK-40. New data is provided in SI and USC units for TP 347LN on the following pages. Paragraph 6.7 and Tables 4, 5, and 6 have been revised to provide the corrected Larson-Miller Constants, figure numbers, and limiting design metal temperature for the heater-tube alloys noted above. This addendum also incorporates corrections to errors found after the 7th Edition of API Standard 530 was published.

Front matter: The following notice shall be added to the front matter because this standard is now revised under continuous maintenance (as opposed to periodic maintenance).

Notice

Instructions for Submitting a Proposed Revision to this Standard Under Continuous Maintenance

The American Petroleum Institute maintains this standard under continuous maintenance procedures. These procedures establish a document program for regular publication of addenda or revisions, including timely and documented consensus action on requests for revisions to any part of the standard. Proposed revisions shall be submitted to the Director, Standards Department, American Petroleum Institute, 200 Massachusetts Avenue, NW, Washington, DC 20001, standards@api.org.

This addendum to API 530, 7th Edition, contains the following changes:

- Updated rupture stress data for 9Cr-1Mo material: The rupture allowable stresses the addendum have been lowered to match the values given by the constants in WRC 541, 2nd Edition.
- The limiting design metal temperature for TP304L, TP316L, and TP317L have been decreased to 593 °C/1100 °F to match WRC 541 maximum temperatures for designs governed by creep properties. The allowable stress curves for TP304L, TP316L, and TP317L have been extended to 816 °C/1500 °F to match WRC 541 data for short-term exposure.
- The limiting design metal temperatures for 800HT and HK40 have been increased to 1010 °C/1850 °F to match WRC 541. The allowable stress curves also extend to this value.
- New material 347LN has been added based on data from WRC 541.

Section 6.7: The section shall be replaced by the following.

6.7 Limiting Design Metal Temperature

The limiting design metal temperature for each heater-tube alloy is given in Table 5. The limiting design metal temperature is the upper limit of the reliability of the rupture strength data, and the stress rupture curves are intended for use where the design stress is greater than 6.9 MPa (1 ksi). Higher temperatures, i.e. up to 28 °C (50 °F) below the lower critical temperature, are permitted for short-term operating conditions, such as those that exist during steam-air decoking or regeneration (approximately 25 hours or less). Operation at higher temperatures can result in changes in the alloy's microstructure. Lower critical temperatures for ferritic steels are shown in Table 5. Austenitic steels do not have lower critical temperatures. Other considerations can require lower long-term operating temperature limits, such as oxidation, graphitization, carburization, and hydrogen attack. These factors shall be considered when furnace tubes are designed.

Table 4: The table shall be replaced with the following:

Table 4—Larson-Miller Constants

Material	Type or Grade	Larson-Miller Constants C_{LM}	
		minimum properties	average properties
Low-carbon steel	—	18.15	17.70
Medium-carbon steel	B	15.6	15.15
C-½Mo steel	T1 or P1	19.007756	18.72537
1-¼Cr-½Mo steel	T11 or P11	22.05480	21.55
2-¼Cr-1Mo steel	T22 or P22	19.565607	18.9181
3Cr-1Mo steel	T21 or P21	15.785226	15.38106
5Cr-½Mo steel	T5 or P5	16.025829	15.58928
5Cr-½Mo-Si steel	T5b or P5b	16.025829	15.58928
9Cr-1Mo steel	T9 or P9	20.946	20.5
9Cr-1Mo V steel	T91 or P91	30.886006	30.36423
18Cr-8Ni steel	304 or 304H	16.145903	15.52195
18Cr-8Ni steel	304L	18.287902	17.55
16Cr-12Ni-2Mo steel	316 or 316H	16.764145	16.30987
16Cr-12Ni-2Mo steel	316L	15.740107	15.2
16Cr-12Ni-3Mo steel	317L	15.740107	15.2
18Cr-10Ni-Ti steel	321	13.325	12.8
18Cr-10Ni-Ti steel	321H	15.293986	14.75958
18Cr-10Ni-Nb ^a steel	347	14.889042	14.25
18Cr-10Ni-Nb ^a steel	347H	14.17	13.65
18Cr-10Ni-Nb ^a steel	347LN	16.6233	16.4067
Ni-Fe-Cr	Alloy 800	17.005384	16.50878
Ni-Fe-Cr	Alloy 800H	16.564046	16.04227
Ni-Fe-Cr	Alloy 800HT	13.606722	13.2341
25Cr-20Ni	HK-40	10.856489	10.4899
^a Formerly called columbium, Cb.			

Table 5: The table shall be replaced with the following:

Table 5—Limiting Design Metal Temperature for Heater-tube Alloys

Materials	Type or grade	Limiting design metal temperature		Lower critical temperature	
		°C	(°F)	°C	(°F)
Low carbon steel	—	540	(1000)	720	(1325)
Medium carbon steel	B	540	(1000)	720	(1325)
C-½Mo steel	T1 or P1	566	(1150)	720	(1325)
1¼Cr-½Mo steel	T11 or P11	650	(1100)	775	(1 30)
2¼Cr-1Mo steel	T22 or P22	650	(1 200)	805	(1480)
3Cr-1Mo steel	T21 or P21	650	(1200)	815	(1500)
5Cr-½Mo steel	T5 or P5	650	(1200)	820	(1510)
5Cr-½Mo-Si steel	T5b or P5b	650	(1200)	845	(1550)
9Cr-1Mo steel	T9 or P9	705	(1300)	825	(1515)
9Cr-1Mo-V steel	T91 or P91	705	(1300)	830	(1525)
18Cr-8Ni steel	304 or 304H	815	(1500) ²	—	—
18Cr-8Ni steel	304L	593 ¹	(1100) ¹	—	—
16Cr-12Ni-2Mo steel	316 or 316H	815	(1500) ²	—	—
16Cr-12Ni-2Mo steel	316L	593 ¹	(1100) ¹	—	—
18Cr-12Ni-3Mo steel	317L	593 ¹	(1100) ¹	—	—
18Cr-10Ni-Ti steel	321	815	(1500)	—	—
18Cr-10Ni-Ti steel	321H	815	(1500)	—	—
18Cr-10Ni-Nb steel	347	815	(1500)	—	—
18Cr-10Ni-Nb steel	347H	815	(1500)	—	—
18Cr-10Ni-Nb steel	347LN	593	(1100)	—	—
Ni-Fe-Cr	Alloy 800	815	(1500)	—	—
Ni-Fe-Cr	Alloy 800H	900	(1650)	—	—
Ni-Fe-Cr	Alloy 800HT	1010	(1850)	—	—
25Cr-20Ni	HK40	1010	(1850)	—	—
NOTE 1 The maximum temperature should be limited to 593 °C (1100 °F) for designs governed by creep properties.					
NOTE 2 The maximum temperature should be limited to 593 °C (1100 °F) when carbon content is less than 0.04 on heat analysis.					

Table 6: The table shall be replaced with the following:

Table 6—Index to Allowable Stress Curves

Steel Type	Figure Number	Alloy
Ferritic	E.1 (F.1)	Low-carbon steel (A 192)
	E.4 (F.4)	Medium-carbon steel (A 106B, A 210A1)
	E.7 (F.7)	C-½ Mo Steel
	E.10 (F.10)	1¼ Cr-½ Mo Steel
	E.13 (F.13)	2¼ Cr-1 Mo Steel
	E.16 (F.16)	3Cr-1 Mo Steel
	E.19 (F.19)	5Cr-½ Mo Steel
	E.22 (F.22)	5Cr-½ Mo-Si Steel
	E.25 (F.25)	9Cr-1Mo Steel
	E.28 (F.28)	9Cr-1Mo-V Steel
Austenitic	E.31 (F.31)	18Cr-8Ni (304 and 304H) Stainless Steel
	E.34 (F.34)	18Cr-8Ni (304L) Stainless Steel
	E.37 (F.37)	16Cr-12Ni-2Mo (316 and 316H) Stainless Steel
	E.40 (F.40)	16Cr-12Ni-2Mo (316L) Stainless Steel
	E.40 (F.40)	16Cr-12Ni-3Mo (317L) Stainless Steel
	E.43 (F.43)	18Cr-10Ni-Ti (321) Stainless Steel
	E.46 (F.46)	18Cr-10Ni-Ti (321H) Stainless Steel
	E.49 (F.49)	18Cr-10Ni-Nb (347) Stainless Steel
	E.52 (F.52)	18Cr-10Ni-Nb (347H) Stainless Steel
	E.65 (F.65)	18Cr-10Ni-Nb (347LN) Stainless Steel
	E.55 (F.55)	Ni-Fe-Cr (Alloy 800)
	E.58 (F.58)	Ni-Fe-Cr (Alloy 800H)
	E.61 (F.61)	Ni-Fe-Cr (Alloy 800HT)
	E.64 (F.64)	25Cr-20Ni (HK-40)

Section 7.4: The entire section shall be replaced with the following:

7.4 Rupture Design with Linearly Changing Temperature

Suppose the tube described in 7.3 operates in a service for which the estimated tube metal temperature varies from 635 °C (1175 °F) at the start of run to 690 °C (1275 °F) at the end of run. Assume that the run lasts a year, during which the thickness changes by about 0.33 mm (0.013 in.).

Assume that the initial minimum thickness is 8.0 mm (0.315 in.); therefore, using Equation (1), the initial stress is as follows:

In SI units:

$$\sigma_o = \frac{p}{2} \left(\frac{D_o}{\delta} - 1 \right)$$

$$\sigma_o = \frac{5.8}{2} \left(\frac{168.3}{8.0} - 1 \right) = 58.1 \text{ MPa}$$

In USC units:

$$\sigma_o = \frac{840}{2} \left(\frac{6.625}{0.315} - 1 \right) = 8413 \text{ psi}$$

At the start-of-run temperature, $n_o = 4.96$. From Table 3, A is 3.74×10^5 MPa (5.43×10^7 psi). The parameters for the temperature fraction are, therefore, as follows:

In SI units:

$$V = n_o \left(\frac{\Delta T^*}{T_{sor}^*} \right) \ln \left(\frac{A}{\sigma_o} \right)$$

$$N = n_o \left(\frac{\Delta \delta}{\delta_o} \right)$$

$$V = 4.96 \left(\frac{55}{908} \right) \ln \left(\frac{3.74 \times 10^5}{58.1} \right) = 2.64$$

$$N = 4.96 \left(\frac{0.33}{8.0} \right) = 0.2$$

In USC units:

$$V = 4.96 \left(\frac{100}{1635} \right) \ln \left(\frac{5.43 \times 10^7}{8413} \right) = 2.64$$

$$N = 4.96 \left(\frac{0.013}{0.315} \right) = 0.2$$

From Figure 2, $f_T = 0.62$, and the equivalent temperature is calculated using Equation (6) as follows:

In SI units:

$$T_{eq} = 635 + (0.62 \times 55) = 669 \text{ }^{\circ}\text{C}$$

In USC units:

$$T_{eq} = 1175 + (0.62 \times 100) = 1237 \text{ }^{\circ}\text{F}$$

A temperature allowance of 15 °C (25 °F) is added to yield a design temperature of 684 °C (1262 °F), which is rounded up to 685 °C (1265 °F). Using this temperature to carry out the design procedure illustrated in 7.3 yields the following:

In SI units:

$$\delta_{\sigma} = 16.0 \text{ mm}$$

$$\delta_{min} = 16.0 + (0.54 \times 3.2)$$

$$\delta_{min} = 17.7 \text{ mm}$$

In USC units:

$$\delta_{\sigma} = 0.622 \text{ in.}$$

$$\delta_{min} = 0.622 + (0.54 \times 0.125)$$

$$\delta_{min} = 0.690 \text{ in.}$$

This thickness is different from the 8.0 mm (0.315 in.) thickness that was initially assumed. Using this thickness, the initial stress is calculated as follows:

In SI units:

$$\sigma_o = \frac{5.8}{2} \left(\frac{168.3}{17.7} - 1 \right) = 24.7 \text{ MPa}$$

In USC units:

$$\sigma_o = \frac{840}{2} \left(\frac{6.625}{0.690} - 1 \right) = 3613 \text{ psi}$$

With this stress, the temperature-fraction parameters V and N become the following:

In SI units:

$$V = 4.96 \left(\frac{55}{908} \right) \ln \left(\frac{3.74 \times 10^5}{24.7} \right) = 2.89$$

$$N = 4.96 \left(\frac{0.33}{17.7} \right) = 0.09$$

In USC units:

$$V = 4.96 \left(\frac{100}{1635} \right) \ln \left(\frac{5.43 \times 10^7}{3613} \right) = 2.92$$

$$N = 4.96 \left(\frac{0.013}{0.690} \right) = 0.09$$

Using these values in Figure 2, $f_T = 0.62$, the value that was determined in the first calculation. Since the temperature fraction did not change, further iteration is not necessary. This design calculation is summarized in the calculation sheet in Figure 6.

CALCULATION SHEET SI units (USC units)		
Heater _____	Plant _____	Refinery _____
Coil _____	Material Type 347	ASTM Spec. A 213/A 213M
Calculation of minimum thickness	Elastic design	Rupture design
Outside diameter, mm (in.)	$D_o =$	$D_o = 168.3 (6.625)$
Design pressure, gauge, MPa (psi)	$p_{el} =$	$p_r = 5.8 (840)$
Maximum or equivalent metal temperature, °C (°F)	$T_{eq} =$	$T_{eq} = 669 (1237)$
Temperature allowance, °C (°F)	$T_A =$	$T_A = 15 (25)$
Design metal temperature, °C (°F)	$T_d =$	$T_d = 685 (1265)$
Design life, h	—	$t_{DL} = 100,000$
Allowable stress at T_d , Figure E17.1 (Figures F17.1) MPa (psi)	$\sigma_{el} =$	$\sigma_r = 27.7 (4050)$
Stress thickness, Equation (2) or (4), mm (in.)	$\delta_\sigma =$	$\delta_\sigma = 16.0 (0.622)$
Corrosion allowance, mm (in.)	$\delta_{CA} =$	$\delta_{CA} = 3.2 (0.125)$
Corrosion fraction, Figure 1, $n = 4.5$; $B = 0.322$	—	$f_{corr} = 0.54$
Minimum thickness, Equation (3) or (5), mm (in.)	$\delta_{min} =$	$\delta_{min} = 17.7 (0.690)$
Calculation of equivalent tube metal temperature		
Duration of operating period, years	$t_{op} = 1.0$	
Metal temperature, start of run, °C (°F)	$T_{sor} = 635 (1175)$	
Metal temperature, end of run, °C (°F)	$T_{eor} = 690 (1275)$	
Temperature change during operating period, K (°R)	$\Delta T^* = 55 (100)$	
Metal absolute temperature, start of run, K (°R)	$T_{sor}^* = 908 (1635)$	
Thickness change during operating period, mm (in.)	$\Delta \delta = 0.33 (0.013)$	
Assumed initial thickness, mm (in.)	$\delta_0 = 8.00 (0.315)$	
Corresponding initial stress, Equation (1), MPa (psi)	$\sigma_0 = 58.1 (8,413)$	
Material constant, Table 3, MPa (psi)	$A = 3.74 \times 10^5 (5.43 \times 10^7)$	
Rupture exponent at T_{sor} , Figures E.1 to E.19 (Figures F.1 to F.19)	$n_0 = 4.96$	
Temperature fraction, Figure 2, $V = 2.64$; $N = 0.2$	$f_T = 0.62$	
Equivalent metal temperature, Equation (6), °C (°F)	$T_{eq} = 669 (1237)$	

Figure 1—Sample Calculation for Rupture Design (Changing Temperature)

Figure B.1: The key shall be changed as indicated in the red box:

Key

- 1 Curve 1 for a double row against a wall, triangular spacing
- 2 Curve 2 for a double row with equal radiation from both sides and two diameters between rows, triangular spacing
- 3 Curve 3 for a single row against a wall
- 4 Curve 4 for a single row with equal radiation from both sides

Annex E, List of Figures and Tables (SI Units): The titles of the indicated tables shall be changed to the following:

Table E.9—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Table E.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

Figure E.40—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

Figure E.41—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Figure E.42—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table E.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table E.21—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table E.22—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A608 Grade HK-40 Steels

Annex E, List of Figures and Tables (SI Units): The following titles shall be added to the list:

TP 347LN Stainless Steels

Figure E.67—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.68—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.69—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table E.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.25: The figure shall be replaced with the following:

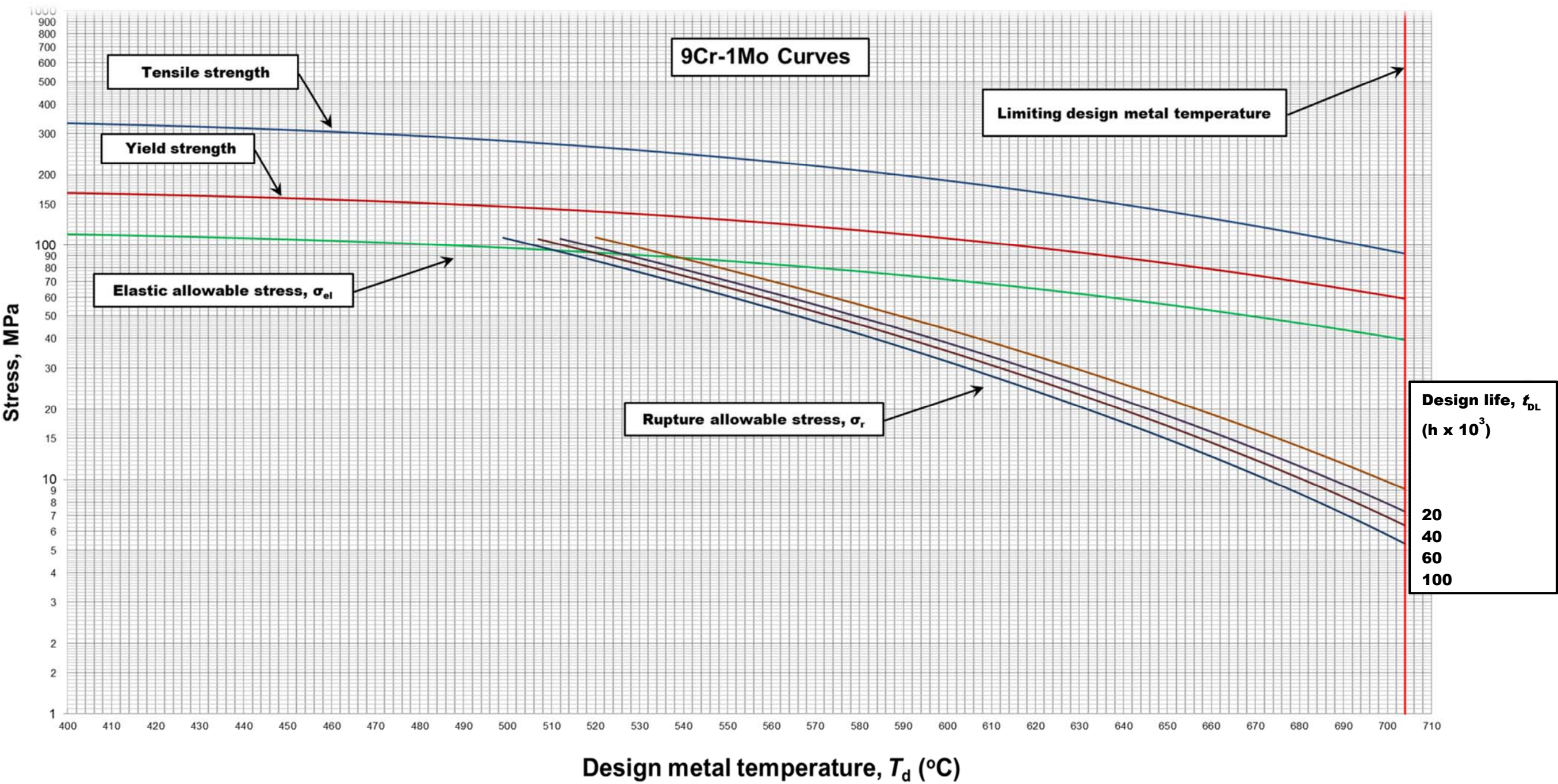


Figure E.26: The figure shall be replaced with the following:

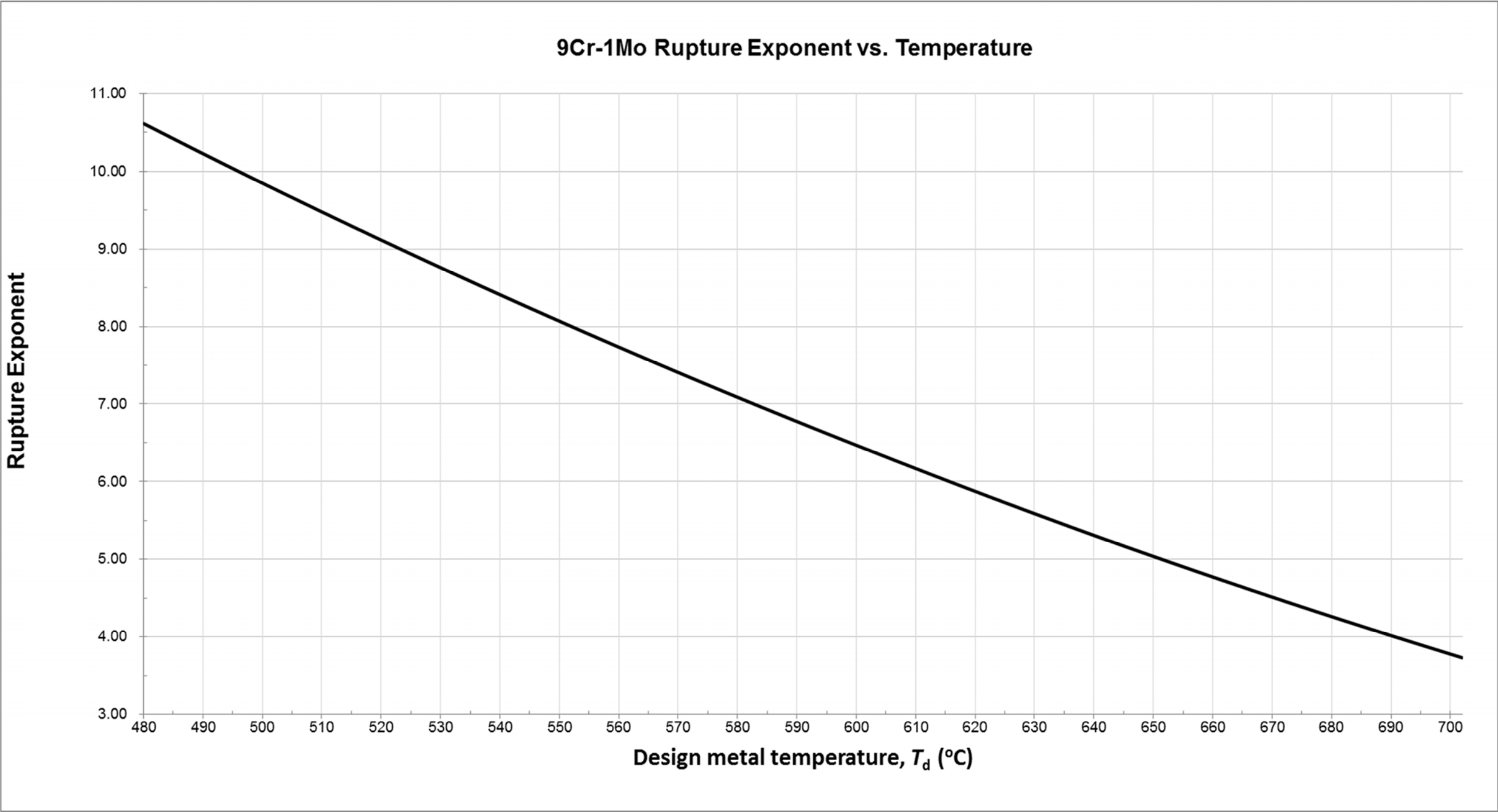


Figure E.27: The figure shall be replaced with the following:

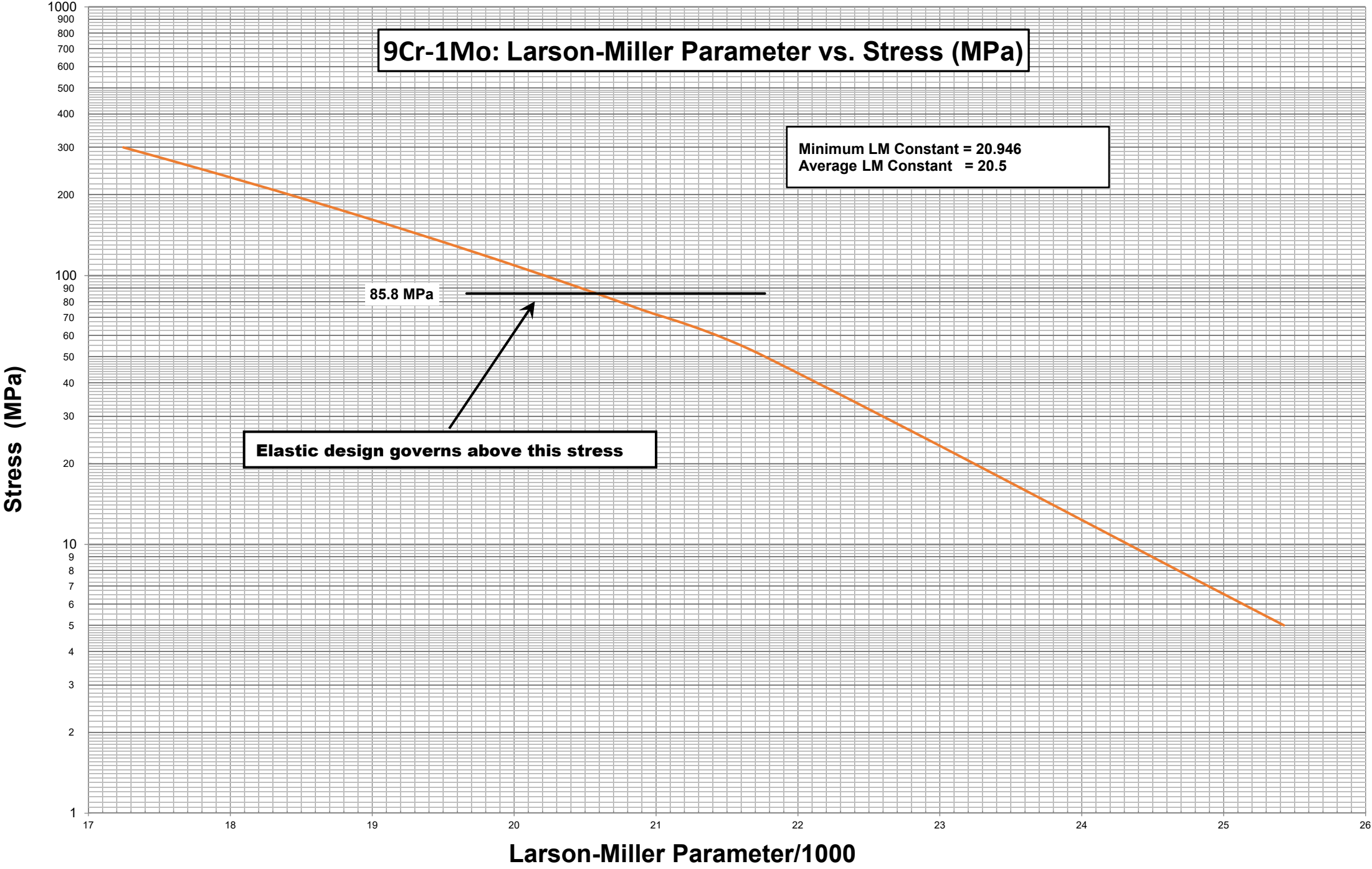


Table E.9: The table shall be replaced with the following:

9Cr-1Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000$ h (MPa)	$t_{DL} = 60,000$ h (MPa)	$t_{DL} = 40,000$ h (MPa)	$t_{DL} = 20,000$ h (MPa)	
300	117.0					
310	116.7					
320	116.3					
330	115.9					
340	115.4					
350	115.0					
360	114.4					
370	113.8					
380	113.2					
390	112.4					
400	111.6					
410	110.7					
420	109.7					
430	108.5					
440	107.3					
450	106.0					
460	104.5					
470	102.9					
480	101.2					
490	99.3	118.4	126.7	133.5	145.9	10.3
500	97.4	106.6	114.3	120.7	132.3	9.9
510	95.3	95.7	102.9	108.9	119.8	9.6
520	93.0	85.8	92.4	98.0	108.2	9.2
530	90.7	76.6	82.8	88.0	97.5	8.8
540	88.2	68.3	74.0	78.8	87.6	8.5
550	85.6	60.7	66.0	70.4	78.6	8.1
560	82.9	53.7	58.6	62.7	70.3	7.8
570	80.2	47.4	51.9	55.7	62.7	7.5
580	77.3	41.7	45.8	49.3	55.7	7.1
590	74.3	36.5	40.3	43.5	49.4	6.8
600	71.3	31.9	35.3	38.2	43.6	6.5
610	68.3	27.7	30.8	33.4	38.4	6.2
620	65.2	23.9	26.7	29.2	33.7	5.9
630	62.0	20.5	23.1	25.3	29.4	5.6
640	58.9	17.5	19.8	21.8	25.6	5.4
650	55.7	14.9	17.0	18.7	22.1	5.1
660	52.6	12.6	14.4	16.0	19.0	4.8
670	49.5	10.5	12.1	13.6	16.3	4.6
680	46.5	8.7	10.1	11.4	13.8	4.3
690	43.5	7.1	8.4	9.5	11.7	4.1
700	40.6	5.8	6.9	7.9	9.8	3.8
704	39.4	5.3	6.4	7.3	9.1	3.7

Figure E.34: The table shall be replaced with the following:

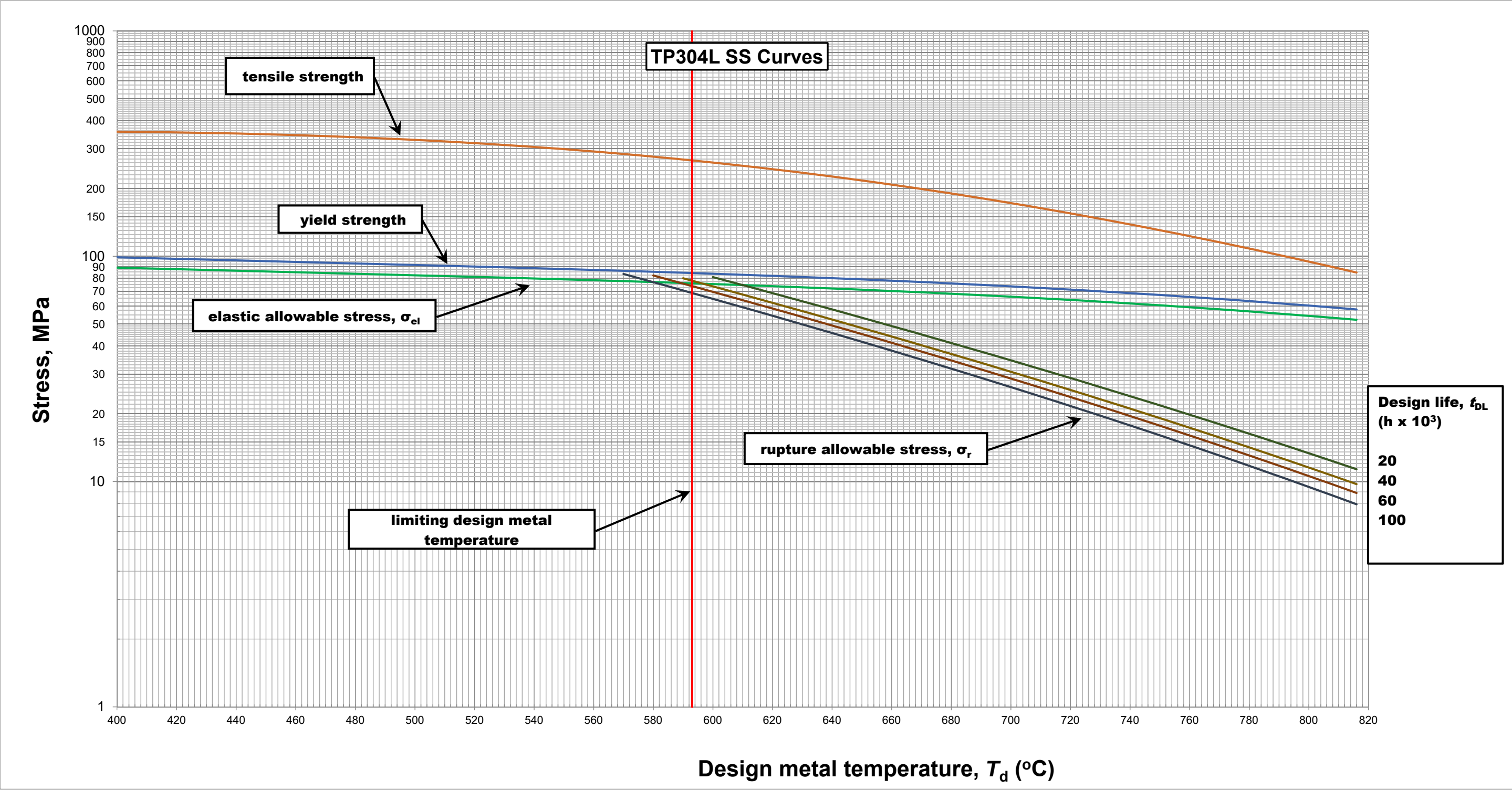


Figure E.35: The table shall be replaced with the following:

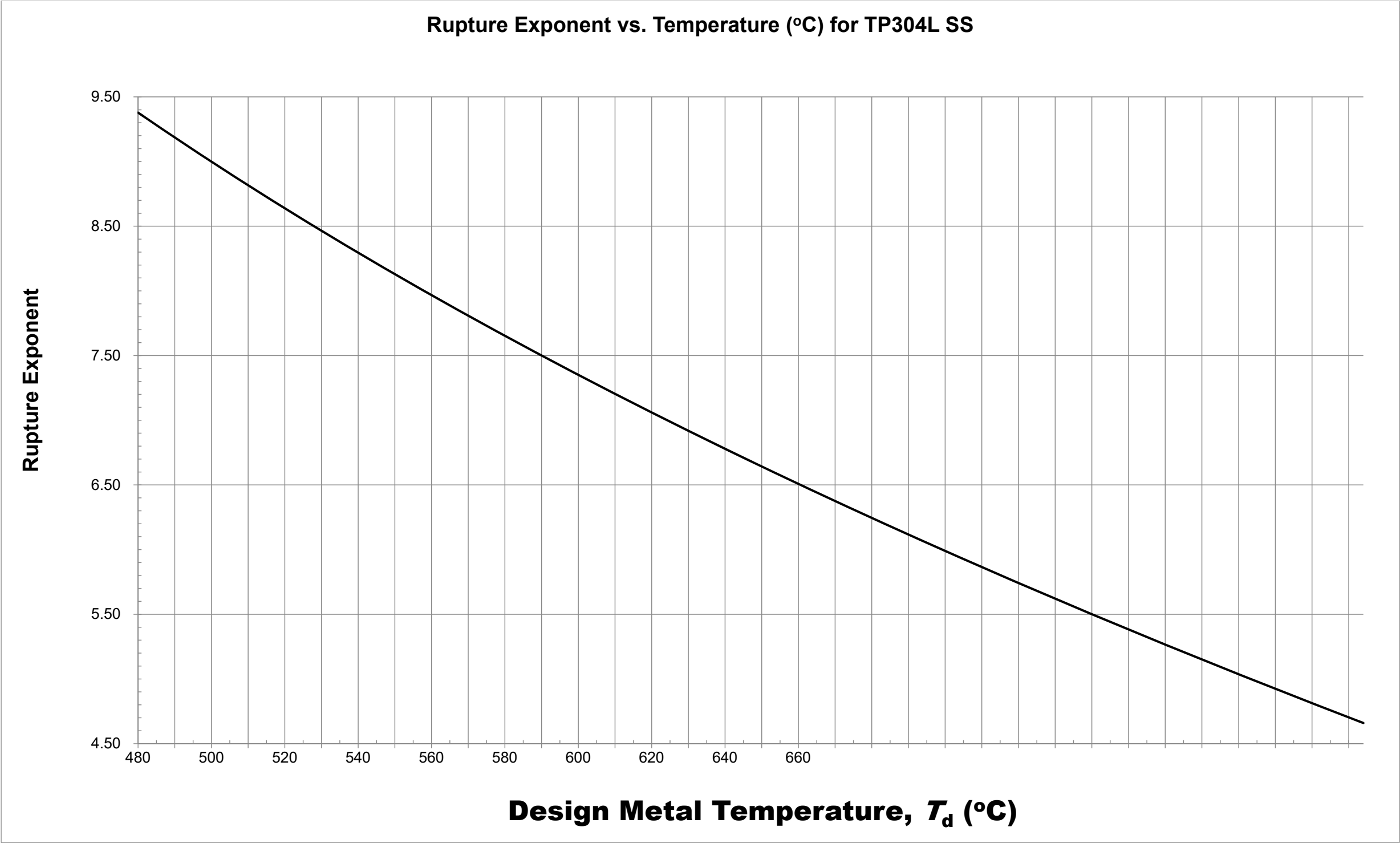


Figure E.36: The table shall be replaced with the following:

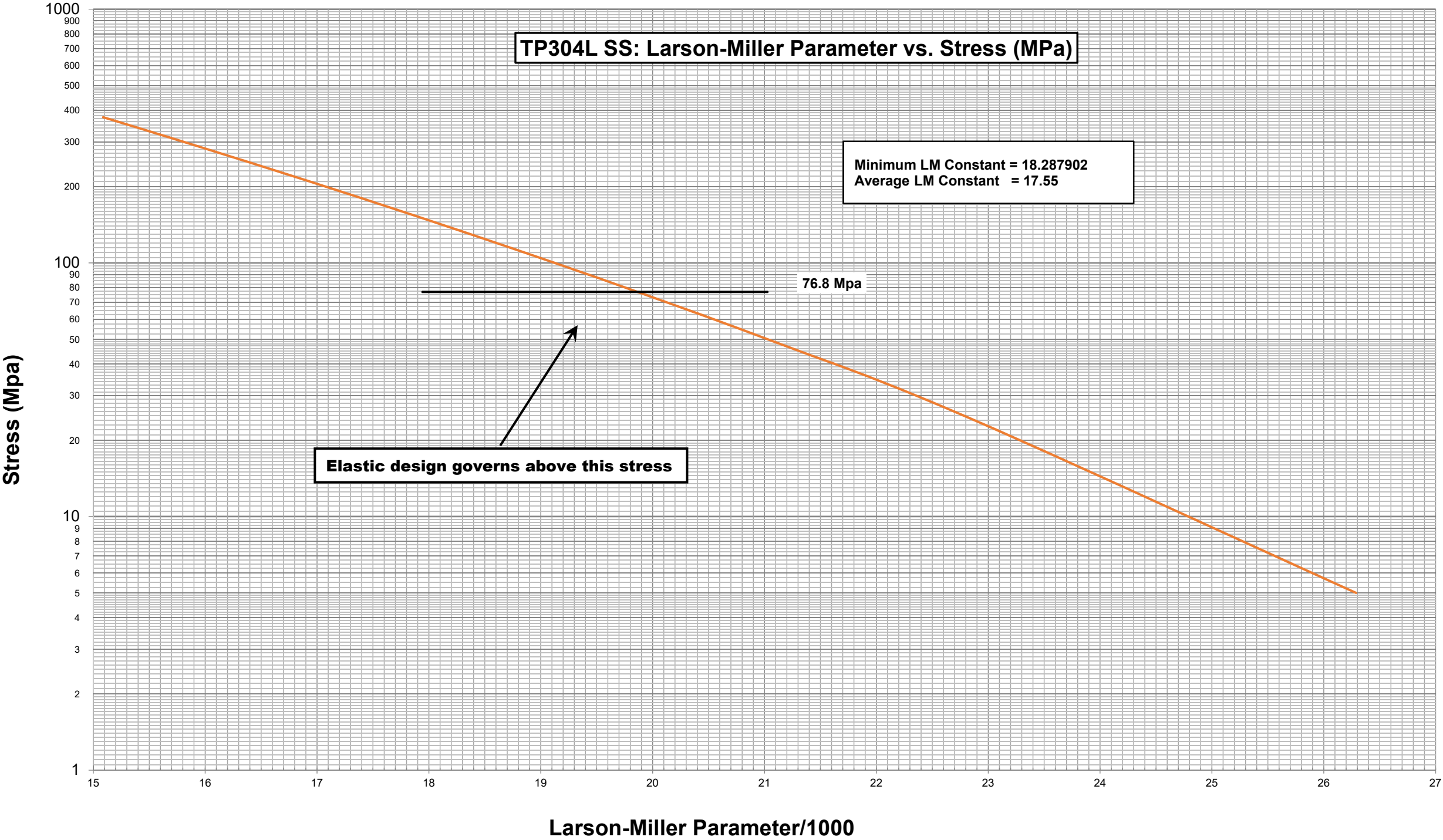


Table E.12: The table shall be replaced with the following:

TP304L SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	89.1					
410	88.4					
420	87.7					
430	87.0					
440	86.3					
450	85.7					
460	85.0					
470	84.3					
480	83.7					
490	83.0					
500	82.4					
510	81.7					
520	81.0					
530	80.4					
540	79.7					
550	79.0					
560	78.3	90.6	96.8	101.9	111.2	8.0
570	77.5	83.4	89.2	94.0	102.8	7.8
580	76.8	76.7	82.1	86.7	94.9	7.7
590	76.0	70.5	75.6	79.8	87.6	7.5
600	75.2	64.7	69.5	73.5	80.8	7.4
610	74.4	59.4	63.9	67.6	74.5	7.2
620	73.6	54.5	58.6	62.2	68.6	7.1
630	72.8	49.9	53.8	57.1	63.2	6.9
640	71.9	45.6	49.3	52.4	58.1	6.8
650	71.0	41.7	45.2	48.0	53.4	6.7
660	70.1	38.1	41.3	44.0	49.0	6.5
670	69.2	34.8	37.8	40.3	45.0	6.4
680	68.2	31.7	34.5	36.8	41.2	6.3
690	67.2	28.9	31.5	33.7	37.7	6.1
700	66.2	26.2	28.7	30.7	34.5	6.0
710	65.1	23.8	26.1	28.0	31.5	5.9
720	64.0	21.6	23.7	25.5	28.8	5.8
730	62.9	19.6	21.5	23.2	26.3	5.6
740	61.8	17.7	19.5	21.1	23.9	5.5
750	60.6	16.0	17.7	19.1	21.8	5.4
760	59.4	14.5	16.0	17.3	19.8	5.3
770	58.2	13.1	14.5	15.7	18.0	5.2
780	57.0	11.7	13.1	14.2	16.3	5.1
790	55.7	10.6	11.8	12.8	14.8	4.9
800	54.4	9.5	10.6	11.5	13.4	4.8
810	53.1	8.5	9.5	10.4	12.1	4.7
816	52.3	7.9	8.9	9.7	11.3	4.7

Figure E.40: The table shall be replaced with the following:

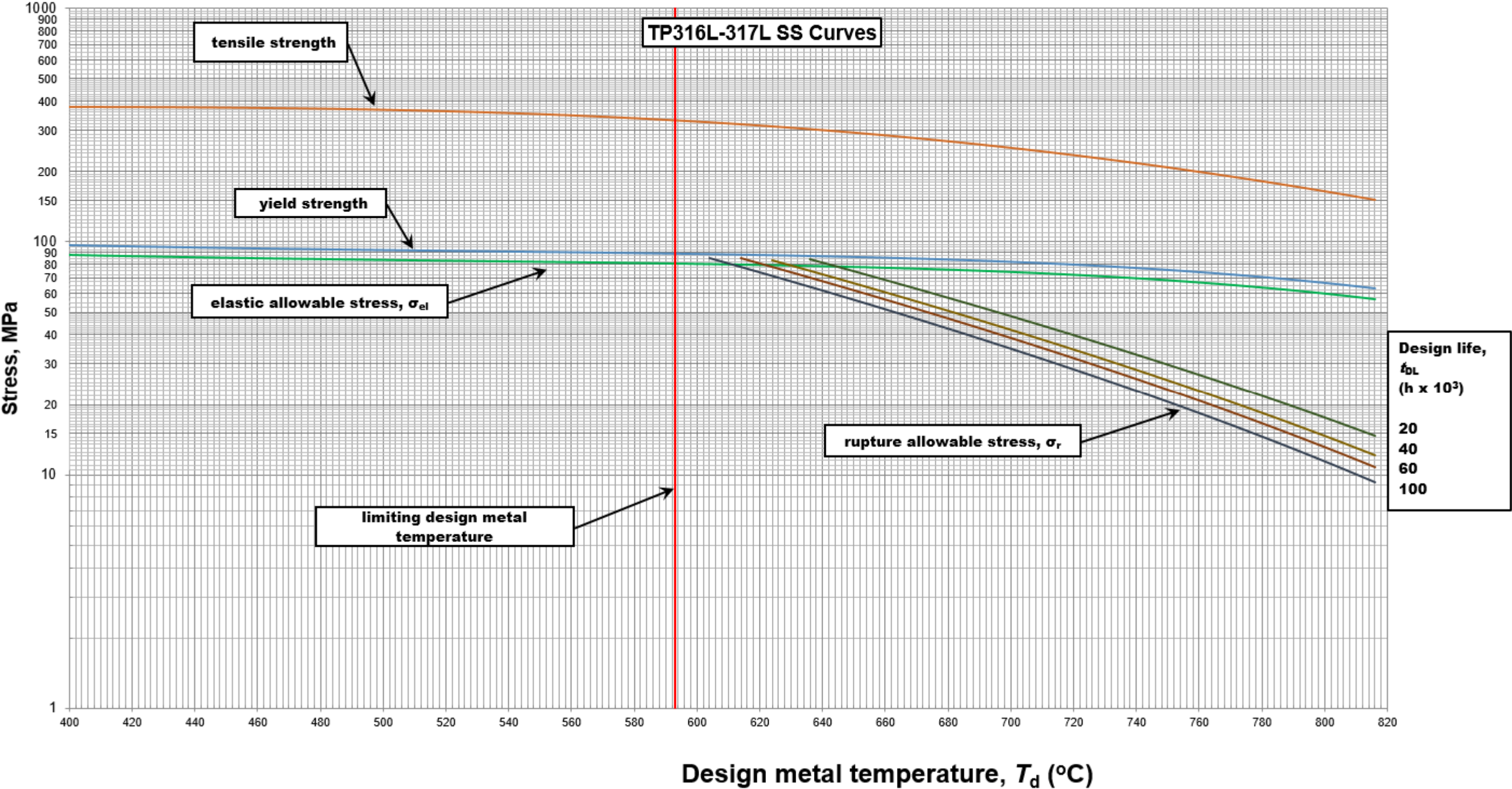


Figure E.41: The table shall be replaced with the following:

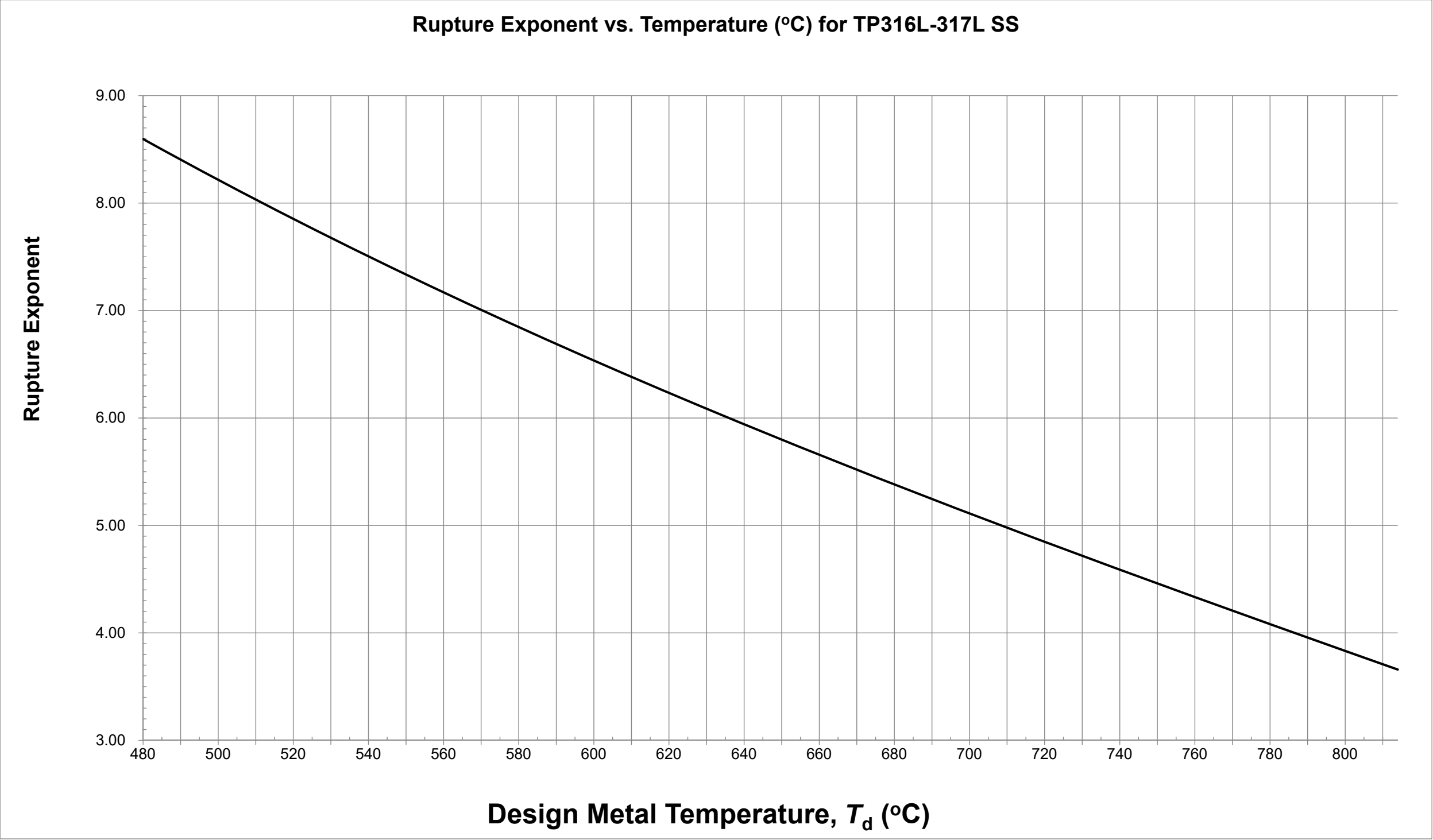


Figure E.42: The table shall be replaced with the following:

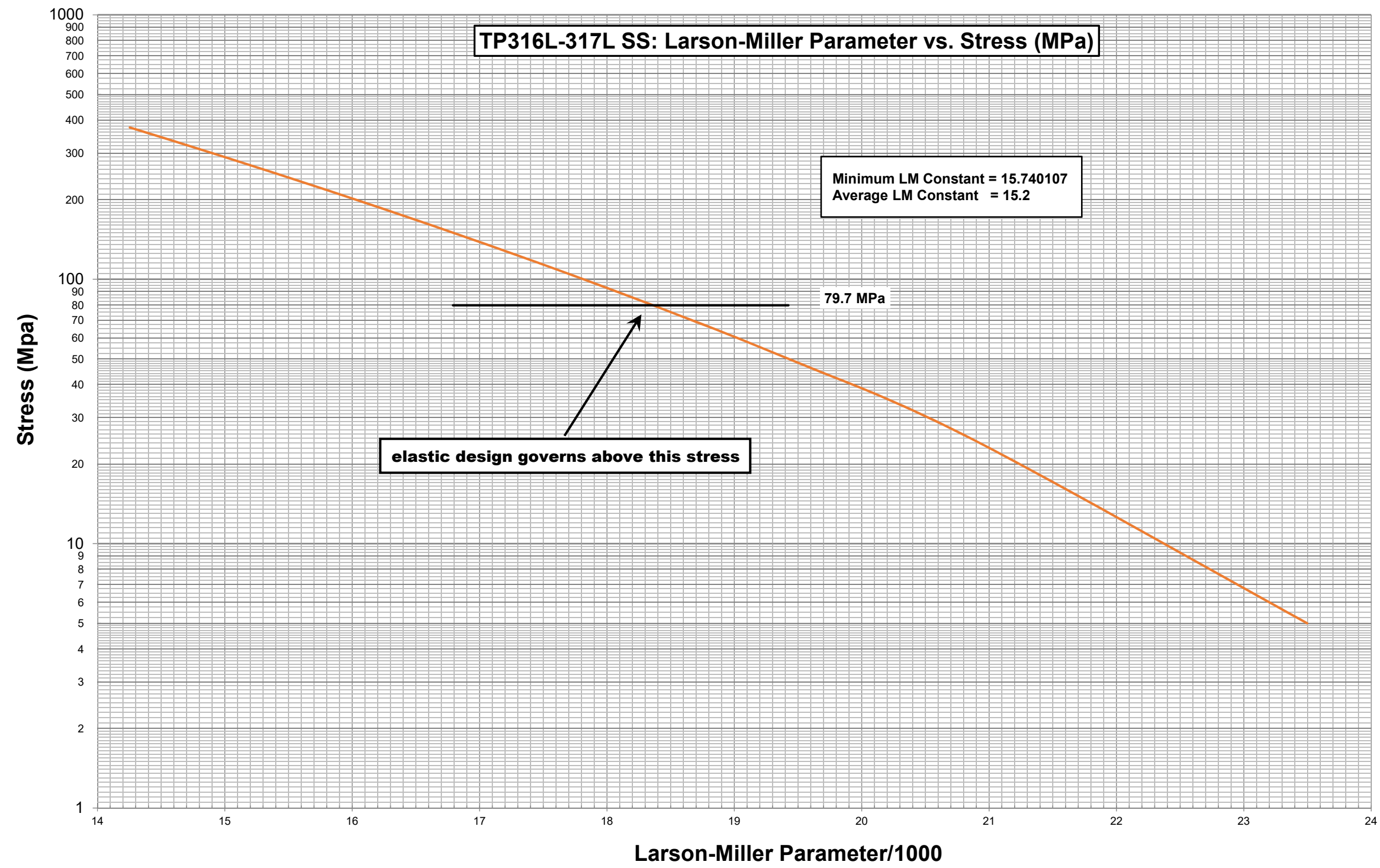


Table E.14: The table shall be replaced with the following:

TP316L-317L SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000 \text{ h}$ (MPa)	$t_{DL} = 60,000 \text{ h}$ (MPa)	$t_{DL} = 40,000 \text{ h}$ (MPa)	$t_{DL} = 20,000 \text{ h}$ (MPa)	
400	87.6					
410	87.0					
420	86.5					
430	86.0					
440	85.6					
450	85.2					
460	84.8					
470	84.4					
480	84.0					
490	83.7					8.4
500	83.4					8.3
510	83.1					8.1
520	82.8					7.9
530	82.5					7.7
540	82.2					7.5
550	81.9					7.4
560	81.6					7.2
570	81.2					7.0
580	80.9					6.9
590	80.6					6.7
600	80.2	88.6	96.0	102.2	113.6	6.6
610	79.8	81.2	88.2	94.0	104.8	6.4
620	79.4	74.4	80.9	86.4	96.6	6.3
630	78.9	68.0	74.2	79.3	88.9	6.1
640	78.4	62.1	67.9	72.8	81.8	6.0
650	77.8	56.7	62.1	66.6	75.1	5.8
660	77.2	51.6	56.7	61.0	68.9	5.7
670	76.6	47.0	51.7	55.7	63.2	5.5
680	75.8	42.7	47.1	50.8	57.8	5.4
690	75.0	38.7	42.8	46.3	52.8	5.3
700	74.1	35.0	38.8	42.1	48.2	5.1
710	73.1	31.6	35.2	38.2	44.0	5.0
720	72.1	28.5	31.8	34.7	40.0	4.9
730	70.9	25.7	28.7	31.4	36.4	4.7
740	69.7	23.0	25.9	28.4	33.0	4.6
750	68.3	20.6	23.3	25.6	29.9	4.5
760	66.9	18.5	20.9	23.0	27.0	4.4
770	65.3	16.5	18.7	20.7	24.4	4.2
780	63.6	14.6	16.7	18.5	21.9	4.1
790	61.9	13.0	14.9	16.5	19.7	4.0
800	60.0	11.4	13.2	14.7	17.7	3.9
810	58.0	10.1	11.7	13.1	15.8	3.7
816	56.8	9.3	10.8	12.2	14.7	3.7

Figure E.61: The figure shall be replaced with the following:

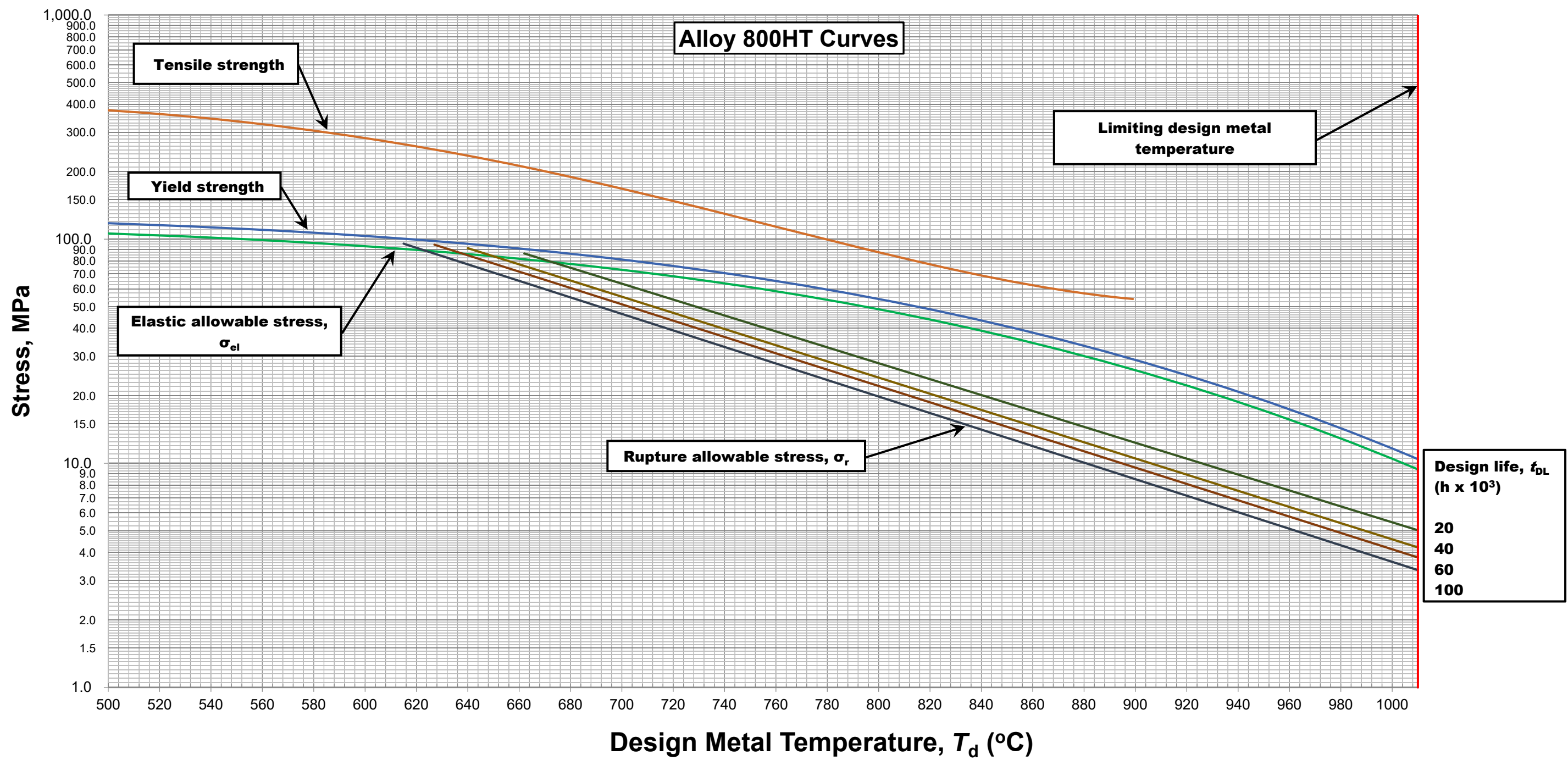


Figure E.62: The figure shall be replaced with the following:

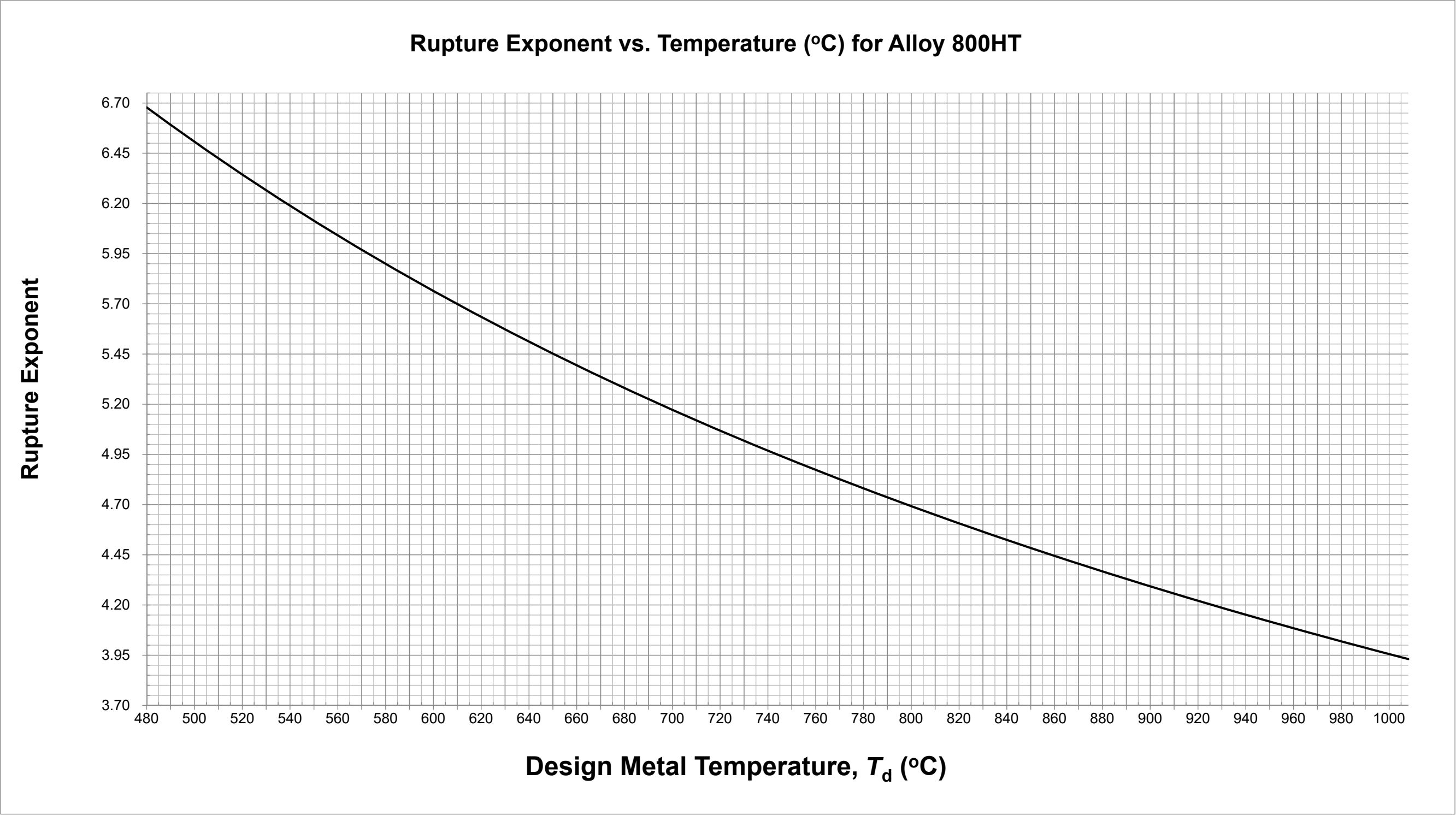


Figure E.63: The figure shall be replaced with the following:

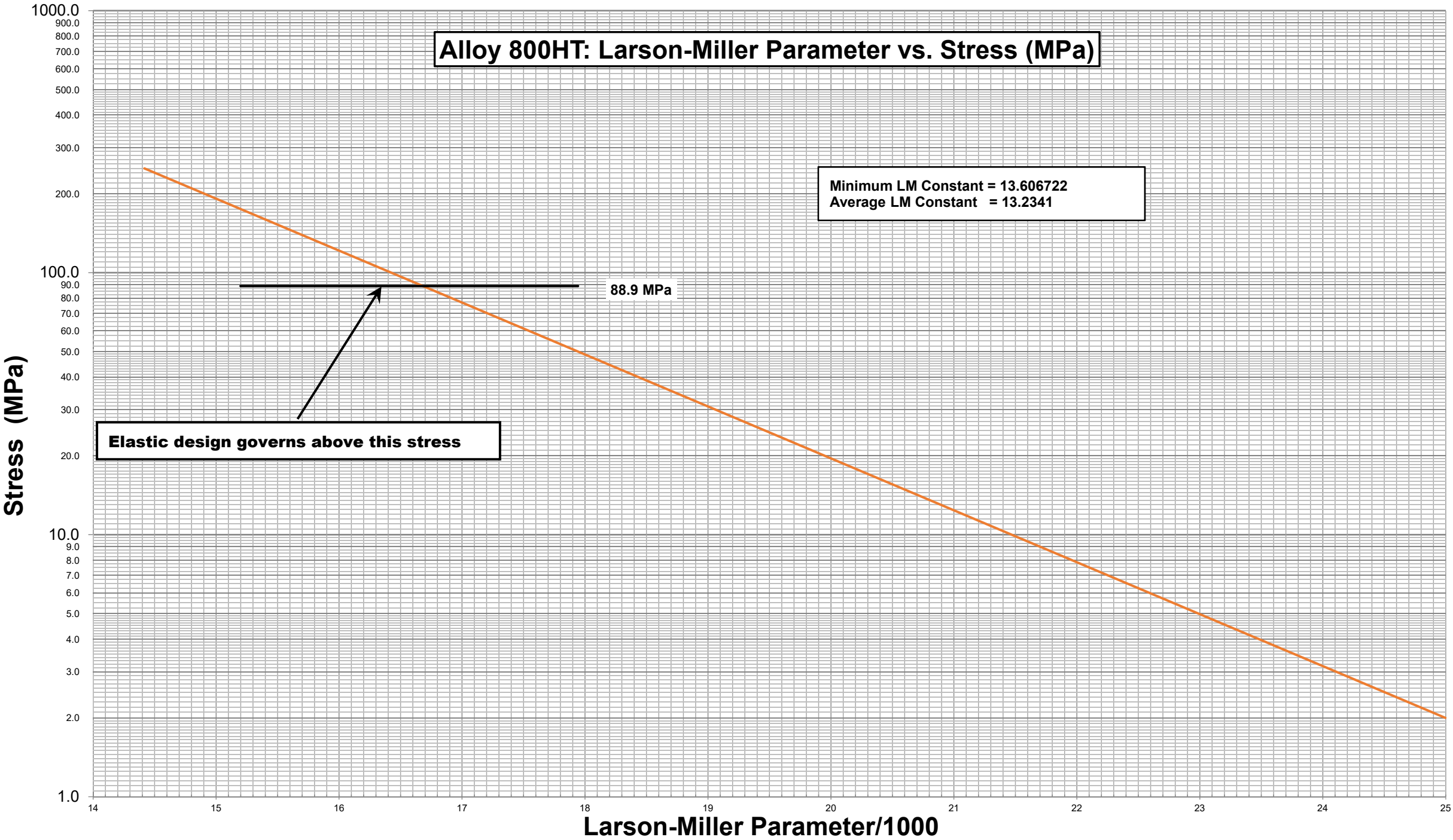


Table E.21: The table shall be replaced with the following:

Alloy 800HT						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
480	107.8					
490	107.0					6.6
500	106.0					6.5
510	105.0					6.4
520	104.0					6.4
530	102.9					6.3
540	101.7					6.2
550	100.4					6.1
560	99.1					6.1
570	97.7					6.0
580	96.2					5.9
590	94.6					5.8
600	93.0	108.5	118.5	127.1	143.3	5.8
610	91.3	99.6	109.0	117.0	132.1	5.7
620	89.6	91.5	100.2	107.7	121.7	5.6
630	87.7	84.1	92.1	99.1	112.2	5.6
640	85.8	77.2	84.7	91.2	103.4	5.5
650	83.8	70.9	77.9	83.9	95.2	5.5
660	81.8	65.2	71.6	77.2	87.8	5.4
670	79.7	59.9	65.9	71.1	80.9	5.3
680	77.5	55.0	60.6	65.4	74.5	5.3
690	75.3	50.5	55.7	60.2	68.7	5.2
700	73.0	46.4	51.2	55.4	63.3	5.2
710	70.7	42.6	47.1	51.0	58.3	5.1
720	68.3	39.2	43.3	46.9	53.7	5.1
730	65.9	36.0	39.8	43.2	49.5	5.0
740	63.5	33.0	36.6	39.7	45.6	5.0
750	61.1	30.3	33.7	36.5	42.1	4.9
760	58.6	27.9	31.0	33.6	38.8	4.9
770	56.1	25.6	28.5	31.0	35.7	4.8
780	53.6	23.5	26.2	28.5	32.9	4.8
790	51.1	21.6	24.1	26.2	30.3	4.7
800	48.7	19.8	22.1	24.1	28.0	4.7
810	46.2	18.2	20.3	22.2	25.8	4.7
820	43.8	16.7	18.7	20.4	23.7	4.6
830	41.4	15.4	17.2	18.8	21.9	4.6
840	39.0	14.1	15.8	17.3	20.2	4.5
850	36.7	13.0	14.5	15.9	18.6	4.5
860	34.5	11.9	13.4	14.7	17.1	4.5
870	32.3	11.0	12.3	13.5	15.8	4.4
880	30.1	10.1	11.3	12.4	14.5	4.4
890	28.0	9.2	10.4	11.4	13.4	4.3
900	26.0	8.5	9.6	10.5	12.3	4.3
910	24.1	7.8	8.8	9.7	11.4	4.3
920	22.2	7.2	8.1	8.9	10.5	4.2
930	20.5	6.6	7.4	8.2	9.7	4.2
940	18.8	6.0	6.8	7.5	8.9	4.2
950	17.2	5.6	6.3	6.9	8.2	4.1
960	15.7	5.1	5.8	6.4	7.6	4.1
970	14.2	4.7	5.3	5.9	7.0	4.1
980	12.9	4.3	4.9	5.4	6.4	4.0
990	11.6	4.0	4.5	5.0	5.9	4.0
1000	10.5	3.6	4.1	4.6	5.5	4.0
1010	9.4	3.3	3.8	4.2	5.0	3.9

Figure E.64: The figure shall be replaced with the following:

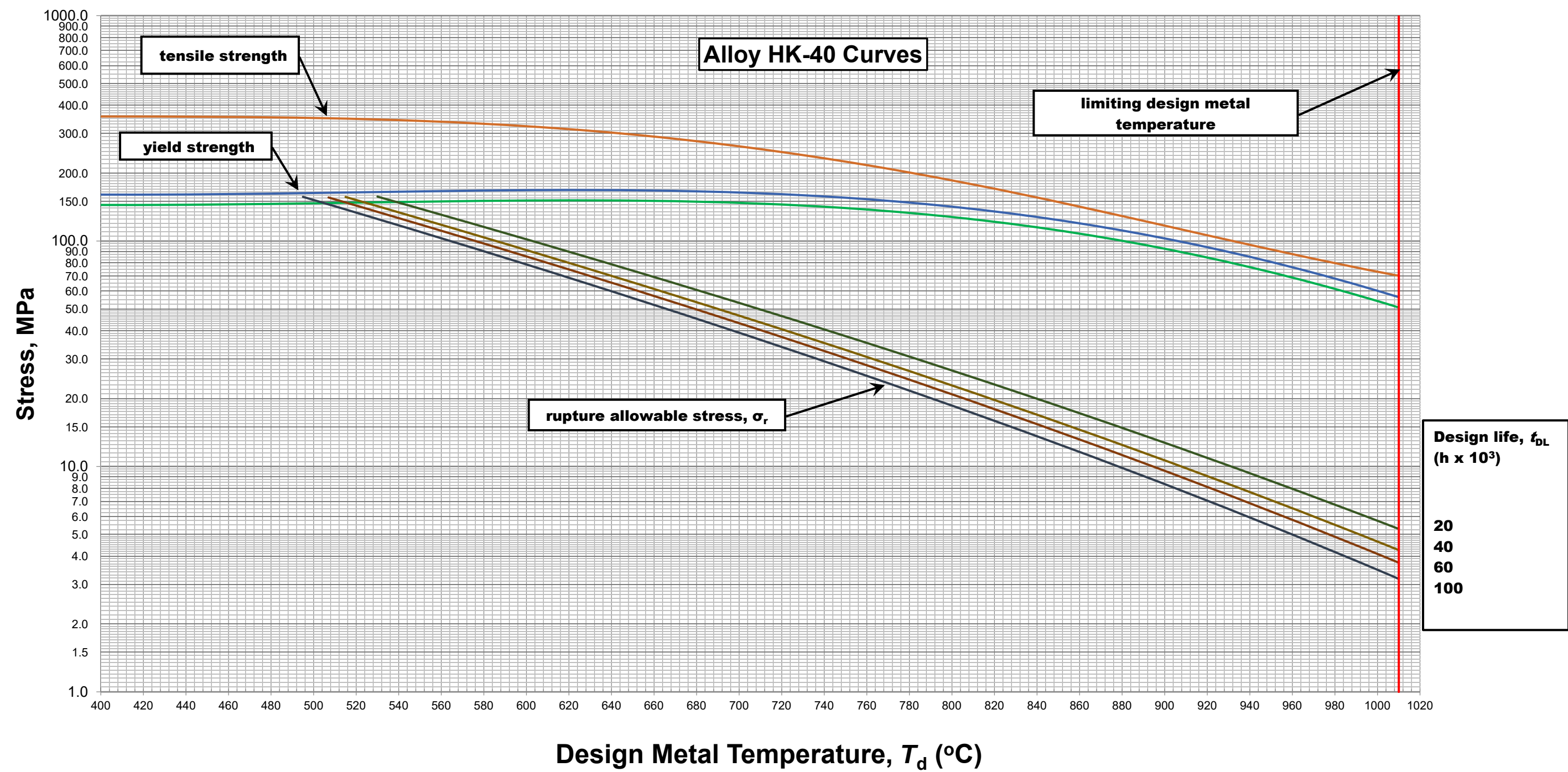


Figure E.65: The figure shall be replaced with the following:

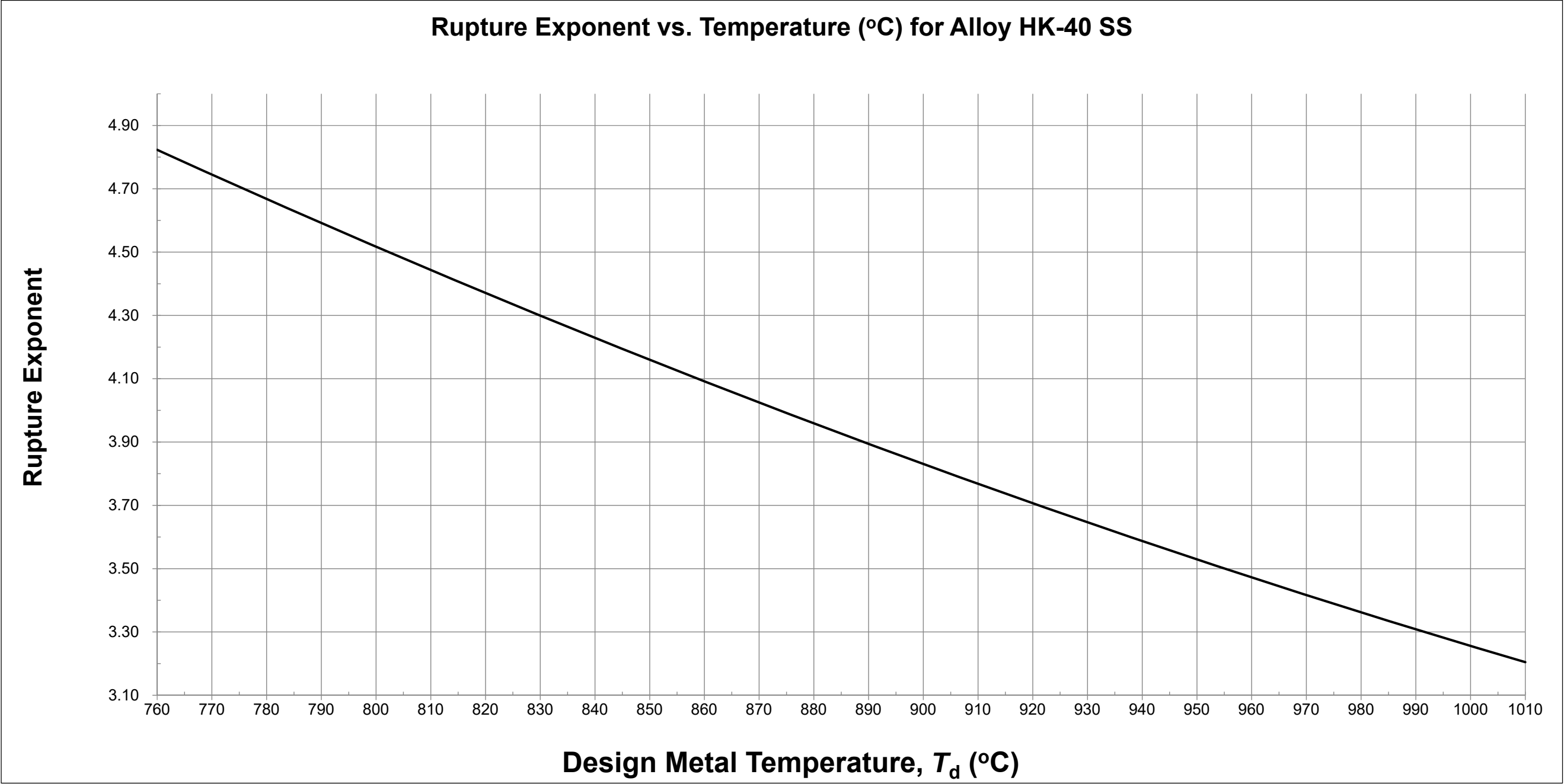


Figure E.66: The figure shall be replaced with the following:

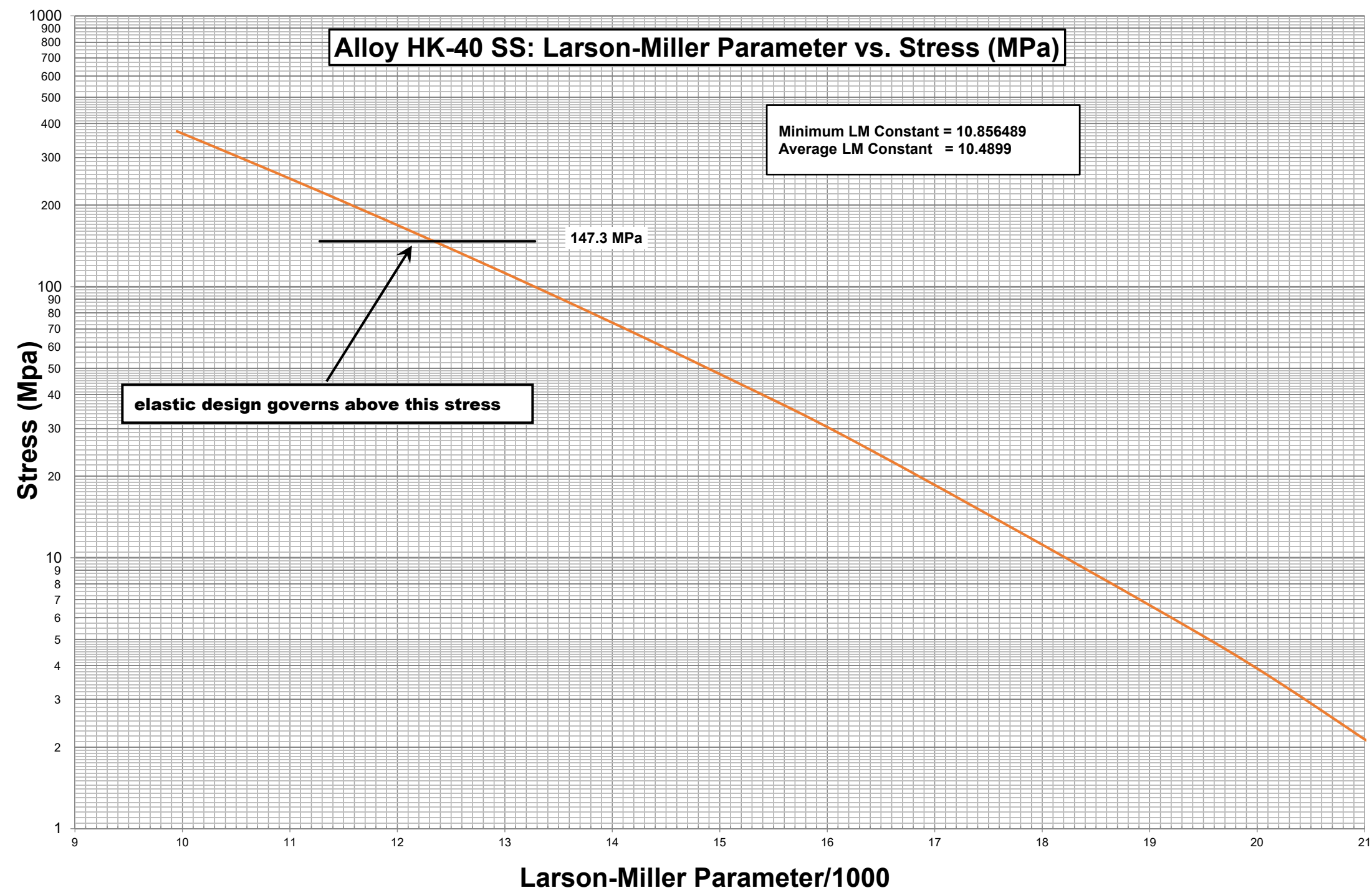


Table E.22: The table shall be replaced with the following:

Alloy HK-40						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
480	146.2					
490	146.6	162.2	173.6	183.2	200.7	
500	147.1	152.2	163.1	172.2	189.0	
510	147.6	142.7	153.1	161.9	177.9	
520	148.1	133.8	143.7	152.1	167.5	
530	148.6	125.4	134.9	142.9	157.5	
540	149.1	117.4	126.5	134.1	148.2	
550	149.6	110.0	118.6	125.9	139.3	
560	150.0	102.9	111.2	118.1	131.0	
570	150.4	96.3	104.2	110.8	123.1	
580	150.8	90.1	97.6	103.9	115.6	
590	151.1	84.3	91.4	97.4	108.6	
600	151.4	78.8	85.5	91.3	101.9	
610	151.5	73.6	80.0	85.5	95.7	
620	151.6	68.7	74.9	80.1	89.7	
630	151.6	64.2	70.0	74.9	84.2	
640	151.5	59.9	65.4	70.1	78.9	
650	151.2	55.9	61.1	65.6	73.9	
660	150.8	52.1	57.1	61.3	69.3	
670	150.3	48.6	53.3	57.3	64.9	
680	149.6	45.2	49.7	53.5	60.7	
690	148.8	42.1	46.4	50.0	56.8	
700	147.8	39.2	43.2	46.7	53.2	
710	146.6	36.5	40.3	43.6	49.7	
720	145.3	33.9	37.5	40.6	46.5	
730	143.8	31.5	34.9	37.9	43.4	
740	142.0	29.3	32.5	35.3	40.5	
750	140.1	27.2	30.2	32.9	37.8	
760	138.1	25.2	28.1	30.6	35.3	4.8
770	135.8	23.4	26.1	28.5	32.9	4.7
780	133.3	21.7	24.3	26.5	30.7	4.7
790	130.7	20.1	22.5	24.6	28.6	4.6
800	127.9	18.6	20.9	22.9	26.7	4.5
810	124.9	17.2	19.4	21.2	24.8	4.4
820	121.8	15.9	18.0	19.7	23.1	4.4
830	118.5	14.7	16.6	18.3	21.5	4.3
840	115.1	13.6	15.4	17.0	20.0	4.2
850	111.5	12.6	14.2	15.7	18.6	4.2
860	107.9	11.6	13.2	14.6	17.2	4.1
870	104.1	10.7	12.2	13.5	16.0	4.0
880	100.3	9.9	11.2	12.5	14.8	4.0
890	96.4	9.1	10.4	11.5	13.8	3.9
900	92.5	8.4	9.6	10.6	12.7	3.8
910	88.5	7.7	8.8	9.8	11.8	3.8
920	84.6	7.1	8.1	9.1	10.9	3.7
930	80.6	6.5	7.5	8.4	10.1	3.6
940	76.6	5.9	6.9	7.7	9.3	3.6
950	72.7	5.4	6.3	7.1	8.6	3.5
960	68.9	5.0	5.8	6.5	8.0	3.5
970	65.1	4.6	5.3	6.0	7.3	3.4
980	61.3	4.2	4.9	5.5	6.8	3.4
990	57.7	3.8	4.5	5.1	6.2	3.3
1000	54.2	3.5	4.1	4.6	5.7	3.3
1010	50.7	3.2	3.7	4.3	5.3	3.2

Figure E.67: The following figure, Figure E.67, shall be added to the document:

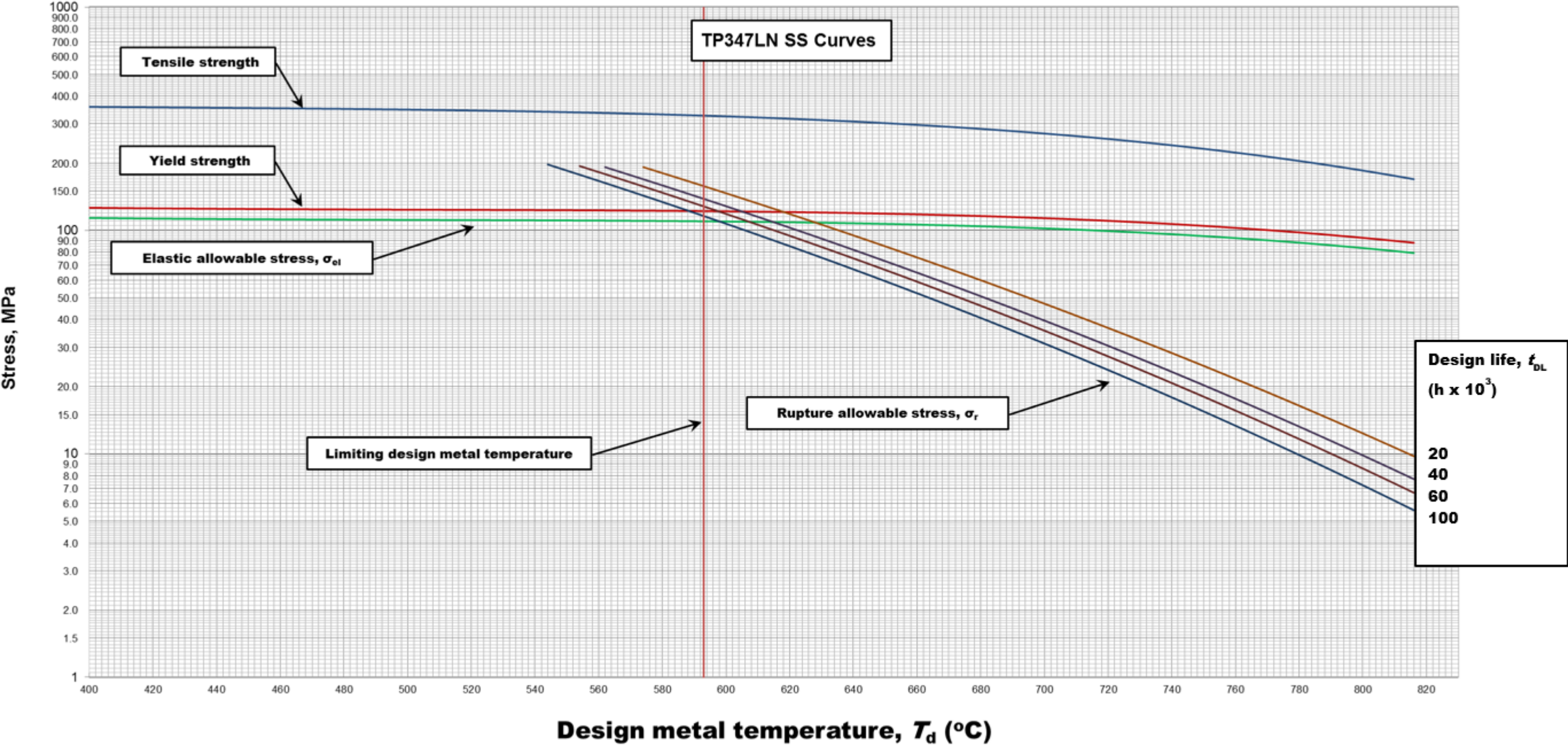


Figure E.67—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.68: The following figure, Figure E.68, shall be added to the document:

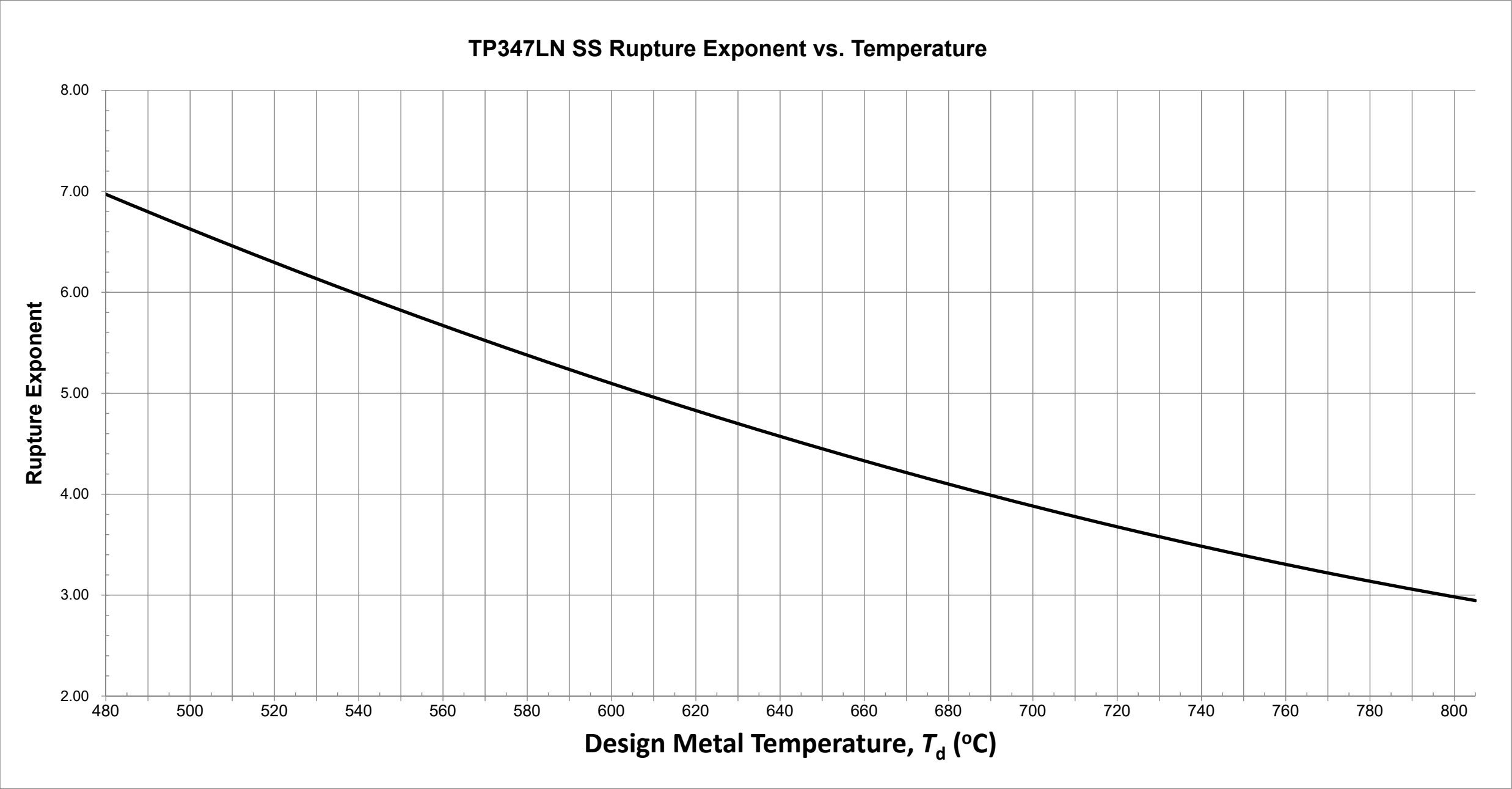


Figure E.68—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.69: The following figure, Figure E.69, shall be added to the document:

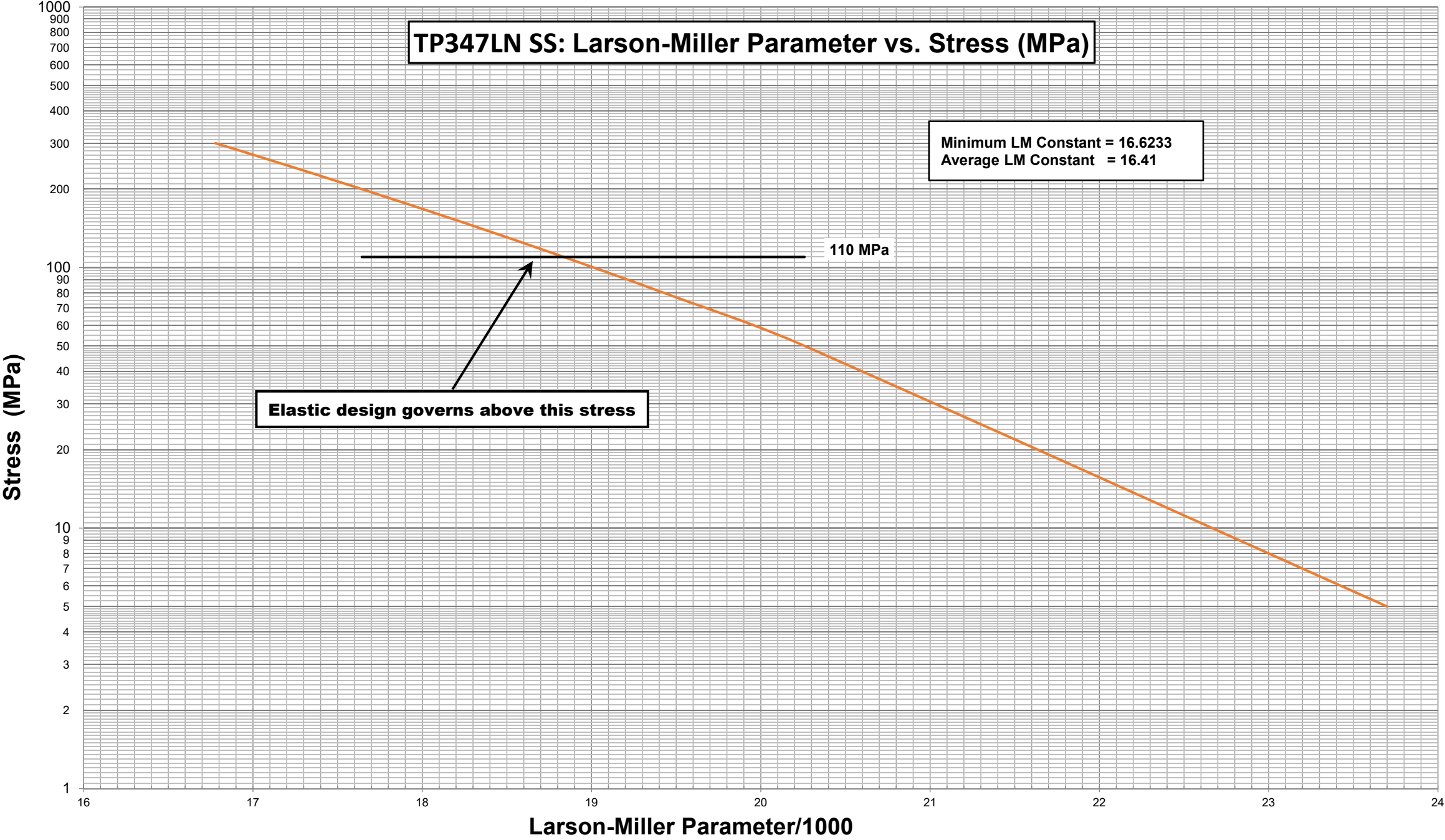


Figure E.69—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table E.23: The following table, Table E.23, shall be added to the document:

TP347LN SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000$ h (MPa)	$t_{DL} = 60,000$ h (MPa)	$t_{DL} = 40,000$ h (MPa)	$t_{DL} = 20,000$ h (MPa)	
400	113.8					
410	113.4					
420	113.1					
430	112.8					
440	112.5					
450	112.3					
460	112.1					
470	111.9					
480	111.8					
490	111.7					
500	111.5					
510	111.4					
520	111.3					
530	111.2					
540	111.1	205.9	224.4	240.2	269.2	6.0
550	110.9	185.4	202.6	217.2	244.2	5.9
560	110.7	166.8	182.6	196.1	221.2	5.7
570	110.5	149.7	164.4	176.9	200.1	5.6
580	110.3	134.2	147.7	159.2	180.8	5.4
590	110.0	120.1	132.5	143.1	163.0	5.3
600	109.7	107.2	118.7	128.5	146.8	5.1
610	109.3	95.6	106.1	115.1	132.1	5.0
620	108.9	85.1	94.7	103.0	118.6	4.9
630	108.3	75.6	84.4	92.0	106.3	4.7
640	107.7	67.0	75.0	82.0	95.1	4.6
650	107.1	59.3	66.6	72.9	85.0	4.5
660	106.3	52.4	59.0	64.8	75.8	4.4
670	105.4	46.2	52.2	57.4	67.4	4.2
680	104.5	40.6	46.0	50.8	59.9	4.1
690	103.4	35.6	40.5	44.8	53.1	4.0
700	102.2	31.2	35.6	39.5	47.0	3.9
710	100.9	27.2	31.2	34.7	41.5	3.8
720	99.5	23.7	27.3	30.5	36.6	3.7
730	97.9	20.6	23.8	26.7	32.2	3.6
740	96.2	17.9	20.8	23.3	28.3	3.5
750	94.4	15.5	18.0	20.3	24.8	3.4
760	92.5	13.4	15.6	17.7	21.7	3.3
770	90.4	11.5	13.5	15.3	18.9	3.2
780	88.2	9.9	11.7	13.2	16.4	3.2
790	85.9	8.5	10.0	11.4	14.3	3.1
800	83.5	7.2	8.6	9.8	12.4	3.0
810	80.9	6.2	7.4	8.5	10.7	2.9
816	79.3	5.6	6.7	7.7	9.8	2.9

Annex F, List of Figures and Tables (USC Units): The titles of the indicated tables shall be changed to the following:

Table F.9—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Figure F.34—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Figure F.35—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Figure F.36—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Table F.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Table F.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Figure F.40—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

Figure F.41—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Figure F.42—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table F.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table F.21—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table F.22—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A608 Grade HK-40 Steels

Annex F, List of Figures and Tables (USC Units): The following titles shall be added to the list:

TP 347LN Stainless Steels

Figure F.67—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.68—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.69—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table F.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.25: The figure shall be replaced with the following:

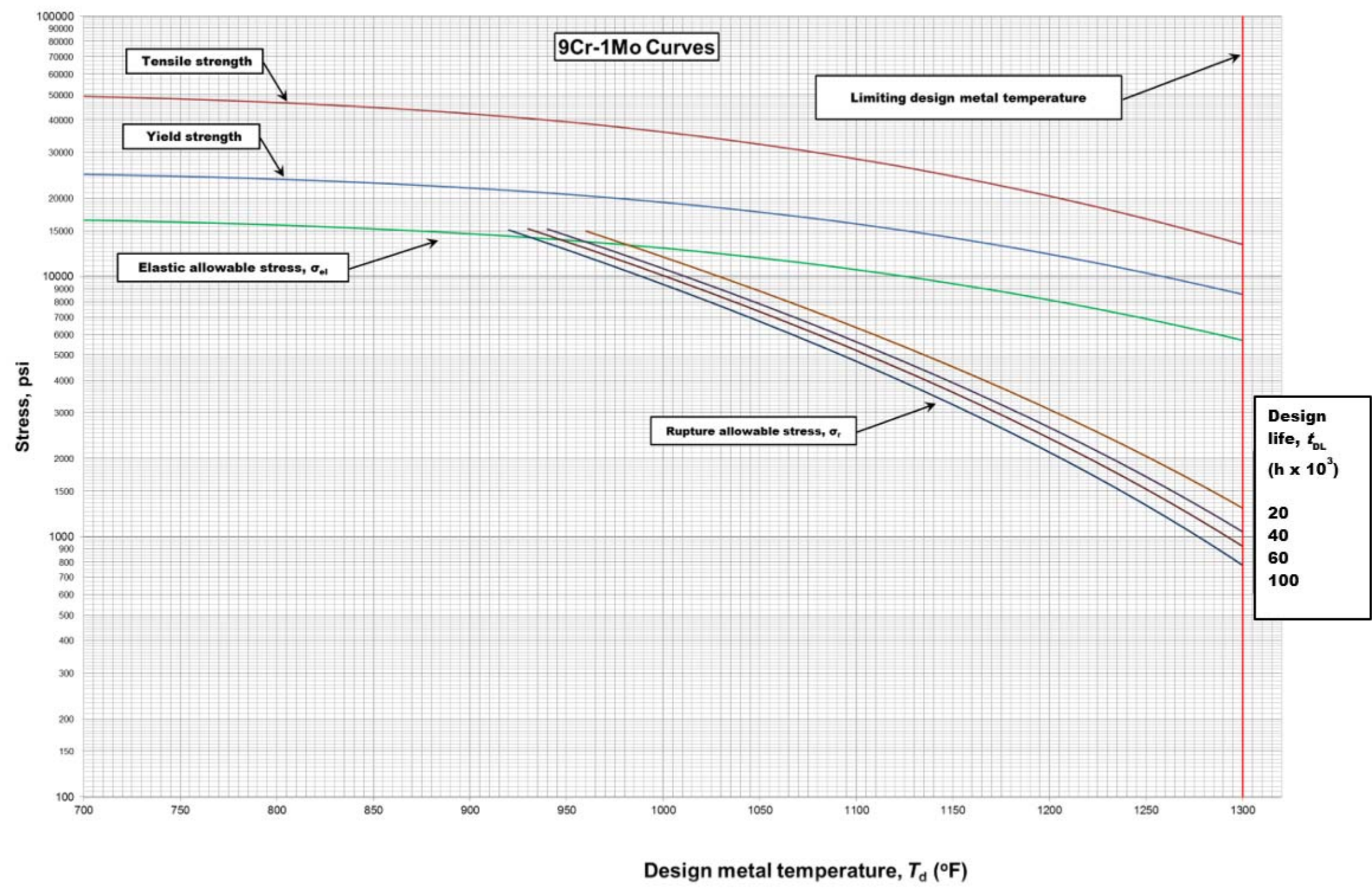


Figure F.26: The figure shall be replaced with the following:

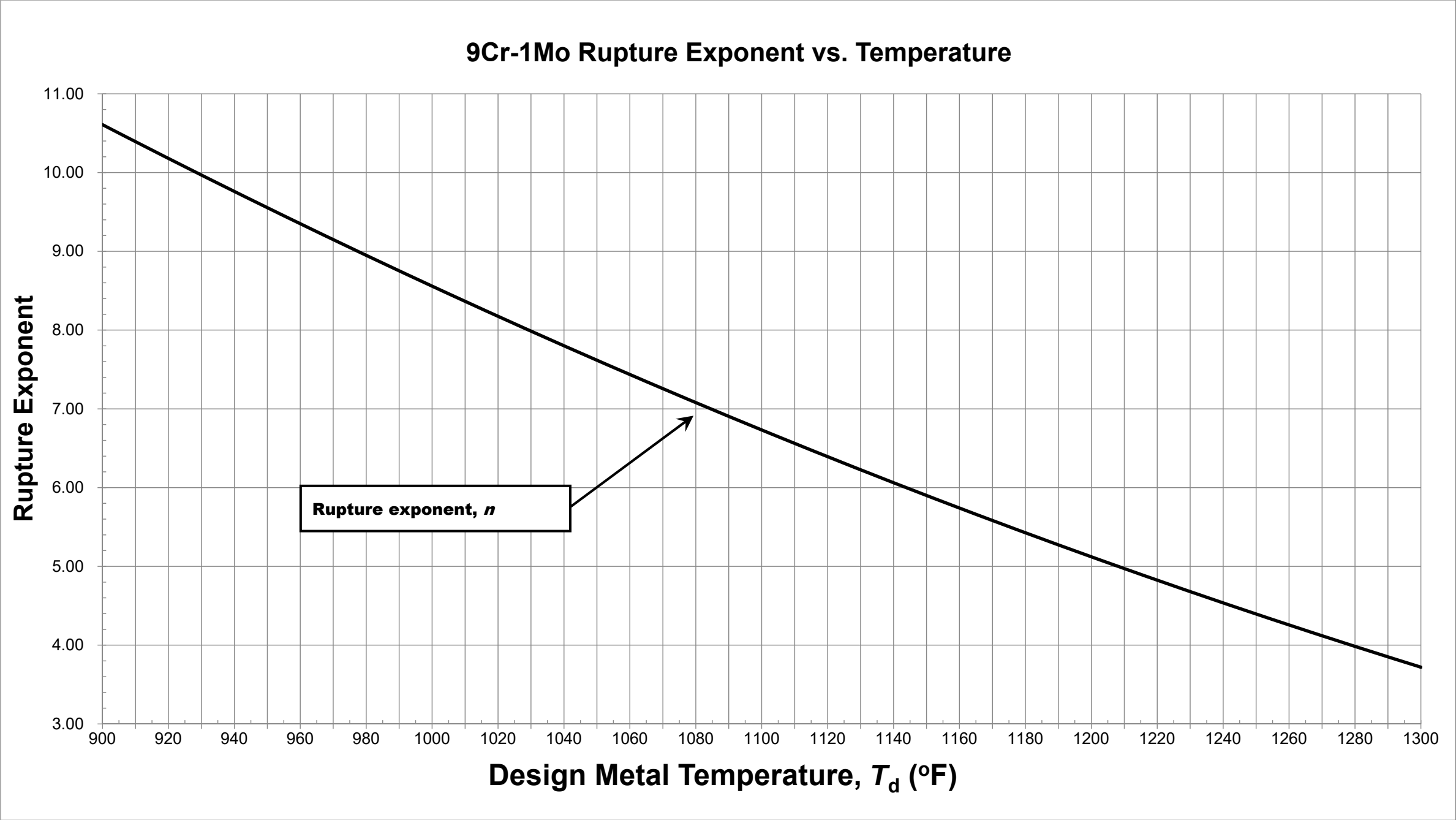


Figure F.27: The figure shall be replaced with the following:

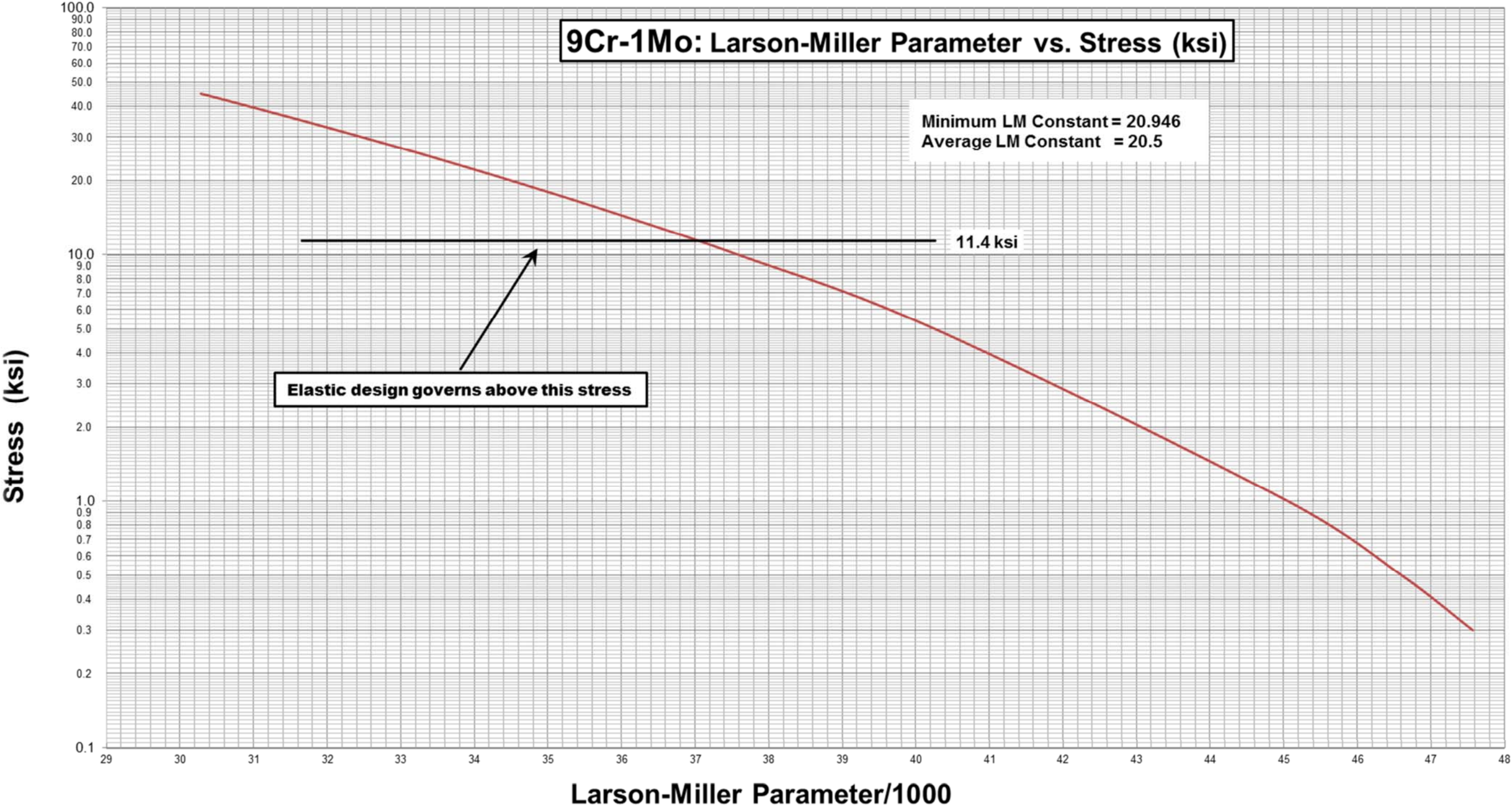


Table F.9: The table shall be replaced by the following:

9Cr-1Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	16.5					
720	16.4					
740	16.3					
760	16.1					
780	16.0					
800	15.8					
820	15.6					
840	15.4					
860	15.1					
880	14.9					
900	14.6					
920	14.3					
920	14.3	15.1	16.2	17.0	18.6	10.6
940	14.0	13.5	14.4	15.2	16.7	10.2
960	13.6	11.9	12.8	13.6	15.0	9.8
980	13.3	10.6	11.4	12.1	13.4	9.4
1000	12.9	9.3	10.1	10.7	11.9	8.9
1020	12.5	8.2	8.9	9.5	10.6	8.6
1040	12.0	7.2	7.8	8.4	9.4	8.2
1060	11.6	6.3	6.9	7.4	8.3	7.8
1080	11.1	5.5	6.0	6.4	7.3	7.4
1100	10.6	4.7	5.2	5.6	6.4	7.1
1120	10.1	4.1	4.5	4.9	5.6	6.7
1140	9.6	3.5	3.9	4.2	4.8	6.4
1160	9.1	3.0	3.3	3.6	4.2	6.1
1180	8.6	2.5	2.8	3.1	3.6	5.7
1200	8.1	2.1	2.4	2.6	3.1	5.4
1220	7.6	1.8	2.0	2.2	2.6	5.1
1240	7.1	1.5	1.7	1.9	2.2	4.8
1260	6.6	1.2	1.4	1.6	1.9	4.5
1280	6.2	1.0	1.1	1.3	1.6	4.3
1300	5.7	0.8	0.9	1.0	1.3	4.0
						3.7

Figure F.34: The figure shall be replaced with the following:

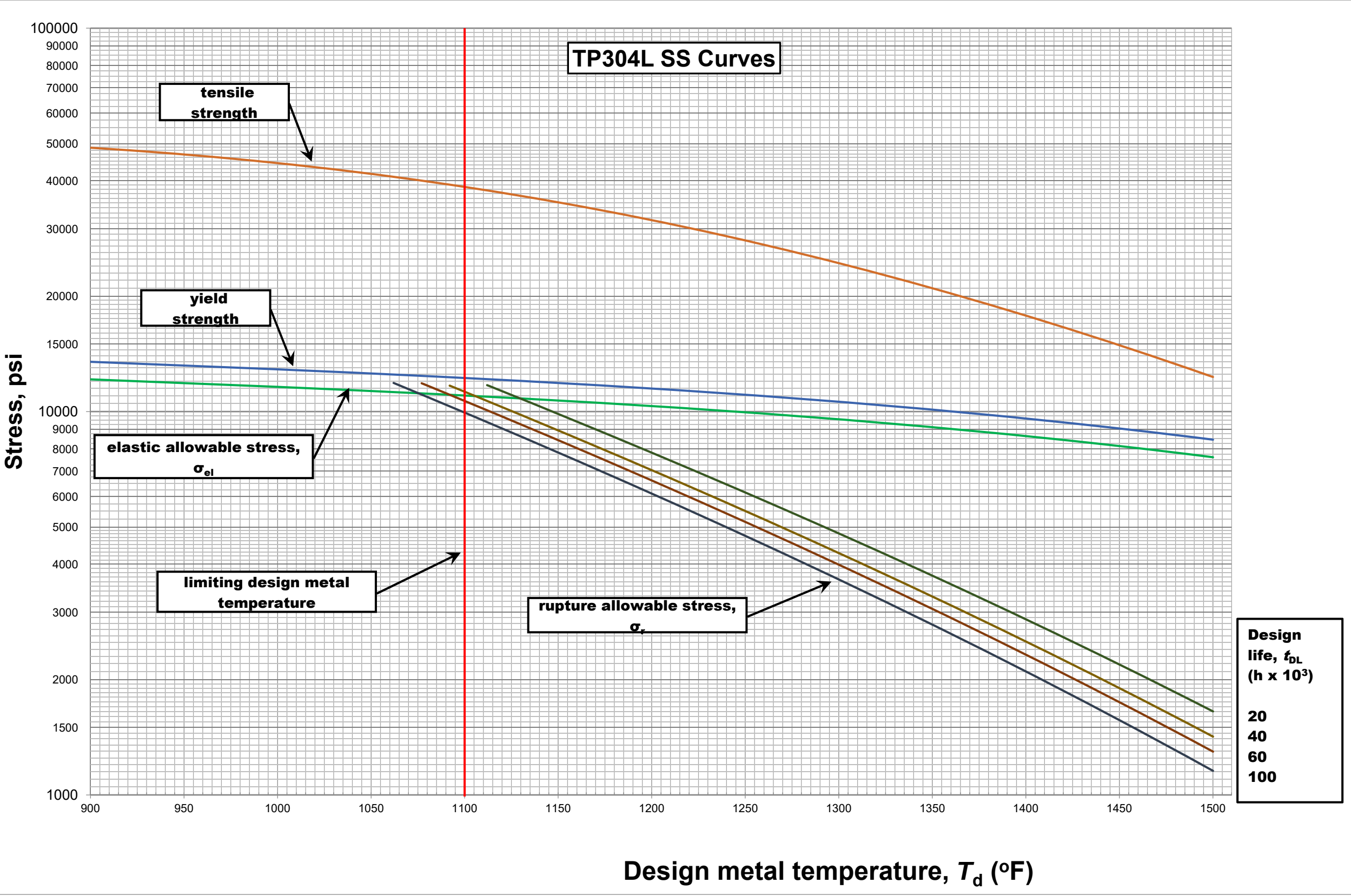


Figure F.35: The figure shall be replaced with the following:

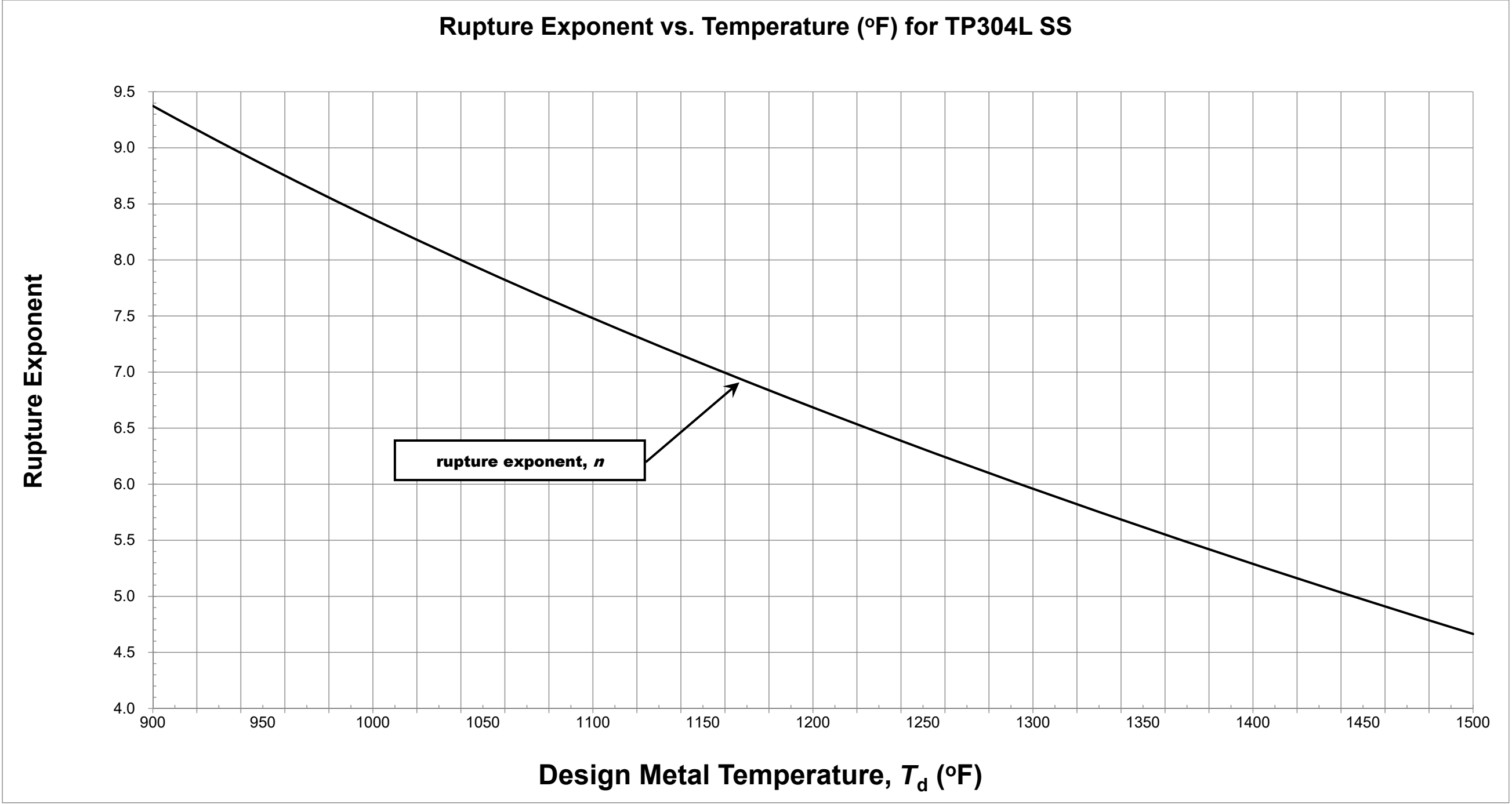


Figure F.36: The figure shall be replaced with the following:

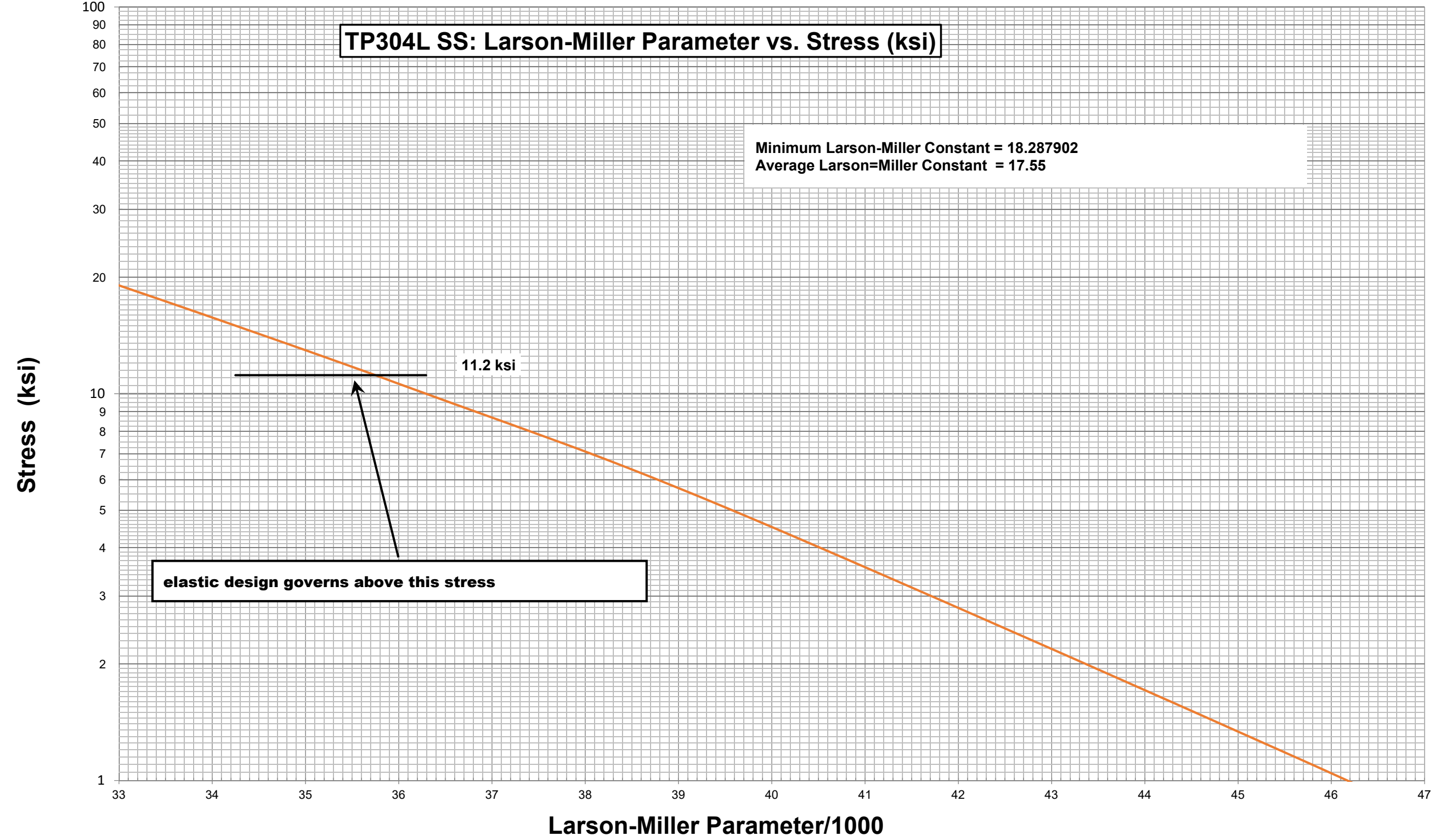


Table F.12: The table shall be replaced with the following:

TP304L SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	12.7					
820	12.6					
840	12.5					
860	12.4					
880	12.2					
900	12.1					9.4
920	12.0					9.2
940	11.9					9.0
960	11.8					8.8
980	11.7					8.6
1000	11.6					8.4
1020	11.5					8.2
1040	11.4					8.0
1060	11.3					7.8
1080	11.1					7.6
1100	11.0					7.5
1120	10.9					7.3
1140	10.8					7.2
1160	10.6					7.0
1180	10.5					6.8
1200	10.3					6.7
1220	10.2					6.5
1240	10.0					6.4
1260	9.9					6.2
1280	9.7					6.1
1300	9.5					6.0
1320	9.4					5.8
1340	9.2					5.7
1360	9.0					5.6
1380	8.8					5.4
1400	8.6					5.3
1420	8.4					5.2
1440	8.2					5.0
1460	8.0					4.9
1480	7.8					4.8
1500	7.6					4.7

Figure F.40: The figure shall be replaced with the following:

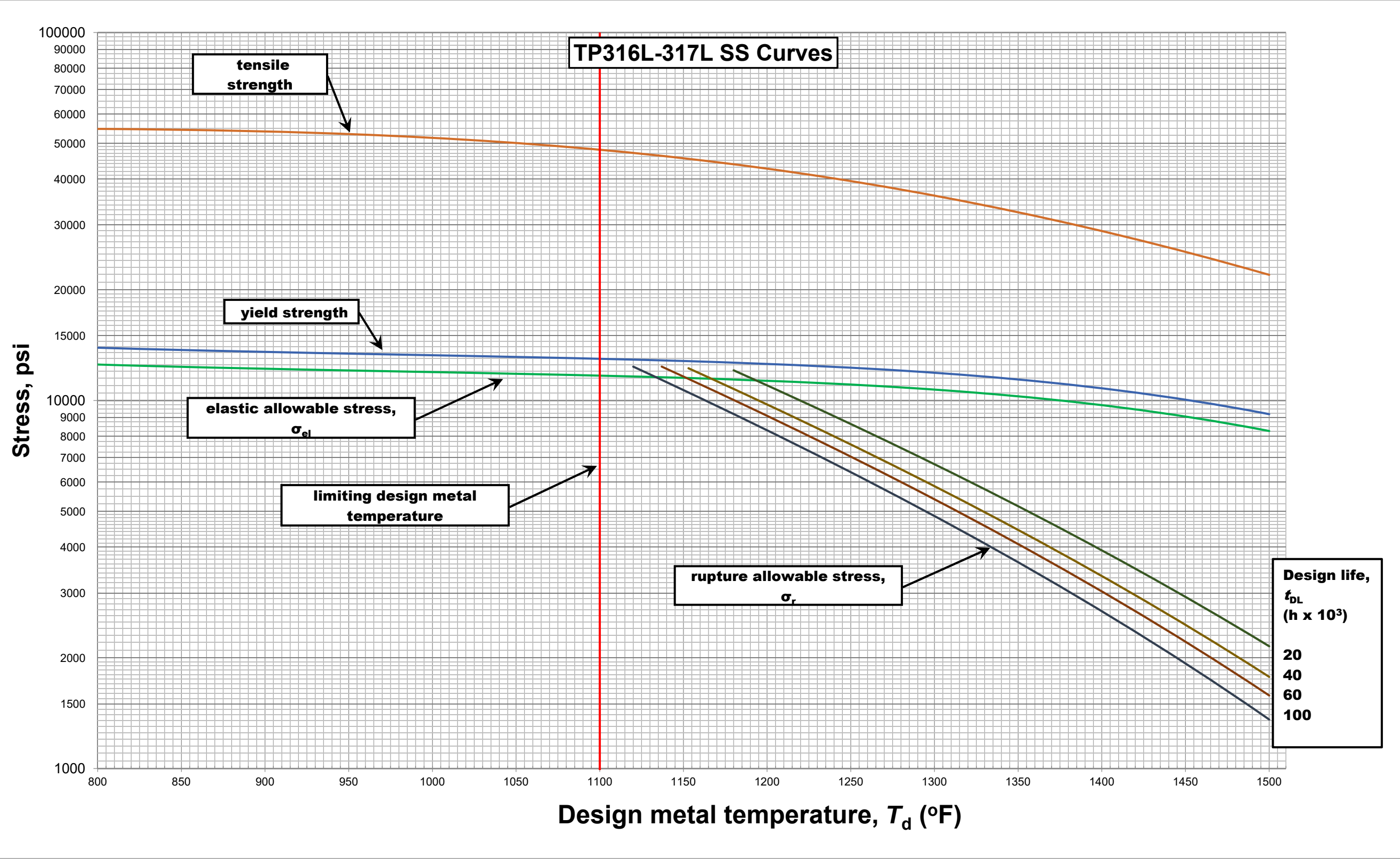


Figure F.41: The figure shall be replaced with the following:

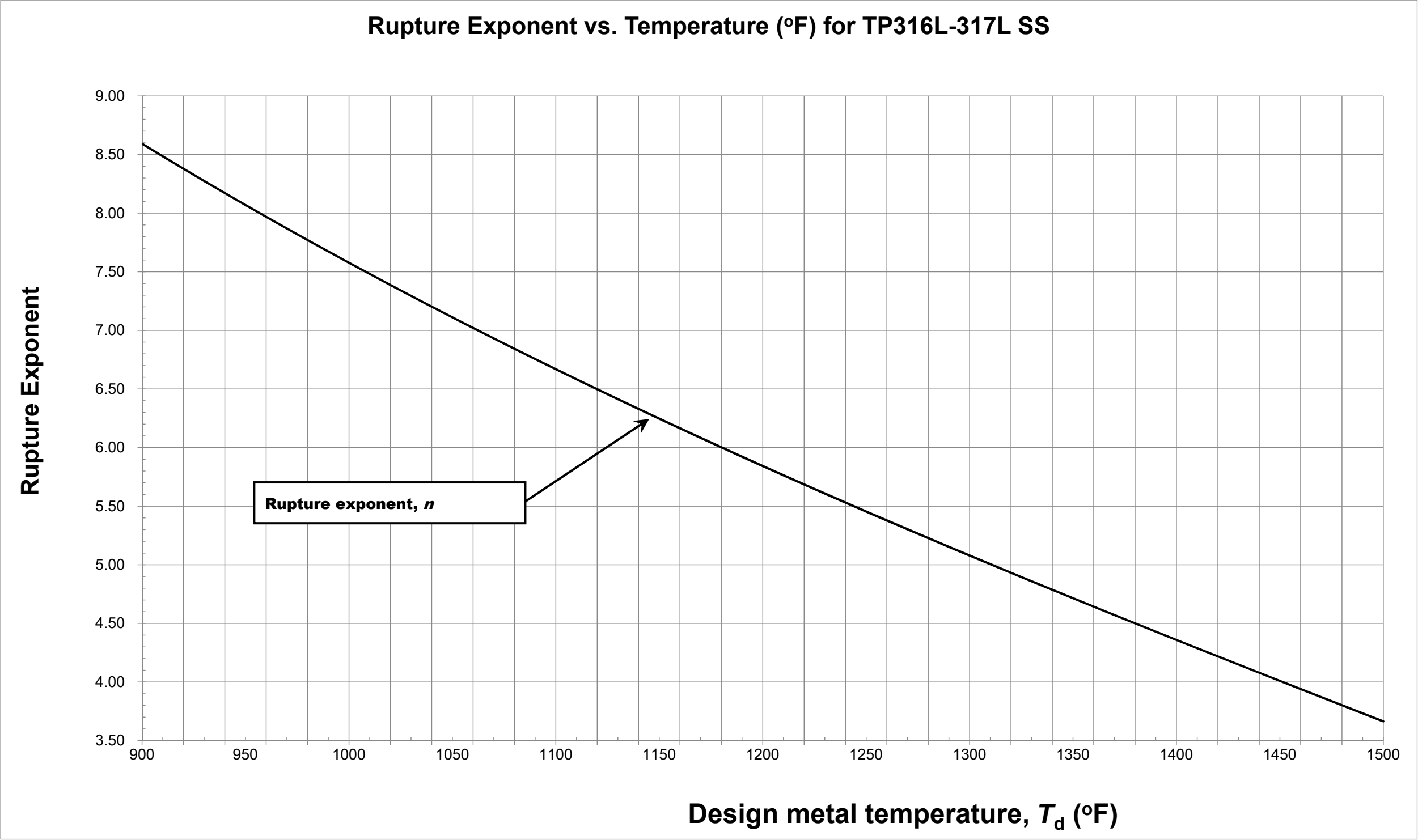


Figure F.42: The figure shall be replaced with the following:

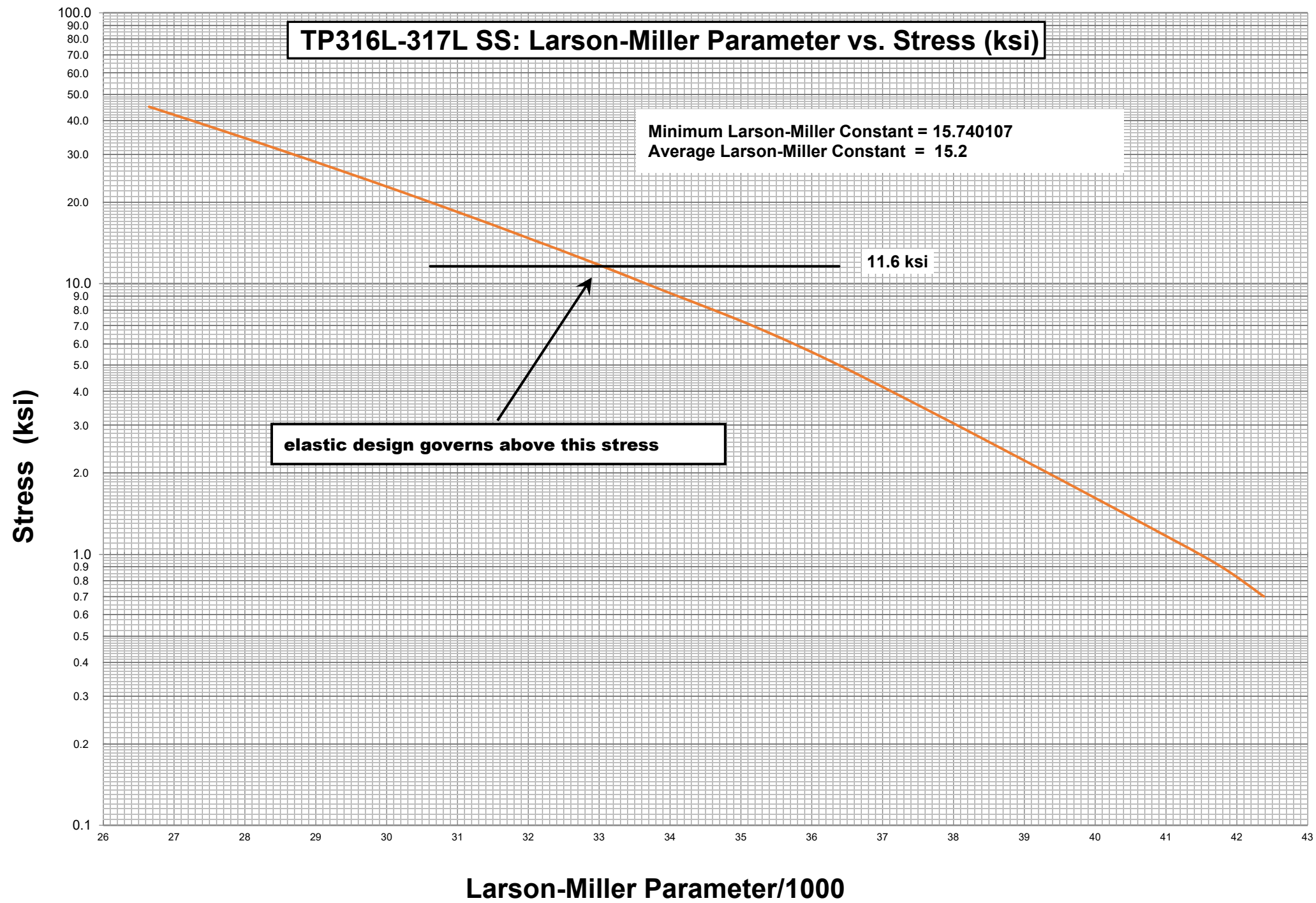


Table F.14: The table shall be replaced with the following:

TP316L-317L SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	12.5					
820	12.5					
840	12.4					
860	12.3					
880	12.3					
900	12.2					8.6
920	12.2					8.4
940	12.1					8.2
960	12.0					8.0
980	12.0					7.8
1000	12.0					7.6
1020	11.9					7.4
1040	11.9					7.2
1060	11.8					7.0
1080	11.7					6.8
1100	11.7					6.7
1120	11.6					6.5
1140	11.6					6.3
1160	11.5					6.2
1180	11.4					6.0
1200	11.3					5.8
1220	11.2					5.7
1240	11.1					5.5
1260	11.0					5.4
1280	10.9					5.2
1300	10.7					5.1
1320	10.5					4.9
1340	10.4					4.8
1360	10.2					4.6
1380	10.0					4.5
1400	9.7					4.4
1420	9.5					4.2
1440	9.2					4.1
1460	8.9					3.9
1480	8.6					3.8
1500	8.3					3.7

Figure F.61: The figure shall be replaced with the following:

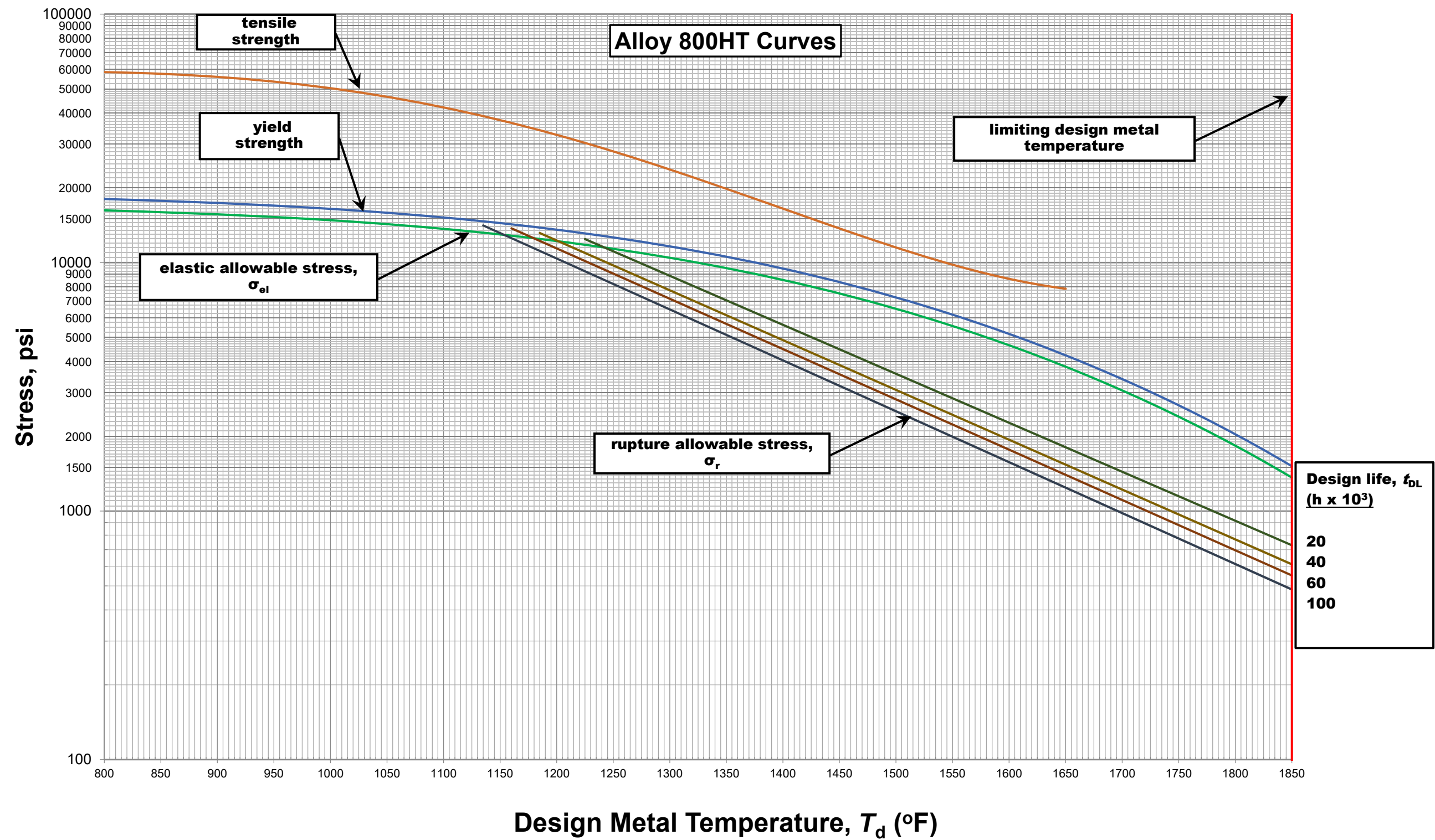


Figure F.62: The figure shall be replaced with the following:

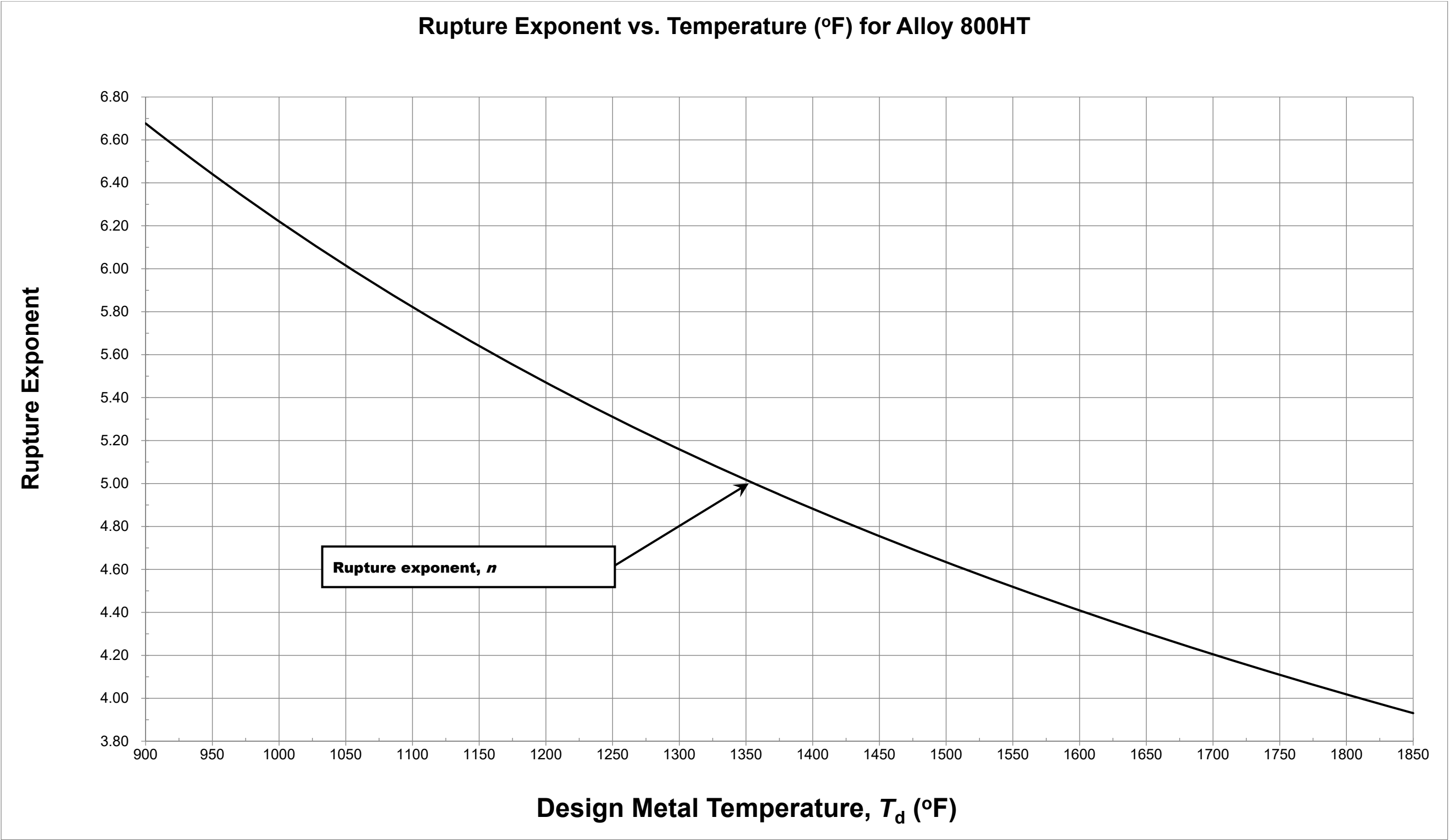


Figure F.63: The figure shall be replaced with the following:

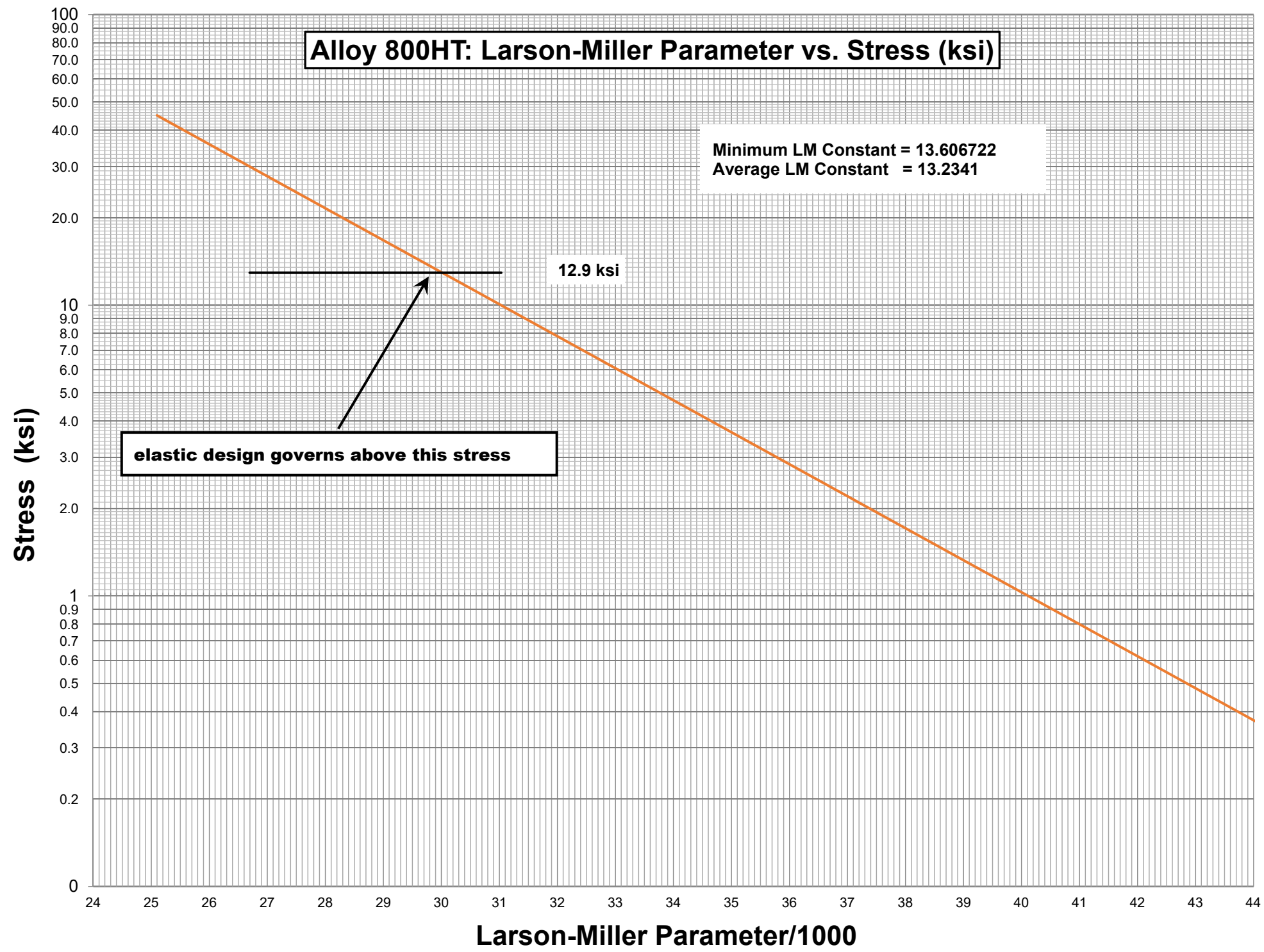


Table F.21: The table shall be replaced with the following:

Alloy 800HT						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	16.2					
820	16.1					
840	16.0					
860	15.9					
880	15.8					
900	15.6					6.7
920	15.5					6.6
940	15.3					6.5
960	15.2					6.4
980	15.0					6.3
1000	14.8					6.2
1020	14.6					6.1
1040	14.4					6.1
1060	14.2					6.0
1080	13.9					5.9
1100	13.7					5.8
1120	13.4	15.2	16.6	17.8	20.0	5.7
1140	13.1	13.8	15.1	16.2	18.3	5.7
1160	12.8	12.5	13.7	14.8	16.7	5.6
1180	12.5	11.4	12.5	13.5	15.3	5.5
1200	12.2	10.4	11.4	12.3	13.9	5.5
1220	11.9	9.5	10.4	11.2	12.7	5.4
1240	11.5	8.6	9.5	10.2	11.6	5.3
1260	11.2	7.8	8.6	9.3	10.6	5.3
1280	10.8	7.1	7.9	8.5	9.7	5.2
1300	10.5	6.5	7.2	7.7	8.9	5.2
1320	10.1	5.9	6.5	7.1	8.1	5.1
1340	9.7	5.4	5.9	6.4	7.4	5.0
1360	9.3	4.9	5.4	5.9	6.7	5.0
1380	8.9	4.4	4.9	5.3	6.2	4.9
1400	8.5	4.0	4.5	4.9	5.6	4.9
1420	8.1	3.7	4.1	4.4	5.1	4.8
1440	7.7	3.3	3.7	4.1	4.7	4.8
1460	7.3	3.0	3.4	3.7	4.3	4.7
1480	6.9	2.8	3.1	3.4	3.9	4.7
1500	6.5	2.5	2.8	3.1	3.6	4.6
1520	6.1	2.3	2.6	2.8	3.3	4.6
1540	5.8	2.1	2.3	2.6	3.0	4.5
1560	5.4	1.9	2.1	2.3	2.7	4.5
1580	5.0	1.7	1.9	2.1	2.5	4.5
1600	4.7	1.6	1.8	1.9	2.3	4.4
1620	4.3	1.4	1.6	1.8	2.1	4.4
1640	4.0	1.3	1.5	1.6	1.9	4.3
1660	3.7	1.2	1.3	1.5	1.7	4.3
1680	3.4	1.1	1.2	1.3	1.6	4.2
1700	3.1	1.0	1.1	1.2	1.4	4.2
1720	2.8	0.9	1.0	1.1	1.3	4.2
1740	2.5	0.8	0.9	1.0	1.2	4.1
1760	2.3	0.7	0.8	0.9	1.1	4.1
1780	2.0	0.7	0.8	0.8	1.0	4.1
1800	1.8	0.6	0.7	0.8	0.9	4.0
1820	1.6	0.6	0.6	0.7	0.8	4.0
1840	1.5	0.5	0.6	0.6	0.8	3.9
1850	1.4	0.5	0.6	0.6	0.7	3.9

Figure F.64: The figure shall be replaced with the following:

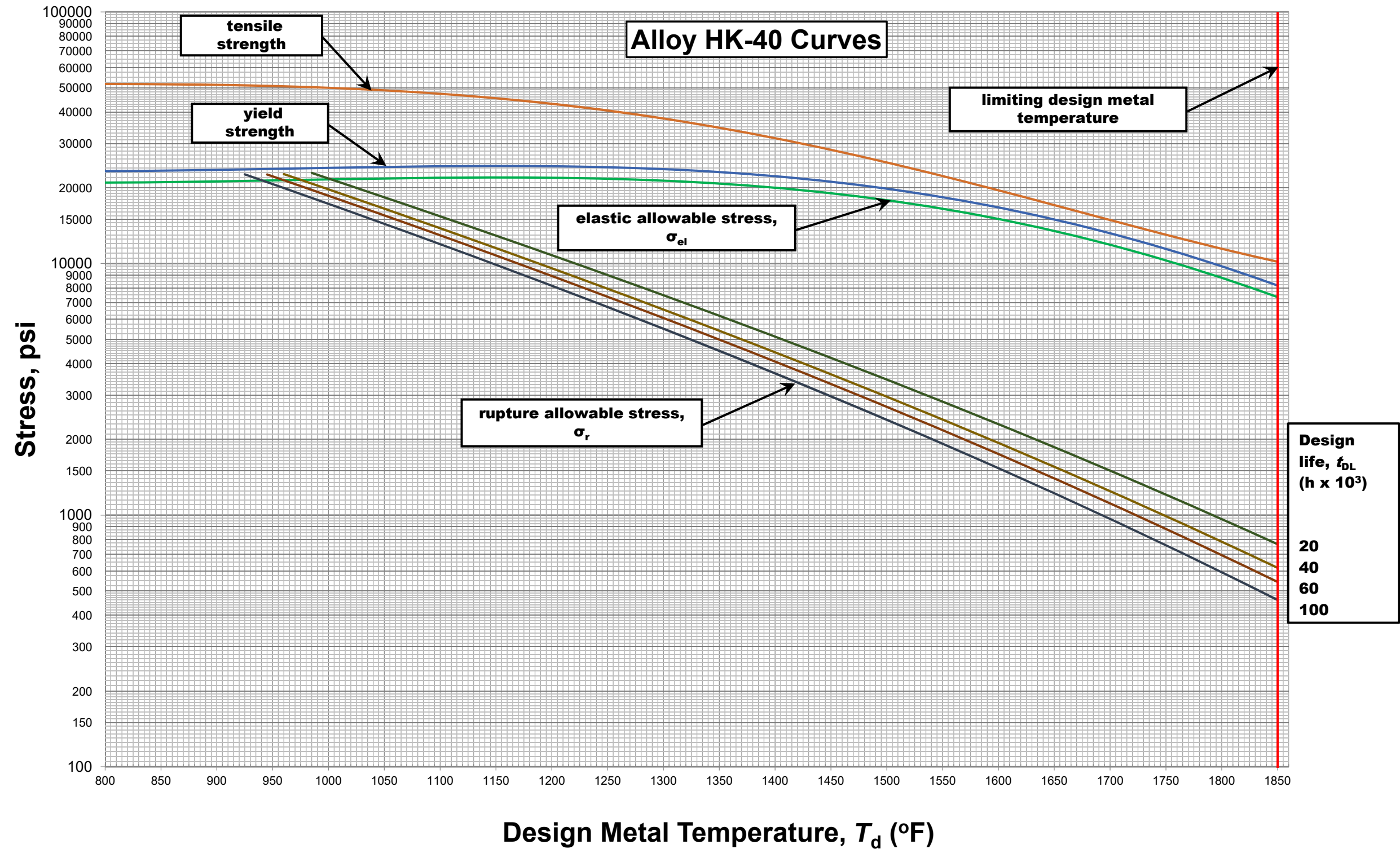


Figure F.65: The figure shall be replaced with the following:

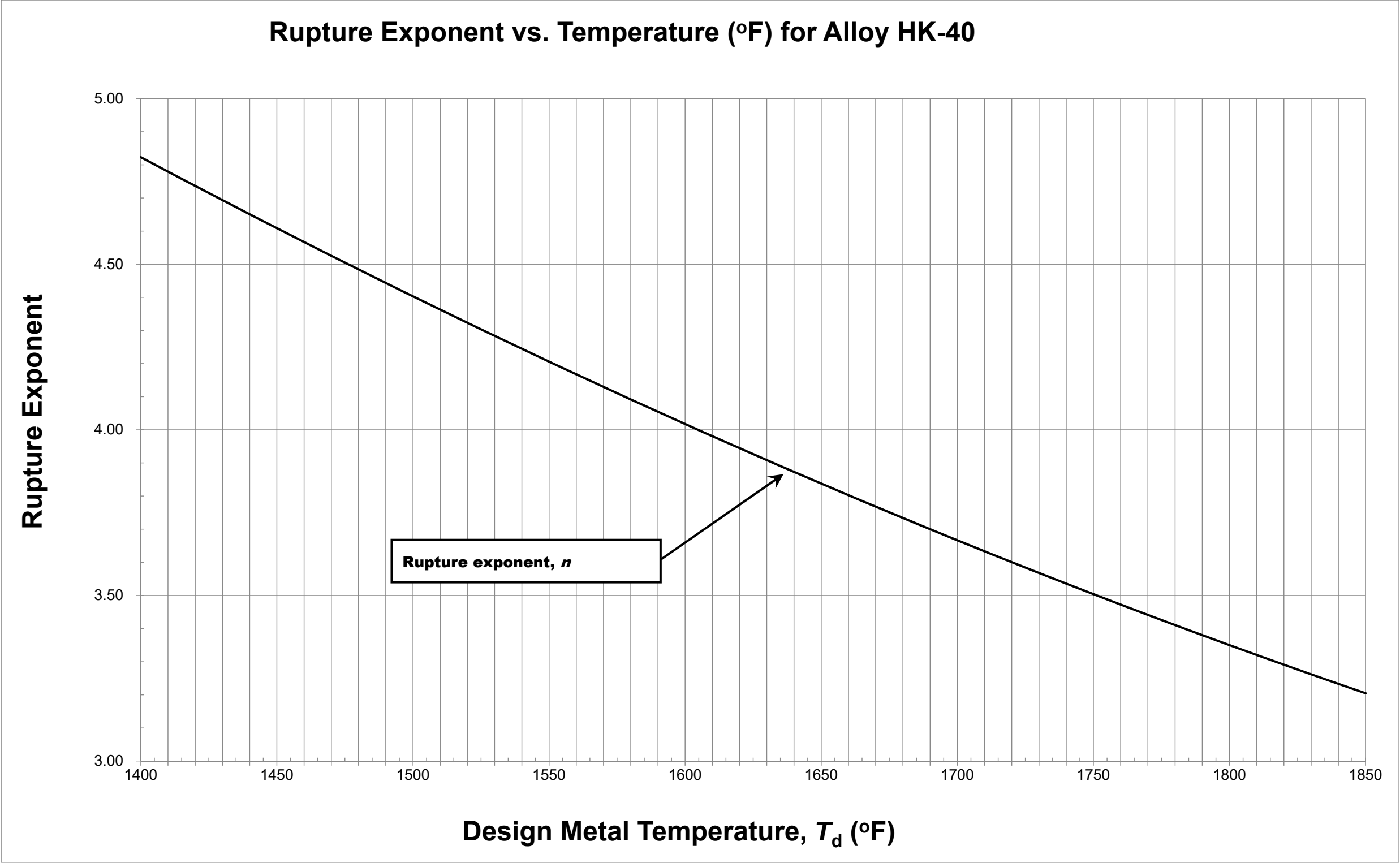


Figure F.66: The figure shall be replaced with the following:

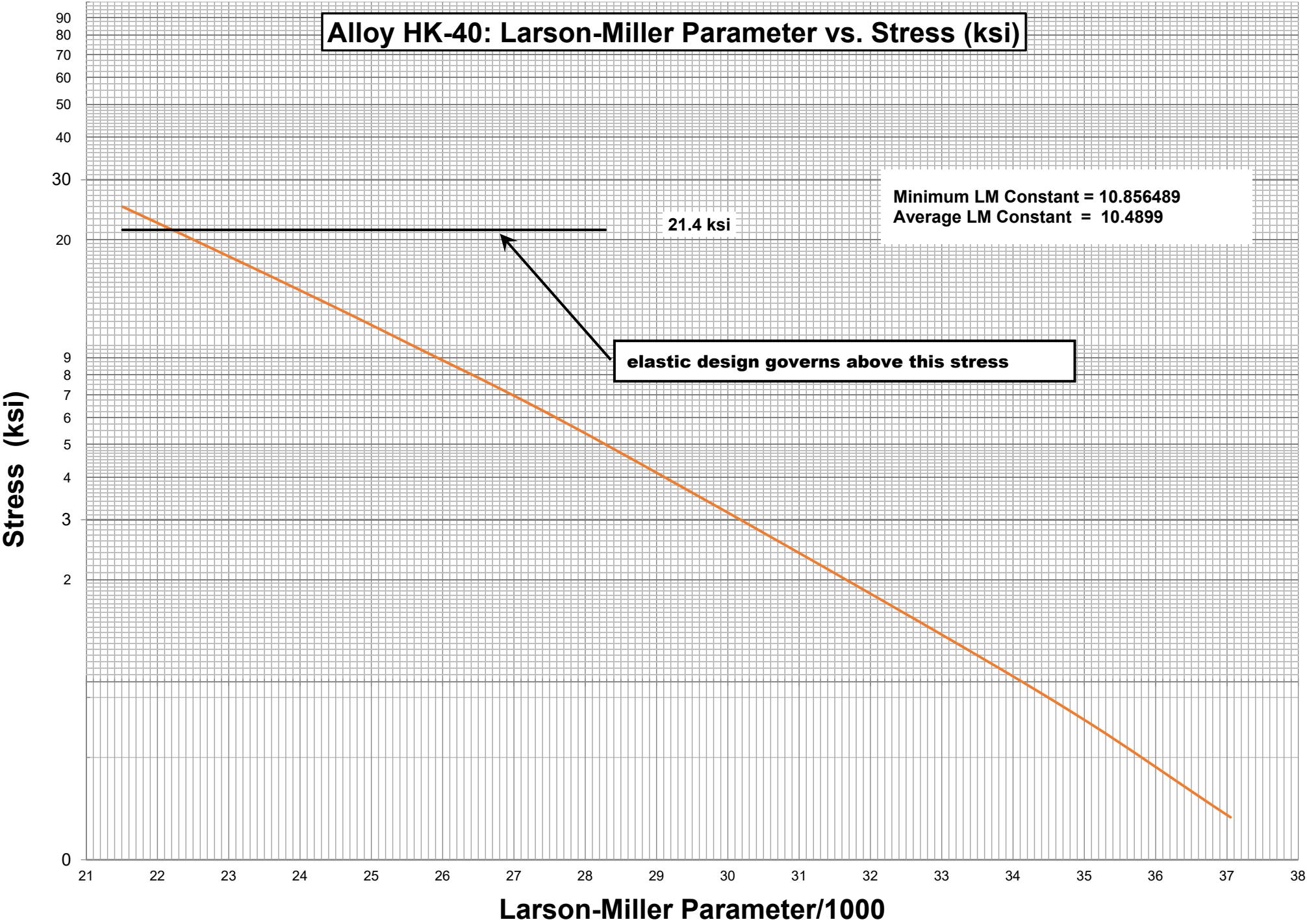


Table F.22: The table shall be replaced with the following:

Alloy HK-40						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	21.0					
820	21.0					
840	21.0					
860	21.1					
880	21.2					
900	21.2	24.7	26.4	27.9	30.5	
920	21.3	23.0	24.7	26.0	28.5	
940	21.4	21.5	23.0	24.3	26.7	
960	21.4	20.0	21.4	22.7	25.0	
980	21.5	18.6	20.0	21.2	23.3	
1000	21.6	17.3	18.6	19.7	21.8	
1020	21.7	16.1	17.3	18.4	20.3	
1040	21.8	14.9	16.1	17.1	19.0	
1060	21.8	13.9	15.0	16.0	17.7	
1080	21.9	12.9	13.9	14.9	16.5	
1100	21.9	12.0	13.0	13.8	15.4	
1120	22.0	11.1	12.0	12.9	14.4	
1140	22.0	10.3	11.2	12.0	13.4	
1160	22.0	9.5	10.4	11.1	12.5	
1180	22.0	8.8	9.6	10.3	11.6	
1200	21.9	8.2	8.9	9.6	10.8	
1220	21.9	7.6	8.3	8.9	10.0	
1240	21.8	7.0	7.7	8.2	9.3	
1260	21.7	6.5	7.1	7.6	8.7	
1280	21.5	6.0	6.6	7.1	8.1	
1300	21.4	5.5	6.1	6.6	7.5	
1320	21.2	5.1	5.6	6.1	6.9	
1340	20.9	4.7	5.2	5.6	6.4	
1360	20.7	4.3	4.8	5.2	6.0	
1380	20.4	4.0	4.4	4.8	5.5	
1400	20.0	3.7	4.1	4.4	5.1	4.8
1420	19.7	3.4	3.8	4.1	4.7	4.7
1440	19.3	3.1	3.5	3.8	4.4	4.7
1460	18.8	2.8	3.2	3.5	4.1	4.6
1480	18.4	2.6	2.9	3.2	3.7	4.5
1500	17.9	2.4	2.7	3.0	3.5	4.4
1520	17.3	2.2	2.5	2.7	3.2	4.3
1540	16.8	2.0	2.3	2.5	2.9	4.2
1560	16.2	1.8	2.1	2.3	2.7	4.2
1580	15.6	1.7	1.9	2.1	2.5	4.1
1600	15.0	1.5	1.8	1.9	2.3	4.0
1620	14.4	1.4	1.6	1.8	2.1	3.9
1640	13.8	1.3	1.5	1.6	1.9	3.9
1660	13.2	1.2	1.3	1.5	1.8	3.8
1680	12.5	1.1	1.2	1.4	1.6	3.7
1700	11.9	1.0	1.1	1.2	1.5	3.7
1720	11.2	0.9	1.0	1.1	1.4	3.6
1740	10.6	0.8	0.9	1.0	1.3	3.5
1760	10.0	0.7	0.8	0.9	1.2	3.5
1780	9.4	0.7	0.8	0.9	1.1	3.4
1800	8.8	0.6	0.7	0.8	1.0	3.3
1820	8.2	0.5	0.6	0.7	0.9	3.3
1840	7.6	0.5	0.6	0.6	0.8	3.2
1850	7.4	0.5	0.5	0.6	0.8	3.2

Figure F.67: The following figure shall be added to the document:

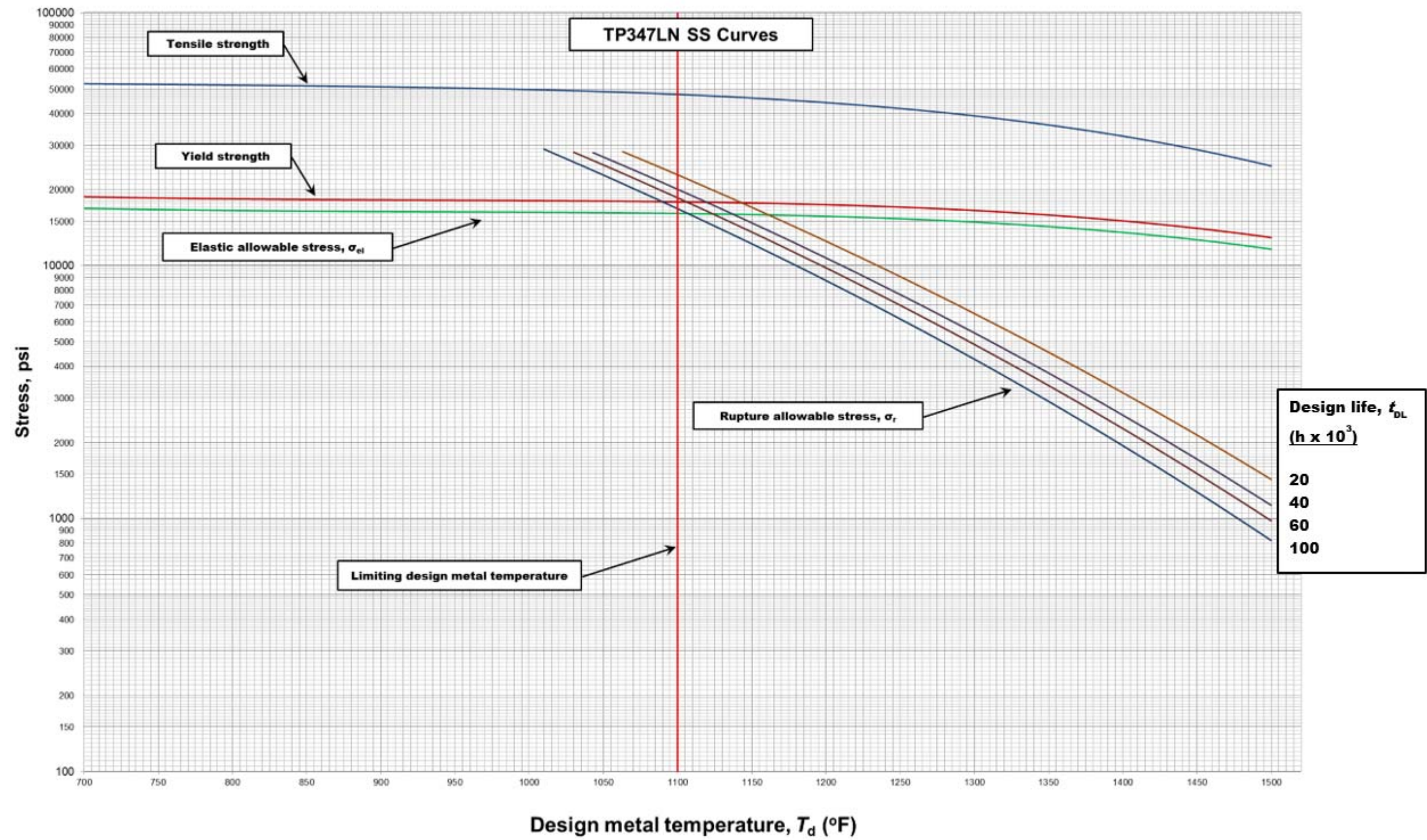


Figure F.67—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.68: The following figure shall be added to the document:

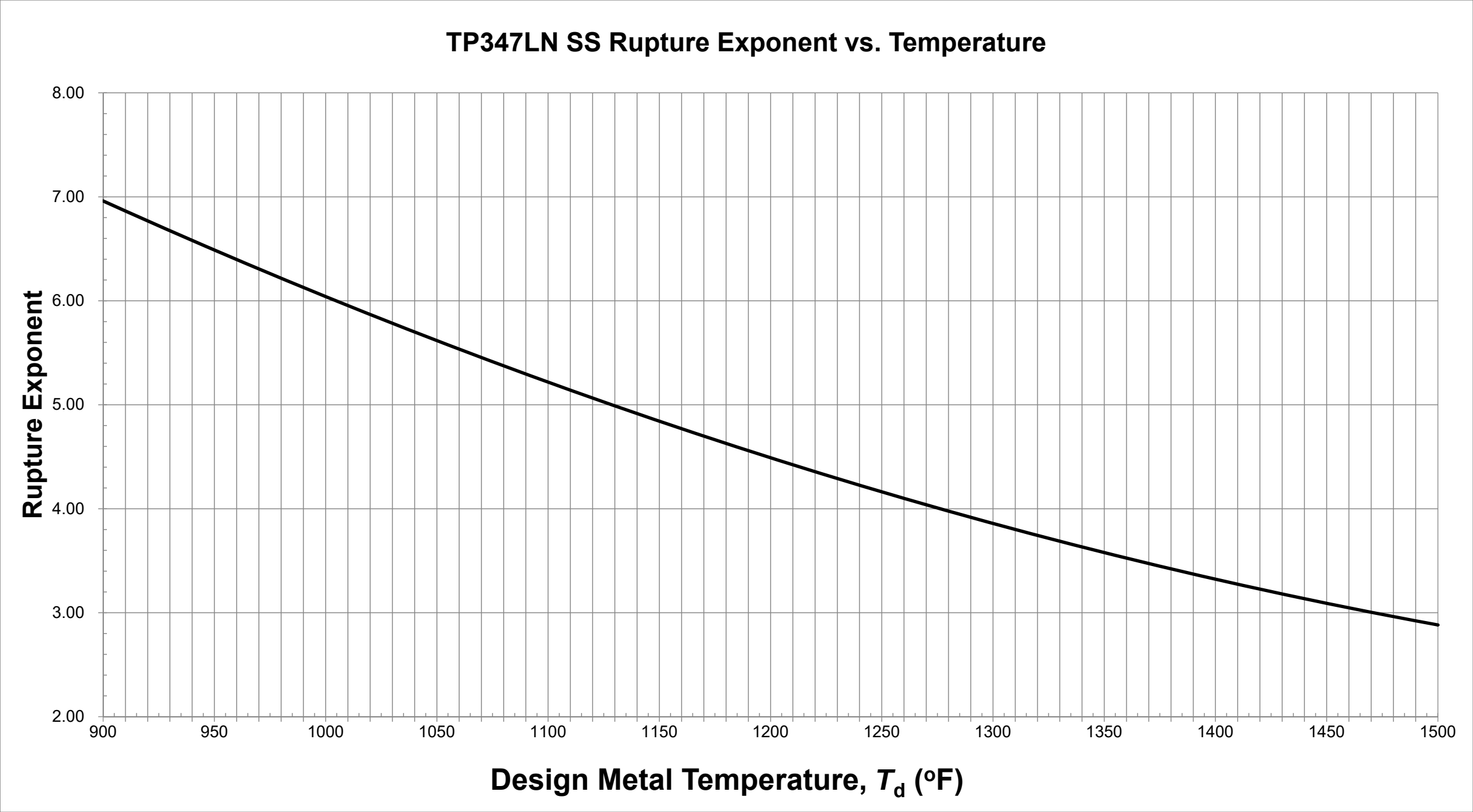


Figure F.68—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.69: The following figure shall be added to the document:

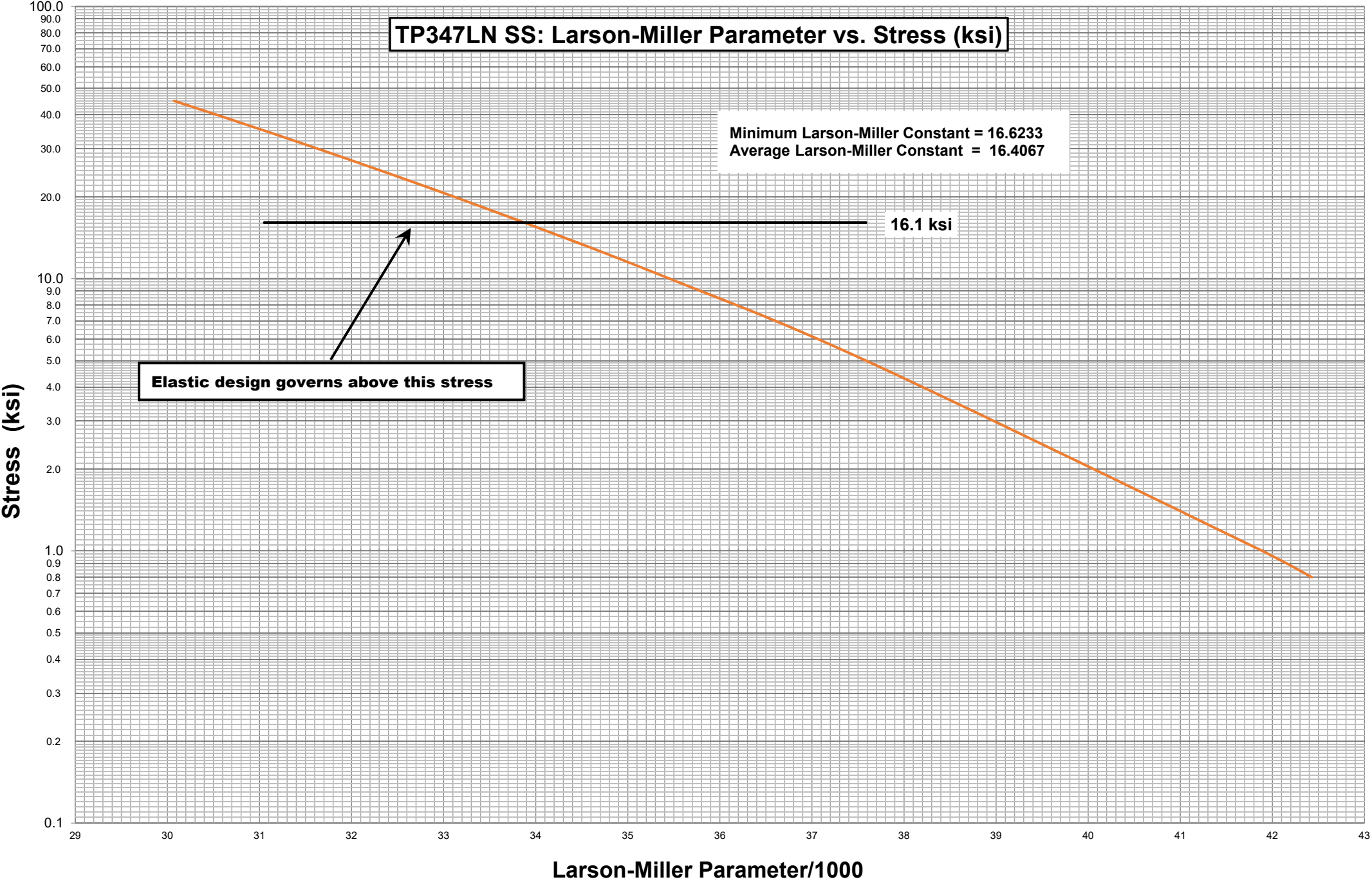


Figure F.69—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table F.23: The following table shall be added to the document:

TP347LN SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	16.9					
720	16.8					
740	16.7					
760	16.6					
780	16.6					
800	16.5					
820	16.5					
840	16.4					
860	16.4					
880	16.4					
900	16.4					7.0
920	16.3					6.8
940	16.3					6.6
960	16.3					6.4
980	16.3					6.2
1000	16.3					6.0
1020	16.2					5.9
1040	16.2					5.7
1060	16.2					5.5
1080	16.1					5.4
1100	16.1					5.2
1120	16.0					5.1
1140	16.0					4.9
1160	15.9					4.8
1180	15.8					4.6
1200	15.7					4.5
1220	15.6					4.4
1240	15.4					4.2
1260	15.3					4.1
1280	15.1					4.0
1300	14.9					3.9
1320	14.7					3.7
1340	14.4					3.6
1360	14.1					3.5
1380	13.8					3.4
1400	13.5					3.3
1420	13.2					3.2
1440	12.8					3.1
1460	12.5					3.0
1480	12.0					3.0
1500	11.6					2.9

Annex H: Equation H.5 shall be changed to the following:

$$n = \text{abs} \frac{\log_{10} [100,000] - \log_{10} [60,000]}{\log_{10} [S_{100,000}] - \log_{10} [S_{60,000}]}$$

(H.5)

Calculation of Heater-tube Thickness in Petroleum Refineries

API STANDARD 530
SEVENTH EDITION, APRIL 2015

ADDENDUM 1, JULY 2019

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Notice

Instructions for Submitting a Proposed Revision to this Standard Under Continuous Maintenance

The American Petroleum Institute maintains this standard under continuous maintenance procedures. These procedures establish a document program for regular publication of addenda or revisions, including timely and documented consensus action on requests for revisions to any part of the standard. Proposed revisions shall be submitted to the Director, Standards Department, American Petroleum Institute, 200 Massachusetts Avenue, NW, Suite 1100, Washington, DC 20001, standards@api.org.

This addendum to API 530, 7th Edition, contains the following changes:

- Updated rupture stress data for 9Cr-1Mo material: The rupture allowable stresses the addendum have been lowered to match the values given by the constants in WRC 541, 2nd Edition.
- The limiting design metal temperature for TP304L, TP316L, and TP317L have been decreased to 593 °C/ 1100 °F to match WRC 541 maximum temperatures for designs governed by creep properties. The allowable stress curves for TP304L, TP316L, and TP317L have been extended to 816 °C/1500 °F to match WRC 541 data for short-term exposure.
- The limiting design metal temperatures for 800HT and HK40 have been increased to 1010 °C/1850 °F to match WRC 541. The allowable stress curves also extend to this value.
- New material 347LN has been added based on data from WRC 541.

Calculation of Heater-tube Thickness in Petroleum Refineries

1 Scope

This standard specifies the requirements and gives recommendations for the procedures and design criteria used for calculating the required wall thickness of new tubes and associated component fittings for fired heaters for the petroleum, petrochemical, and natural gas industries. These procedures are appropriate for designing tubes for service in both corrosive and noncorrosive applications. These procedures have been developed specifically for the design of refinery and related fired heater tubes (direct-fired, heat-absorbing tubes within enclosures). These procedures are not intended to be used for the design of external piping.

This standard does not give recommendations for tube retirement thickness; Annex A describes a technique for estimating the life remaining for a heater tube.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ANSI/API Standard 560, *Fired Heaters for General Refinery Service*

ASME Boiler and Pressure Vessel Code (BPVC)¹, Section VIII, Division 1: *Pressure Vessels—Rules for Construction of Pressure Vessels*

ASME Boiler and Pressure Vessel Code (BPVC), Section VIII, Division 2: *Pressure Vessels—Rules for Construction of Pressure Vessels—Alternative Rules*

ASME B31.3, *Process Piping*

ASTM A106/A106M², *Specification for Seamless Carbon Steel Pipe for High-Temperature Service*

ASTM A192/A192M, *Specification for Seamless Carbon Steel Boiler Tubes for High-Pressure Service*

ASTM A209/A209M, *Specification for Seamless Carbon-Molybdenum Alloy-Steel Boiler and Superheater Tubes*

ASTM A210/A210M, *Specification for Seamless Medium-Carbon Steel Boiler and Superheater Tubes*

ASTM A213/A213M, *Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater and Heat-Exchanger Tubes*

ASTM A312/A312M, *Specification for Seamless and Welded Austenitic Stainless Steel Pipes*

ASTM A335/A335M, *Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

ASTM A376/A376M, *Specification for Seamless Austenitic Steel Pipe for High-Temperature Central-Station Service*

¹ ASME International, 3 Park Avenue, New York, NY 10016, www.asme.org.

² ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

ASTM A608/A608M, *Standard Specification for Centrifugally Cast Iron-Chromium-Nickel High-Alloy Tubing for Pressure Application at High Temperatures*

ASTM B407, *Standard Specification for Nickel-Iron-Chromium Alloy Seamless Pipe and Tube*

WRC Bulletin 541³, *Evaluation of Material Strength Data for Use in API Std 530*, M. Prager, D.A. Osage, and C.H. Panzarella, 2013

3 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1

actual inside diameter

D_i

Inside diameter of a new tube.

NOTE The actual inside diameter is used to calculate the tube skin temperature in Annex B and the thermal stress in Annex C.

3.2

component fitting

Fittings connected to the fired heater tubes.

EXAMPLES Return bends, elbows, reducers.

NOTE 1 There is a distinction between standard component fittings and specially designed component fittings; see 5.9.

NOTE 2 Typical material specifications for standard component fittings are ASTM A234/A234M, ASTM A403/A403M, and ASTM B366.

3.3

corrosion allowance

δ_{CA}

Additional material thickness added to allow for material loss during the design life of the component.

3.4

design life

t_{DL}

Operating time used as a basis for tube design.

NOTE The design life is not necessarily the same as the retirement or replacement life.

3.5

design metal temperature

T_d

Tube-metal or skin temperature used for design.

NOTE This is determined by calculating the maximum tube metal temperature (T_{max} in Annex B) or the equivalent tube metal temperature (T_{eq} in 3.8) and adding an appropriate temperature allowance (see 3.16). A procedure for calculating the maximum tube metal temperature from the heat-flux is included in Annex B. When the equivalent tube metal temperature is used, the maximum operating temperature can be greater than the design metal temperature.

³ Welding Research Council, P.O. Box 201547, Shaker Heights, Ohio 44122, forengineers.org.

When the equivalent tube metal temperature is used to determine the design metal temperature, this design metal temperature is only applicable to the rupture design. It is necessary to develop a separate design metal temperature applicable to the elastic design. The design metal temperature applicable to the elastic design is the maximum calculated tube metal temperature among all operating cases plus the appropriate temperature allowance.

3.6

elastic allowable stress

time-independent allowable stress

σ_{el}

Allowable stress for the elastic range. See 6.2.

3.7

elastic design pressure

p_{el}

Maximum pressure that the heater coil can sustain for short periods of time.

NOTE This pressure is usually related to relief-valve settings, pump shut-in pressures, etc.

3.8

equivalent tube metal temperature

T_{eq}

Calculated constant metal temperature that in a specified period of time produces the same creep damage as does a changing metal temperature.

NOTE The equivalent tube metal temperature concept is described in more detail in 5.8. It provides a procedure to calculate the equivalent tube metal temperature based on a linear change of tube metal temperature from start-of-run to end-of-run.

3.9

inside diameter

D_i^*

Inside diameter of a tube with the corrosion allowance removed; used in the design calculations.

NOTE The inside diameter of an as-cast tube is the inside diameter of the tube with the porosity and corrosion allowances removed.

3.10

minimum thickness

δ_{min}

Minimum required thickness of a new tube, taking into account all appropriate allowances.

NOTE See 5.4, Equation (5).

3.11

outside diameter

D_o

Outside diameter of a new tube.

3.12

rupture allowable stress

time-dependent allowable stress

σ_r

Allowable stress for the creep-rupture range. See 5.4.

3.13**rupture design pressure** p_r

Maximum operating pressure that the coil section can sustain during normal operation.

3.14**rupture exponent** n

Parameter used for design in the creep-rupture range.

NOTE See Figures E.2 through E.65 and Tables E.1 through E.22 (and Figures F.2 through F.65 and Tables F.1 through F.22).

3.15**stress thickness** δ_σ

Thickness, excluding all thickness allowances, calculated from an equation that uses an allowable stress.

3.16**temperature allowance** T_A

Part of the design metal temperature that is included for process- or flue-gas mal-distribution, operating unknowns, and design inaccuracies.

NOTE The temperature allowance is added to the calculated maximum tube metal temperature or to the equivalent tube metal temperature to obtain the design metal temperature (see 3.5).

4 General Design Information**4.1 Information Required**

The design parameters (design pressures, design fluid temperature, corrosion allowance, and tube material) shall be defined. In addition, the following information shall be furnished:

- a) design life of the heater tube;
- b) whether the equivalent-temperature concept is to be applied and, if so, the operating conditions at the start and at the end of the run;
- c) temperature allowance (see ANSI/API 560), if any;
- d) corrosion fraction (if different from that shown in Figure 1);
- e) whether elastic-range thermal-stress limits are to be applied.

If any of items a) to e) are not furnished, use the following applicable parameters:

- design life equal to 100,000 hours;
- design metal temperature based on the maximum metal temperature (the equivalent-temperature concept shall not apply);
- temperature allowance equal to 15 °C (25 °F);

- corrosion fraction given in Figure 1;
- elastic-range thermal-stress limits.

4.2 Limitations for Design Procedures

4.2.1 The allowable stresses are based on a consideration of yield strength and rupture strength only; plastic or creep strain has not been considered. Using these allowable stresses can result in small permanent strains in some applications; however, these small strains do not affect the safety or operability of heater tubes.

4.2.2 No considerations are included for adverse environmental effects, such as graphitization, carburization or hydrogen attack. Limitations imposed by hydrogen attack may be developed from the Nelson curves in API 941^[4].

4.2.3 These design procedures have been developed for seamless tubes. They are not applicable to tubes that have a longitudinal weld. ANSI/API 560 allows only seamless tubes.

4.2.4 These design procedures have been developed for thin tubes (tubes with a thickness-to-outside-diameter ratio, $\delta_{\min}/D_o$, of less than 0.15). Additional considerations can apply to the design of thicker tubes.

4.2.5 No considerations are included for the effects of cyclic pressure or cyclic thermal loading.

4.2.6 Limits for thermal stresses are provided in Annex C. Stresses imposed by tube/fluid weight, supports, end connections, and so forth are not discussed in this standard.

4.2.7 The relationship between temperature, stress, and time to failure (taken here to mean test, service, or design life) is represented by the Larson-Miller Parameter (LMP) as explained 6.6 and in H.5. The limiting design metal temperature ranges for each material for which the LMP applies are shown in Table 5.

4.2.8 The procedures in this standard have been developed for systems in which the heater tubes are subject to an internal pressure that exceeds the external pressure. There are some cases in which a heater tube can be subject to a greater external pressure than the internal pressure. This can occur, for example, in vacuum heaters or on other types of heaters during shutdown or trip conditions, especially when a unit is cooling or draining, forming a vacuum inside the heater tubes. Conditions where external pressures exceed the internal pressures can govern heater-tube wall thickness. Determination of this (i.e. vacuum design) is not covered in this standard. In the absence of applicable local or national codes, it is recommended that a pressure vessel code, such as ASME BPVC, Section VIII, Division 1 be used to address external pressure designs.

5 Design

5.1 General

There is a fundamental difference between the behavior of carbon steel in a hot-oil heater tube operating at 300 °C (575 °F) and that of chromium-molybdenum steel in a catalytic-reformer heater tube operating at 600 °C (1110 °F). The steel operating at the higher temperature creeps, or deforms permanently, even at stress levels well below the yield strength. If the tube metal temperature is high enough for the effects of creep to be significant, the tube eventually fails due to creep rupture, although no corrosion or oxidation mechanism is active. For the steel operating at the lower temperature, the effects of creep are nonexistent or negligible. Experience indicates that, in this case, the tube lasts indefinitely, unless a corrosion or an oxidation mechanism is active.

Since there is a fundamental difference between the behaviors of the materials at these two temperatures, there are two different design considerations for heater tubes: elastic design and creep-rupture design. Elastic design is design in the elastic range, in which allowable stresses are based on the yield strength (see 5.3) and are independent of service time. Creep-rupture design (referred to below as rupture design) is the design for the creep-rupture range, at higher temperatures, in which allowable stresses are based on the rupture strength (see 5.4) and are dependent of service time.

The temperature that separates the elastic and creep-rupture ranges of a heater tube is not a single value; it is a range of temperatures that depends on the alloy. For carbon steel, the lower end of this temperature range is about 425 °C (800 °F); for type 347 stainless steel, the lower end of this temperature range is about 590 °C (1100 °F). The considerations that govern the design range also include the elastic design pressure, the rupture design pressure, the design life, and the corrosion allowance.

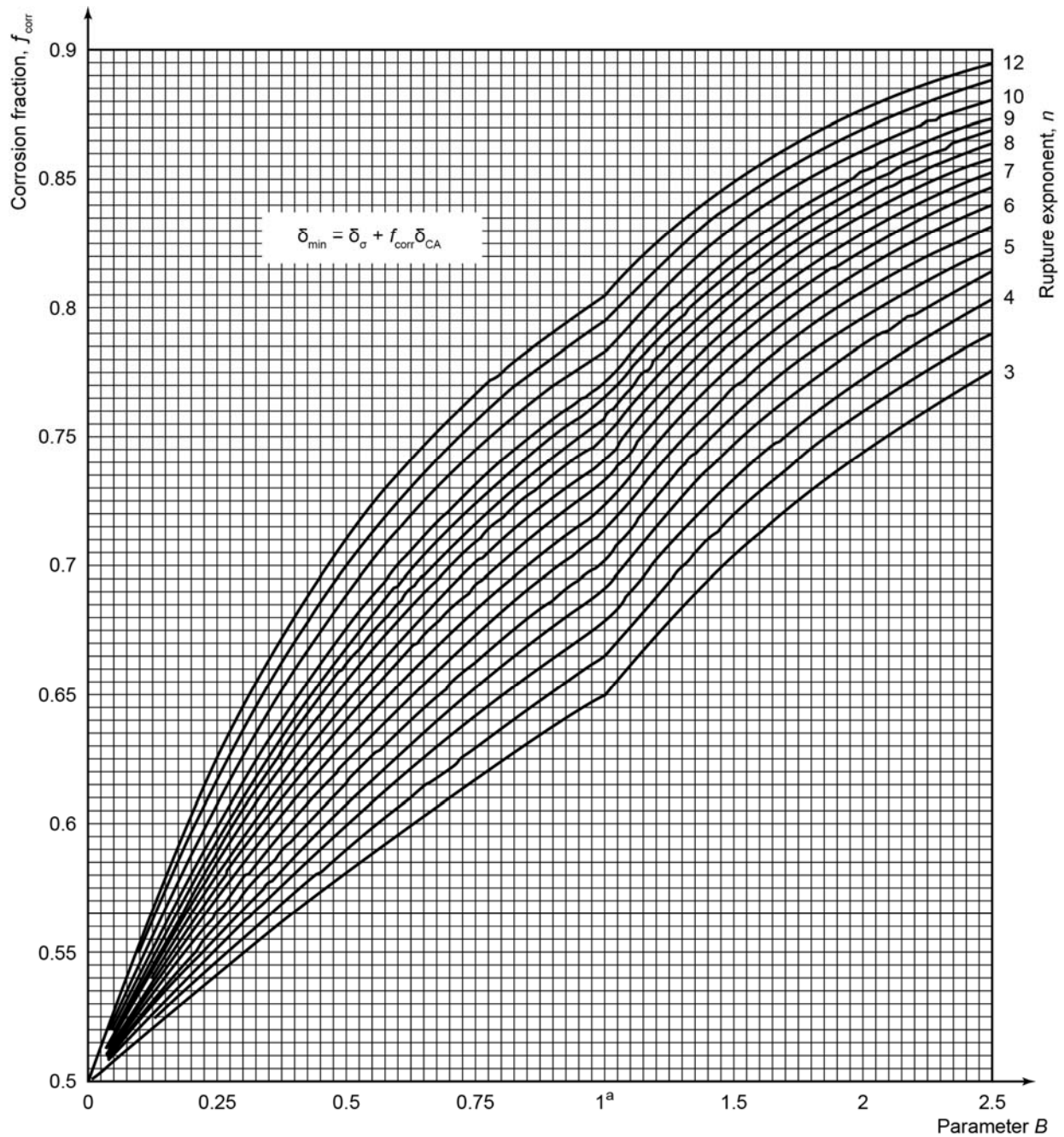
The rupture design pressure is never more than the elastic design pressure. The characteristic that differentiates these two pressures is the relative length of time over which they are sustained. The rupture design pressure is a long-term loading condition over a period of years. The elastic design pressure is usually a short-term loading condition that typically lasts only hours or days. The rupture design pressure is used in the rupture design equation, since creep damage accumulates as a result of the action of the operating, or long-term, stress. The elastic design pressure is used in the elastic design equation to prevent excessive stresses in the tube during periods of operation at the maximum pressure.

The tube shall be designed to withstand the rupture design pressure for long periods of operation. If the operating pressure increases during an operating run, the highest pressure shall be taken as the rupture design pressure.

In the temperature range near or above the point where the elastic and rupture allowable stress curves cross, both elastic and rupture design equations are to be used. The larger value of $\delta_{\min}$ shall govern the design (see 5.5). A sample calculation that uses these methods is included in Section 7. Calculation sheets (see Annex D) are available for summarizing the calculations of minimum thickness and equivalent tube metal temperature.

The minimum allowable thickness of a new tube is given in Table 1. All of the design equations described in Section 5 are summarized in Table 2.

If the heater is required to operate in turndown or operating conditions other than design mode, the purchaser shall identify this on the datasheet. A review of these operations is required with the purpose of identifying the most conservative case.

**Key**

$$\delta_{\sigma} = \frac{p_r D_o}{2\sigma_r + p_r}$$

δ_{CA} is the corrosion allowance

D_o is the outside diameter

σ_r is the rupture allowable stress

p_r is the rupture design pressure

$$B = \delta_{\text{CA}} / \delta_{\sigma}$$

^a Note change of scale at $X = 1$.

Figure 1—Corrosion Fraction

5.2 Equation for Stress

In both the elastic range and the creep-rupture range, the design equation is based on the mean-diameter equation for stress in a tube. In the elastic range, the elastic design pressure, p_{el} , and the elastic allowable stress, σ_{el} , are used. In the creep-rupture range, the rupture design pressure, p_r , and the rupture allowable stress, σ_r , are used.

The mean-diameter equation gives a good estimate of the pressure that produces yielding through the entire tube wall in thin tubes (see 4.2, fourth paragraph, for a definition of thin tubes). The mean-diameter equation also provides a good correlation between the creep rupture of a pressurized tube and a uniaxial test specimen. Therefore, it shall be used in both the elastic range and the creep-rupture range [5], [6], [7], [8]. The mean-diameter equation for stress is as given in Equation (1):

$$\sigma = \frac{p}{2} \left(\frac{D_o}{\delta} - 1 \right) = \frac{p}{2} \left(\frac{D_i}{\delta} + 1 \right) \quad (1)$$

where

σ is the stress, expressed in megapascals (pounds per square inch);

p is the pressure, expressed in megapascals (pounds per square inch);

D_o is the outside diameter, expressed in millimeters (inches);

D_i is the inside diameter, expressed in millimeters (inches), including the corrosion allowance;

δ is the thickness, expressed in millimeters (inches).

The equations for the stress thickness, δ_σ , in 5.3 and 5.4 are derived from Equation (1).

5.3 Elastic Design

The elastic design is based on preventing failure by bursting when the pressure is at its maximum (that is, when a pressure excursion has reached p_{el}) near the end of the design life after the corrosion allowance has been used up. With the elastic design, δ_σ and δ_{min} (see 5.6) are calculated as given in Equations (2) and (3):

$$\delta_\sigma = \frac{p_{el} D_o}{2\sigma_{el} + p_{el}} \text{ or } \delta_\sigma = \frac{p_{el} D_i^*}{2\sigma_{el} - p_{el}} \quad (2)$$

$$\delta_{min} = \delta_\sigma + \delta_{CA} \quad (3)$$

where

D_i^* is the inside diameter, expressed in millimeters (inches), with corrosion allowance removed;

σ_{el} is the elastic allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature.

5.4 Rupture Design

The rupture design is based on preventing failure by creep rupture during the design life. With the rupture design, δ_σ and $\delta_{\min}$ (see 5.6) are calculated from Equations (4) and (5):

$$\delta_\sigma = \frac{p_r D_o}{2\sigma_r + p_r} \text{ or } \delta_\sigma = \frac{p_r D_i^*}{2\sigma_r - p_r} \quad (4)$$

$$\delta_{\min} = \delta_\sigma + f_{\text{corr}} \delta_{\text{CA}} \quad (5)$$

where

σ_r is the rupture allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature and the design life;

f_{corr} is the corrosion fraction, given as a function of B and n in Figure 1;

$$B = \delta_{\text{CA}} / \delta_\sigma;$$

n is the rupture exponent at the design metal temperature (shown in the figures given in Annexes E and F).

The derivation of the corrosion fraction is described in Annex G. It is recognized in this derivation that stress is reduced by the corrosion allowance; correspondingly, the rupture life is increased.

Equations (4) and (5) are suitable for heater tubes; however, if special circumstances require that the user choose a more conservative design, a corrosion fraction of unity ($f_{\text{corr}} = 1$) may be specified.

5.5 Intermediate Temperature Range

At temperatures near or above the point where the curves of σ_{el} and σ_r intersect in the figures given in Annex E and Annex F, either elastic or rupture considerations govern the design. In this temperature range, it is necessary to apply both the elastic and the rupture designs. The larger value of $\delta_{\min}$ shall govern the design.

5.6 Minimum Allowable Thickness

The minimum thickness, $\delta_{\min}$, of a new tube (including the corrosion allowance) shall not be less than that shown in Table 1. For ferritic steels, the values shown are the minimum allowable thicknesses of schedule 40 average wall pipe. For austenitic steels, the values are the minimum allowable thicknesses of schedule 10S average wall pipe. (Table 6 shows which alloys are ferritic and which are austenitic.) The minimum allowable thicknesses are as defined in applicable ASTM specifications. These minima are based on industry practice. The minimum allowable thickness is not the retirement or replacement thickness of a used tube.

5.7 Minimum and Average Thicknesses

All thickness specifications shall indicate whether the specified value is a minimum or an average thickness. The tolerance used to relate the minimum and average wall thicknesses shall be the tolerance given in the ASTM specification to which the tubes or pipes are purchased.

Table 1—Minimum Allowable Thickness of New Tubes

Tube Outside Diameter		Minimum Thickness			
		Ferritic Steel Tubes		Austenitic Steel Tubes	
mm	(in.)	mm	(in.)	mm	(in.)
60.3	(2.375)	3.4	(0.135)	2.4	(0.095)
73.0	(2.875)	4.5	(0.178)	2.7	(0.105)
88.9	(3.50)	4.8	(0.189)	2.7	(0.105)
101.6	(4.00)	5.0	(0.198)	2.7	(0.105)
114.3	(4.50)	5.3	(0.207)	2.7	(0.105)
141.3	(5.563)	5.7	(0.226)	3.0	(0.117)
168.3	(6.625)	6.2	(0.245)	3.0	(0.117)
219.1	(8.625)	7.2	(0.282)	3.3	(0.130)
273.1	(10.75)	8.1	(0.319)	3.7	(0.144)

5.8 Equivalent Tube Metal Temperature

In the creep-rupture range, the accumulation of damage is a function of the actual operating tube metal temperatures (TMTs). For applications in which there are significant differences between start-of-run and end-of-run TMTs, a design based on the maximum temperature can be excessive, since the actual operating TMT is usually less than the maximum.

For a linear change in metal temperature from start of run, T_{sor} , to end of run, T_{eor} , an equivalent tube metal temperature, T_{eq} , may be calculated as shown in Equation (6). A tube operating at the equivalent tube metal temperature sustains the same creep damage as one that operates from the start-of-run to end-of-run temperatures.

$$T_{eq} = T_{sor} + f_T (T_{eor} - T_{sor}) \quad (6)$$

where

T_{eq} is the equivalent tube metal temperature, expressed in degrees Celsius (Fahrenheit);

T_{sor} is the tube metal temperature, expressed in degrees Celsius (Fahrenheit), at start of run;

T_{eor} is the tube metal temperature, expressed in degrees Celsius (Fahrenheit), at end of run;

f_T is the temperature fraction given in Figure 2.

The derivation of the temperature fraction is described in Annex G. The temperature fraction is a function of two parameters, V and N , as given in Equations (7) and (8):

$$V = n_0 \left(\frac{\Delta T^*}{T_{sor}^*} \right) \ln \left(\frac{A}{\sigma_0} \right) \quad (7)$$

$$N = n_0 \left(\frac{\Delta \delta}{\delta_0} \right) \quad (8)$$

where

n_0 is the rupture exponent at T_{sor} ;

ΔT^* is the temperature change, equal to $T_{\text{eor}} - T_{\text{sor}}$ during the operating period;

$T_{\text{sor}}^* = T_{\text{sor}} + 273 \text{ }^\circ\text{K}$ (or $T_{\text{sor}} + 460 \text{ }^\circ\text{R}$);

$\ln$ is the natural logarithm;

$\Delta\delta$ is the change in thickness, equal to $\phi_{\text{corr}} t_{\text{op}}$, expressed in millimeters (inches), during the operating period;

ϕ_{corr} is the corrosion rate, expressed in millimeters per year (or inches per year);

t_{op} is the duration of operating period, expressed in years;

δ_0 is the initial thickness, expressed in millimeters (inches), at the start of the run;

σ_0 is the initial stress, expressed in megapascals (pounds per square inch), at the start of the run, using Equation (1);

A is the material constant, expressed in megapascals (pounds per square inch).

The constant A is given in Table 3. The significance of the material constant is explained in G.5.

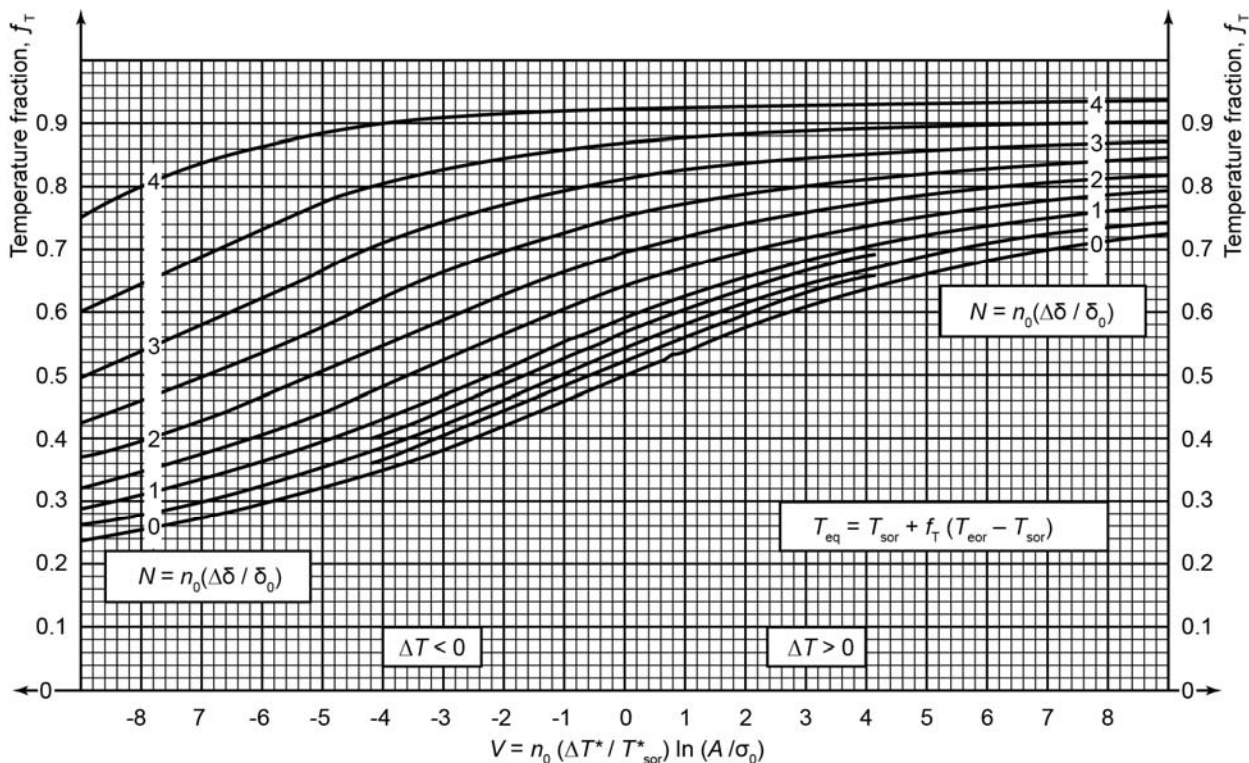


Figure 2—Temperature Fraction

Table 2—Summary of Working Equations**Elastic design:**

$$\delta_{\sigma} = \frac{p_{el} D_o}{2\sigma_{el} + p_{el}} \quad \text{or} \quad \delta_{\sigma} = \frac{p_{el} D_i^*}{2\sigma_{el} - p_{el}} \quad (2)$$

$$\delta_{min} = \delta_{\sigma} + \delta_{CA} \quad (3)$$

Rupture design:

$$\delta_{\sigma} = \frac{p_r D_o}{2\sigma_r + p_r} \quad \text{or} \quad \delta_{\sigma} = \frac{p_r D_i^*}{2\sigma_r - p_r} \quad (4)$$

$$\delta_{min} = \delta_{\sigma} + f_{corr} \delta_{CA} \quad (5)$$

where

- δ_{σ} is the stress thickness, expressed in millimeters (inches);
- p_{el} is the elastic design gauge pressure, expressed in megapascals (pounds per square inch);
- p_r is the rupture design gauge pressure, expressed in megapascals (pounds per square inch);
- D_o is the outside diameter, expressed in millimeters (inches);
- D_i^* is the inside diameter, expressed in millimeters (inches), with the corrosion allowance removed;
- σ_{el} is the elastic allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature;
- σ_r is the rupture allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature and design life;
- δ_{min} is the minimum thickness, expressed in millimeters (inches), including corrosion allowance;
- δ_{CA} is the corrosion allowance, expressed in millimeters (inches);
- f_{corr} is the corrosion fraction, given in Figure 1 as a function of B and n , where $B = \delta_{CA} / \delta_{\sigma}$;
- n is the rupture exponent at the design metal temperature.

Equivalent tube metal temperature:

$$T_{eq} = T_{sor} + f_T (T_{eor} - T_{sor}) \quad (6)$$

where

- ΔT^* ($= T_{eor} - T_{sor}$) is the temperature change, expressed in degrees Kelvin (degrees Rankine), during the operating period;
- T_{sor} is the tube metal temperature, expressed in degrees Celsius (Fahrenheit), at the start of the run;
- T_{eor} is the tube metal temperature, expressed in degrees Celsius (Fahrenheit), at the end of the run;
- $T_{sor}^* = T_{sor} + 273 \text{ }^{\circ}\text{K}$ (or $T_{sor} + 460 \text{ }^{\circ}\text{R}$);
- A is the material constant, expressed in megapascals (pounds per square inch) from Table 3;
- σ_0 is the initial stress, expressed in megapascals (pounds per square inch), at the start of the run using Equation (1);
- $\Delta \delta$ ($= \phi_{corr} t_{op}$) is the change in thickness, expressed in millimeters (inches), during the operating period;
- δ_0 is the initial thickness, expressed in millimeters (inches), at the start of the run;
- ϕ_{corr} is the corrosion rate, expressed in millimeters per year (inches per year);
- t_{op} is the duration, expressed in years, of the operating period.

Table 3—Material Constant for Temperature Fraction

Material	Type or Grade	Constant <i>A</i>	
		MPa	(psi)
Low-carbon steel	—	4.10×10^5	(5.95×10^7)
Medium-carbon steel	B	3.55×10^5	(5.15×10^7)
C-½Mo steel	T1 or P1	4.73×10^8	(6.86×10^{10})
1-¼Cr-½Mo steel	T11 or P11	9.10×10^6	(1.32×10^9)
2-¼Cr-1Mo steel	T22 or P22	3.30×10^5	(4.79×10^7)
3Cr-1Mo steel	T21 or P21	3.38×10^5	(4.91×10^7)
5Cr-½Mo steel	T5 or P5	3.38×10^5	(4.91×10^7)
5Cr-½Mo-Si steel	T5b or P5b	3.38×10^5	(4.91×10^7)
9Cr-1Mo steel	T9 or P9	1.68×10^6	(2.43×10^8)
9Cr-1Mo V steel	T91 or P91	1.13×10^6	(1.64×10^8)
18Cr-8Ni steel	304 or 304H	2.05×10^5	(2.98×10^7)
18Cr-8Ni steel	304L	1.37×10^5	(1.99×10^7)
16Cr-12Ni-2Mo steel	316 or 316H	4.02×10^5	(5.83×10^7)
16Cr-12Ni-2Mo steel	316L	4.67×10^5	(6.77×10^7)
16Cr-12Ni-3Mo steel	317L	3.23×10^5	(4.69×10^7)
18Cr-10Ni-Ti steel	321	1.57×10^6	(2.28×10^8)
18Cr-10Ni-Ti steel	321H	8.77×10^5	(1.27×10^8)
18Cr-10Ni-Nb ^a steel	347	3.74×10^5	(5.43×10^7)
18Cr-10Ni-Nb ^a steel	347H	5.05×10^5	(7.33×10^7)
Ni-Fe-Cr	Alloy 800	1.37×10^6	(1.99×10^8)
Ni-Fe-Cr	Alloy 800H	2.20×10^5	(3.18×10^7)
Ni-Fe-Cr	Alloy 800HT	1.80×10^5	(2.61×10^7)
25Cr-20Ni	HK-40	9.57×10^4	(1.39×10^7)
^a Formerly called columbium, Cb.			

The temperature fraction and the equivalent temperature shall be calculated for the first operating cycle. In applications that involve very high corrosion rates, the temperature fraction for the last cycle is greater than that for the first. In such cases, the calculation of the temperature fraction and the equivalent temperature should be based on the last cycle.

If the temperature change from start-of-run to end-of-run is other than linear, a judgment shall be made regarding the use of the value of f_T given in Figure 2.

Note that the calculated thickness of a tube is a function of the equivalent temperature, which, in turn, is a function of the thickness (through the initial stress). A few iterations may be necessary to arrive at the design. (See the sample calculation in 7.4.)

5.9 Component Fittings

Component fittings manufactured in accordance with ASME B16.9^[9] are considered suitable for use at the pressure-temperature ratings specified therein. Other wrought (non-ASME B16.9) component fittings shall be specially designed in accordance with this. Cast components are not covered by this standard.

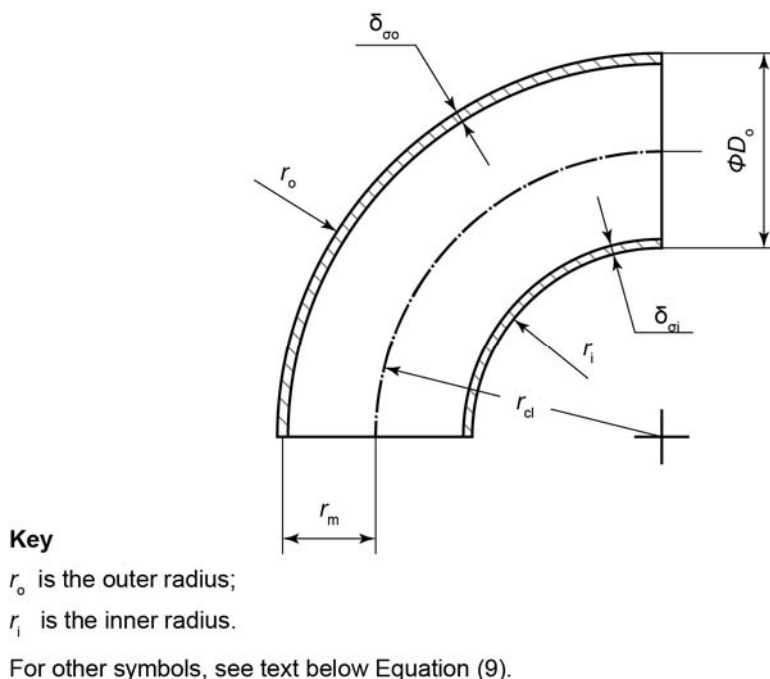


Figure 3—Return Bend and Elbow Geometry

The stress variations in a return bend or elbow (see Figure 3) are far more complex than in a straight tube. The hoop stresses at the inner radius of a return bend are higher than in a straight tube of the same thickness. It might be necessary for the minimum thickness at the inner radius to be greater than the minimum thickness of the attached tube. Forged return bends generally result in greater thickness at the inner radius.

The hoop stress σ_i , expressed in megapascals (pounds per square inch), along the inner radius of the bend is given by Equation (9):

$$\sigma_i = \frac{2r_{cl} - r_m}{2(r_{cl} - r_m)} \sigma \quad (9)$$

where

r_{cl} is the center line radius of the bend, expressed in millimeters (inches);

r_m is the mean radius of the tube, expressed in millimeters (inches);

σ is the stress, expressed in megapascals (pounds per square inch), given by Equation (1).

The hoop stress σ_o , expressed in megapascals (pounds per square inch), along the outer radius is given by Equation (10):

$$\sigma_o = \frac{2r_{cl} + r_m}{2(r_{cl} + r_m)} \sigma \quad (10)$$

Using the approximation that r_m is almost equal to $D_o/2$, Equation (9) can be solved for the stress thickness at the inner radius. For design, the stress thickness is given by Equation (11).

$$\delta_{\sigma i} = \frac{D_o p}{2N_i \sigma + p} \quad (11)$$

where

$\delta_{\sigma i}$ is the stress thickness, expressed in millimeters (inches), at the inner radius;

$$N_i = \frac{4 \frac{r_{cl}}{D_o} - 2}{4 \frac{r_{cl}}{D_o} - 1} \quad (12)$$

σ is the allowable stress, expressed in megapascals (pounds per square inch) at the design metal temperature.

NOTE 1 p represents both elastic design pressure and rupture design pressure.

The return bend thickness evaluations shall be made using both elastic design pressure and rupture design pressure, and the governing thicknesses shall be the larger values at the inner and outer radii.

Using the approximation given above, Equation (10) can be solved for the stress thickness at the outer radius. For elastic design, the stress thickness is as given in Equation (13):

$$\delta_{\sigma o} = \frac{D_o p}{2N_o \sigma + p} \quad (13)$$

where

$\delta_{\sigma o}$ is the stress thickness, expressed in millimeters (inches), at the outer radius;

$$N_o = \frac{4 \frac{r_{cl}}{D_o} + 2}{4 \frac{r_{cl}}{D_o} + 1} \quad (14)$$

σ is the allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature.

NOTE 2 p represents both elastic design pressure and rupture design pressure.

The return bend thickness evaluations shall be made using both elastic design pressure and rupture design pressure, and the governing thicknesses shall be the larger values at the inner and outer radii.

The minimum thickness, $\delta_{\sigma i}$, at the inside radius and the minimum thickness, $\delta_{\sigma o}$, at the outside radius shall be calculated using Equations (11) and (13). The corrosion allowance, δ_{CA} , shall be added to the minimum calculated thickness.

The minimum thickness along the neutral axis of the bend shall be the same as for a straight tube.

6 Allowable Stresses

6.1 General

The allowable stresses for various heater-tube alloys are plotted against design metal temperature in Figures E.1 to E.64 (SI units) and Figures F.1 to F.64 [U.S. customary (USC) units]. The data is also shown in tabular format in Tables E.1 to E.22 and Tables F.1 to F.22. The values shown in these figures and tables are recommended only for the design of heater tubes. These figures show two different allowable stresses, the elastic allowable stress and the rupture allowable stress. The bases for these allowable stresses are given in 6.2 and 6.3 (see also 4.2.3).

6.2 Elastic Allowable Stress

The elastic allowable stress, σ_{el} , is two-thirds of the yield strength at temperature for ferritic steels and 90 % of the yield strength at temperature for austenitic steels. The data sources for the yield strength are given in Annex H.

If a different design basis is desired for special circumstances, the user shall specify the basis, and the alternative elastic allowable stress shall be developed from the yield strength.

6.3 Rupture Allowable Stress

The rupture allowable stress, σ_r , is 100 % of the minimum rupture strength for a specified design life within the limiting design metal temperatures shown in Table 5. Section H.6 defines rupture strength and provides the data sources. The 20,000-hour, 40,000-hour, 60,000-hour, and 100,000-hour rupture allowable stresses were developed from the Larson-Miller Parameter curves for the minimum rupture strength. For a design life other than those shown, the corresponding rupture allowable stress shall be developed from the Larson-Miller Parameter curves for the minimum rupture strength (see 6.6). The Larson-Miller curves used are based on curves published in WRC Bull 541 and reflect the mechanical property data obtained from tubes manufactured using modern techniques.

If a different design basis is desired, the user shall specify the basis, and the alternative rupture allowable stress shall be developed from the Larson-Miller Parameter curves for the minimum or average rupture strength. If the resulting rupture allowable stress is greater than the minimum rupture strength for the design life, the effects of creep on the tube design equation should be considered.

6.4 Rupture Exponent

Figures E.2 to E.65 and Figures F.2 to F.65 show the rupture exponent, n , as a function of the design metal temperature. The rupture exponent is used for design in the creep-rupture range (see 5.4). The meaning of the rupture exponent is discussed in H.7. The rupture exponent values for each material are also listed in tabular format in Tables E.1 to E.22 and Tables F.1 to F.22.

6.5 Yield and Tensile Strengths

Figures E.1 to E.64 and Figures F.1 to F.64 in Annex F also show the yield and tensile strengths. These curves are included for reference only. Their sources are given in Annex H.

6.6 Larson-Miller Parameter Curves

Figures E.3 to E.66 and Figures F.3 to F.66 show the Larson-Miller Parameter as a function of stress. The Larson-Miller Parameter as a function of stress [$LMP(\sigma)$] is calculated from the design metal temperature, T_d , and the design life, t_{DL} , as given in Equations (15) and (16). LMP dimensions are not specified in this document.

When T_d is expressed in degrees Celsius:

$$\text{LMP}(\sigma) = (T_d + 273) (C_{\text{LM}} + \log_{10} t_{\text{DL}}) \quad (15)$$

When T_d is expressed in degrees Fahrenheit:

$$\text{LMP}(\sigma) = (T_d + 460) (C_{\text{LM}} + \log_{10} t_{\text{DL}}) \quad (16)$$

In past editions of this document, the Larson-Miller constant, C_{LM} , used was a single value used for broad material groups [i.e. $C_{\text{LM}} = 20$ for ferrous materials and $C_{\text{LM}} = 15$ for high alloy and nonferrous (high-nickel) materials].

However, in this document, the Larson-Miller constant have been optimized, specific for each individual material group. Table 4 lists the Larson-Miller Constants for minimum and average properties for each alloy. These values were obtained from Table 3 and Table 3M of WRC Bull 541. Refer to H.5 for a detailed description of how these curves were derived.

The Larson-Miller Parameter versus rupture strength curve are shown as Figures E.3 through E.66 and Figures F.3 through F.66 for each individual material. These curves may be used to calculate remaining tube life, as described in Annex A.

The plot of the minimum rupture strength against the Larson-Miller Parameter is included so that the rupture allowable stress can be determined for any design life. The curves shall not be used to determine rupture allowable stresses for temperatures higher than the limiting design metal temperatures shown in Table 5. Furthermore, the curves can give inaccurate rupture allowable stresses for a tube life of less than 20,000 hours or greater than 200,000 hours (refer to H.5).

6.7 Limiting Design Metal Temperature

The limiting design metal temperature for each heater-tube alloy is given in Table 5. The limiting design metal temperature is the upper limit of the reliability of the rupture strength data, and the stress rupture curves are intended for use where the design stress is greater than 6.9 MPa (1 ksi). Higher temperatures, i.e. up to 28 °C (50 °F) below the lower critical temperature, are permitted for short-term operating conditions, such as those that exist during steam-air decoking or regeneration (approximately 25 hours or less). Operation at higher temperatures can result in changes in the alloy's microstructure. Lower critical temperatures for ferritic steels are shown in Table 5. Austenitic steels do not have lower critical temperatures. Other considerations can require lower long-term operating temperature limits, such as oxidation, graphitization, carburization, and hydrogen attack. These factors shall be considered when furnace tubes are designed.

6.8 Allowable Stress Curves

The rupture allowable stress curves were developed from the information found in Section 6 of WRC Bull 541 and reflect the mechanical property data obtained from tubes manufactured using modern techniques. The figure number for set of curves for each alloy is shown in Table 6 below.

Table 4—Larson-Miller Constants

Material	Type or Grade	Larson-Miller Constants C_{LM}	
		minimum properties	average properties
Low-carbon steel	—	18.15	17.70
Medium-carbon steel	B	15.6	15.15
C-½Mo steel	T1 or P1	19.007756	18.72537
1-¼Cr-½Mo steel	T11 or P11	22.05480	21.55
2-¼Cr-1Mo steel	T22 or P22	19.565607	18.9181
3Cr-1Mo steel	T21 or P21	15.785226	15.38106
5Cr-½Mo steel	T5 or P5	16.025829	15.58928
5Cr-½Mo-Si steel	T5b or P5b	16.025829	15.58928
9Cr-1Mo steel	T9 or P9	20.946	20.5
9Cr-1Mo V steel	T91 or P91	30.886006	30.36423
18Cr-8Ni steel	304 or 304H	16.145903	15.52195
18Cr-8Ni steel	304L	18.287902	17.55
16Cr-12Ni-2Mo steel	316 or 316H	16.764145	16.30987
16Cr-12Ni-2Mo steel	316L	15.740107	15.2
16Cr-12Ni-3Mo steel	317L	15.740107	15.2
18Cr-10Ni-Ti steel	321	13.325	12.8
18Cr-10Ni-Ti steel	321H	15.293986	14.75958
18Cr-10Ni-Nb ^a steel	347	14.889042	14.25
18Cr-10Ni-Nb ^a steel	347H	14.17	13.65
Ni-Fe-Cr	Alloy 800	17.005384	16.50878
Ni-Fe-Cr	Alloy 800H	16.564046	16.04227
Ni-Fe-Cr	Alloy 800HT	13.606722	13.2341
25Cr-20Ni	HK-40	10.856489	10.4899
^a Formerly called columbium, Cb.			

Table 5—Limiting Design Metal Temperature for Heater-tube Alloys

Materials	Type or grade	Limiting design metal temperature		Lower critical temperature	
		°C	(°F)	°C	(°F)
Low carbon steel	—	540	(1000)	720	(1325)
Medium carbon steel	B	540	(1000)	720	(1325)
C-½Mo steel	T1 or P1	566	(1150)	720	(1325)
1¼Cr-½Mo steel	T11 or P11	650	(1100)	775	(1 30)
2¼Cr-1Mo steel	T22 or P22	650	(1 200)	805	(1480)
3Cr-1Mo steel	T21 or P21	650	(1200)	815	(1500)
5Cr-½Mo steel	T5 or P5	650	(1200)	820	(1510)
5Cr-½Mo-Si steel	T5b or P5b	650	(1200)	845	(1550)
9Cr-1Mo steel	T9 or P9	705	(1300)	825	(1515)
9Cr-1Mo-V steel	T91 or P91	705	(1300)	830	(1525)
18Cr-8Ni steel	304 or 304H	815	(1500) ²	—	—
18Cr-8Ni steel	304L	593 ¹	(1100) ¹	—	—
16Cr-12Ni-2Mo steel	316 or 316H	815	(1500) ²	—	—
16Cr-12Ni-2Mo steel	316L	593 ¹	(1100) ¹	—	—
18Cr-12Ni-3Mo steel	317L	593 ¹	(1100) ¹	—	—
18Cr-10Ni-Ti steel	321	815	(1500)	—	—
18Cr-10Ni-Ti steel	321H	815	(1500)	—	—
18Cr-10Ni-Nb steel	347	815	(1500)	—	—
18Cr-10Ni-Nb steel	347H	815	(1500)	—	—
18Cr-10Ni-Nb steel	347LN	593	(1100)	—	—
Ni-Fe-Cr	Alloy 800	815	(1500)	—	—
Ni-Fe-Cr	Alloy 800H	900	(1650)	—	—
Ni-Fe-Cr	Alloy 800HT	1010	(1850)	—	—
25Cr-20Ni	HK40	1010	(1850)	—	—
NOTE 1 The maximum temperature should be limited to 593 °C (1100 °F) for designs governed by creep properties.					
NOTE 2 The maximum temperature should be limited to 593 °C (1100 °F) when carbon content is less than 0.04 on heat analysis.					

Table 6—Index to Allowable Stress Curves

Steel Type	Figure Number	Alloy
Ferritic	E.1 (F.1)	Low-carbon steel (A 192)
	E.4 (F.4)	Medium-carbon steel (A 106B, A 210A1)
	E.7 (F.7)	C-½ Mo Steel
	E.10 (F.10)	1¼ Cr-½ Mo Steel
	E.13 (F.13)	2¼ Cr-1 Mo Steel
	E.16 (F.16)	3Cr-1 Mo Steel
	E.19 (F.19)	5Cr-½ Mo Steel
	E.22 (F.22)	5Cr-½ Mo-Si Steel
	E.25 (F.25)	9Cr-1Mo Steel
	E.28 (F.28)	9Cr-1Mo-V Steel
Austenitic	E.31 (F.31)	18Cr-8Ni (304 and 304H) Stainless Steel
	E.34 (F.34)	18Cr-8Ni (304L) Stainless Steel
	E.37 (F.37)	16Cr-12Ni-2Mo (316 and 316H) Stainless Steel
	E.40 (F.40)	16Cr-12Ni-2Mo (316L) Stainless Steel
	E.40 (F.40)	16Cr-12Ni-3Mo (317L) Stainless Steel
	E.43 (F.43)	18Cr-10Ni-Ti (321) Stainless Steel
	E.46 (F.46)	18Cr-10Ni-Ti (321H) Stainless Steel
	E.49 (F.49)	18Cr-10Ni-Nb (347) Stainless Steel
	E.52 (F.52)	18Cr-10Ni-Nb (347H) Stainless Steel
	E.65 (F.65)	18Cr-10Ni-Nb (347LN) Stainless Steel
	E.55 (F.55)	Ni-Fe-Cr (Alloy 800)
	E.58 (F.58)	Ni-Fe-Cr (Alloy 800H)
	E.61 (F.61)	Ni-Fe-Cr (Alloy 800HT)
	E.64 (F.64)	25Cr-20Ni (HK-40)

7 Sample Calculations

7.1 Elastic Design

The following example illustrates the use of design equations for the elastic range. Suppose the following information is given (the USC unit conversions in parentheses are approximate):

Material = 18Cr-10Ni-Nb, type 347 stainless steel

$$D_o = 168.3 \text{ mm (6.625 in.)}$$

$$p_{el} = 6.2 \text{ MPa gauge (900 psig)}$$

$$T_d = 425 \text{ °C (800 °F)}$$

$$\delta_{CA} = 3.2 \text{ mm (0.125 in.)}$$

From Figure E.49 (SI units) or Figure F.49 (USC units):

$$\sigma_{el} = 125 \text{ MPa (18,130 psi)}$$

Using Equations (2) and (3):

$$\delta_{\sigma} = \frac{(6.2)(168.3)}{2(125) + 6.2} = 4.1 \text{ mm}$$

$$\delta_{min} = 4.1 + 3.2 = 7.3 \text{ mm}$$

In USC units:

$$\delta_{\sigma} = \frac{(900)(6.625)}{2(18,130) + 900} = 0.161 \text{ in.}$$

$$\delta_{min} = 0.161 + 0.125 = 0.286 \text{ in.}$$

This design calculation is summarized in the calculation sheet in Figure 4.

CALCULATION SHEET SI Units (USC Units)		
Heater _____	Plant _____	Refinery _____
Coil _____	Material Type 347	ASTM Spec A 213/A 213M
Calculation of Minimum Thickness	Elastic Design	Rupture Design
Outside diameter, mm (in.)	$D_o = 168.3 \text{ (6.625)}$	$D_o =$
Design pressure, gauge, MPa (psi)	$p_{el} = 6.2 \text{ (900)}$	$p_r =$
Maximum or equivalent metal temperature, °C (°F)	$T_{max} =$	$T_{max} =$
Temperature allowance, °C (°F)	$T_A =$	$T_A =$
Design metal temperature, °C (°F)	$T_d = 425 \text{ (800)}$	$T_d =$
Design life, h	—	$t_{DL} =$
Allowable stress at T_d , Figure E.49 (Figure F.49), MPa (psi)	$\sigma_{el} = 125 \text{ (18,130)}$	$\sigma_r =$
Stress thickness, Equation (2) or (4), mm (in.)	$\delta_{\sigma} = 4.1 \text{ (0.161)}$	$\delta_{\sigma} =$
Corrosion allowance, mm (in.)	$\delta_{CA} = 3.2 \text{ (0.125)}$	$\delta_{CA} =$
Corrosion fraction, Figure 1, $n =$ B =	—	$f_{corr} =$
Minimum thickness, Equations (3) or (5), mm (in.)	$\delta_{min} = 7.3 \text{ (0.286)}$	$\delta_{min} =$

Figure 4—Sample Calculation for Elastic Design

7.2 Thermal-stress Check (for Elastic Range Only)

The thermal stress, σ_T , in the tube designed in accordance with 7.1 shall be checked using the following values for the variables in the equations given in Annex C:

$$\alpha = 1.81 \times 10^{-5} \text{ K}^{-1} \quad (10.05 \times 10^{-6} \text{ R}^{-1}) \quad \text{(thermal expansion coefficient taken from ASME B31.3, *Process Piping Code*);}$$

$$E = 1.66 \times 10^5 \text{ MPa} \quad (24.1 \times 10^6 \text{ psi}) \quad \text{(modulus of elasticity taken from ASME B31.3, *Process Piping Code*);}$$

$$\nu = 0.3 \quad \text{(Poisson's ratio value commonly used for steels);}$$

$$q_o = 63.1 \text{ kW/m}^2 \quad [20,000 \text{ Btu/(h}\cdot\text{ft}^2)] \quad \text{(assumed heat-flux);}$$

$$\lambda_s = 20.6 \text{ W/(m}\cdot\text{K)} \quad [11.9 \text{ Btu/(h}\cdot\text{ft } ^\circ\text{F)}] \quad \text{(thermal conductivity).}$$

Using SI units in Equation (C.2):

$$X = \left[\frac{\alpha E}{2(1-\nu)} \right] \left[\frac{\Delta T}{\ln y} \right] = \left[\frac{\alpha E}{4(1-\nu)} \right] \left[\frac{q_o D_o}{\lambda_s} \right]$$

$$X = \left[\frac{(1.81)(1.66)}{4(1-0.3)} \right] \left[\frac{(63.1)(168.3)}{20.6} \right]$$

$$X = 553.2 \text{ MPa}$$

Using USC units in Equation (C.2):

$$X = \left[\frac{(10.05)(24.1)}{4(1-0.3)} \right] \left[\frac{(20,000)(6.625)}{(11.9)(12)} \right]$$

$$X = 8.026 \times 10^4 \text{ psi}$$

The thickness calculated in 7.1 is the minimum. The average thickness shall be used in the thermal-stress calculation. The average thickness (see 5.7) is calculated as follows:

In SI units:

$$(7.2) (1 + 0.14) = 8.2 \text{ mm}$$

In USC units:

$$(0.284) (1 + 0.14) = 0.324 \text{ in.}$$

The actual inside diameter is calculated as follows:

In SI units:

$$D_i = 168.3 - 2(8.2) = 151.9 \text{ mm}$$

$$y = 168.3/151.9 = 1.108$$

where y is the ratio of outside diameter to actual inside diameter, D_o/D_i .

In USC units:

$$D_i = 6.625 - 2(0.324) = 5.977 \text{ in.}$$

$$y = 6.625/5.977 = 1.108$$

The term in brackets in Equation (C.1) is calculated as follows:

$$\frac{2(1.108)^2}{(1.108)^2 - 1} \ln(1.108) - 1 = 0.106$$

Using Equation (C.1), the maximum thermal stress, σ_{Tmax} , is calculated as follows:

$$\sigma_{Tmax} = (553.2) (0.106)$$

$$\sigma_{Tmax} = 58.6 \text{ MPa}$$

In USC units:

$$\sigma_{Tmax} = (8.026 \times 10^4) (0.106)$$

$$\sigma_{Tmax} = 8508 \text{ psi}$$

The limits for this stress for austenitic steels are given by Equations (C.4) and (C.6), in which the yield strength is 139 MPa (20,000 psi).

$$\sigma_{T,lim1} = [2.7 - 0.9(1.108)] (139)$$

$$\sigma_{T,lim1} = 237 \text{ MPa}$$

$$\sigma_{T,lim2} = (1.8) (139)$$

$$\sigma_{T,lim2} = 250 \text{ MPa}$$

In USC units:

$$\sigma_{T,lim1} = [2.7 - 0.9(1.108)] (20,000)$$

$$\sigma_{T,lim1} = 34,100 \text{ psi}$$

$$\sigma_{T,lim2} = (1.8) (20,000)$$

$$\sigma_{T,lim2} = 36,000 \text{ psi}$$

Since the maximum thermal stress is less than these limits, the design is acceptable.

If a thicker tube is specified arbitrarily (as Schedule 80S can be in this example), the actual average tube thickness shall be used in calculating the thermal stress and its limits as follows:

The inside diameter of a 6-in. Schedule 80S tube is as follows:

$$D_i = 146.3 \text{ mm}$$

therefore

$$y = 168.3/146.3 = 1.150$$

In USC units:

$$D_i = 5.761 \text{ in.}$$

$$y = 6.625/5.761 = 1.150$$

The term in brackets in Equation (C.1) is calculated as follows:

$$\frac{2(1.150)^2}{(1.150)^2 - 1} \ln(1.150) - 1 = 0.146$$

Using Equation (C.1), the maximum thermal stress is calculated as follows:

$$\sigma_{Tmax} = (553.2) (0.146)$$

$$\sigma_{Tmax} = 80.9 \text{ MPa}$$

In USC units:

$$\sigma_{Tmax} = (8.026 \times 10^4) (0.146)$$

$$\sigma_{Tmax} = 11,718 \text{ psi}$$

The average thickness of this tube is 11.0 mm (0.432 in.), so the minimum thickness is calculated as follows:

$$d_{min} = \frac{11.0}{1 + 0.14} = 9.6 \text{ mm}$$

In USC units:

$$d_{min} = \frac{0.432}{1 + 0.14} = 0.379 \text{ in.}$$

Using Equation (C.9), the stress is calculated as follows:

$$\sigma_{pm} = \frac{6.2}{2} \left(\frac{168.3}{9.6} - 1 \right) = 51.2 \text{ MPa}$$

In USC units:

$$\sigma_{pm} = \frac{900}{2} \left(\frac{6.625}{0.379} - 1 \right) = 7416 \text{ psi}$$

The thermal-stress limit based on the primary plus secondary stress intensity is calculated using Equation (C.14). Using the values above, this limit is calculated as follows:

$$\sigma_{T,lim1} = (2.7 \times 139) - (1.15 \times 51.2)$$

$$\sigma_{T,lim1} = 316.4 \text{ MPa}$$

In USC units:

$$\sigma_{T,lim1} = (2.7 \times 20,000) - (1.15 \times 7416)$$

$$\sigma_{T,lim2} = 45,470 \text{ psi}$$

The thermal-stress ratchet limit is calculated using Equation (C.19). In this case, the limit is as follows:

$$\sigma_{T,lim2} = 4[(1.35 \times 139) - 51.2]$$

$$\sigma_{T,lim2} = 540.4 \text{ MPa}$$

In USC units:

$$\sigma_{T,lim2} = 4[(1.35 \times 20,000) - 7416]$$

$$\sigma_{T,lim2} = 78,340 \text{ psi}$$

The thermal stress in the thicker tube is well below these limits.

7.3 Rupture Design with Constant Temperature

A modification of the example in 7.1 illustrates how the design equations are used for the creep-rupture range. Suppose the tube described in 7.1 is designed for the following conditions:

$$T_d = 705 \text{ }^\circ\text{C} \text{ (1300 }^\circ\text{F)}$$

$$t_{DL} = 100,000 \text{ hours}$$

$$p_r = 5.8 \text{ MPa gauge (840 psig)}$$

From Figure E.49 (SI units) or Figure F.49 (USC units):

$$\sigma_r = 20.7 \text{ MPa (3000 psi)}$$

Using Equation (4):

In SI units:

$$\delta_{\sigma} = \frac{(5.8)(168.3)}{2(20.7) + 5.8} = 20.7 \text{ mm}$$

In USC units:

$$\delta_{\sigma} = \frac{(840)(6.625)}{2(3000) + 840} = 0.81 \text{ in.}$$

From this:

In SI units:

$$B = \frac{3.2}{20.7} = 0.155$$

In USC units:

$$B = \frac{0.125}{0.81} = 0.155$$

From Figure E.50 (SI units) or Figure F.50 (USC units):

$$n = 3.5$$

With these values for B and n , use Figure 1 to obtain the following corrosion fraction:

$$f_{\text{corr}} = 0.53$$

Hence, using Equation (5):

In SI units:

$$\delta_{\text{min}} = 20.7 + (0.53 \times 3.2)$$

$$\delta_{\text{min}} = 22.4 \text{ mm}$$

In USC units:

$$\delta_{\text{min}} = 0.81 + (0.53 \times 0.125)$$

$$\delta_{\text{min}} = 0.876 \text{ in.}$$

To confirm that this is an appropriate design, the elastic design is checked using the elastic design pressure instead of the rupture design pressure. Using Equations (2) and (3) with the conditions given above:

In SI units:

$$\sigma_{\text{el}} = 117 \text{ MPa}$$

$$\delta_{\sigma} = \frac{(5.8)(168.3)}{2(117) + 5.8} = 4.07 \text{ mm}$$

$$\delta_{\min} = 4.07 + 3.2 = 7.27 \text{ mm}$$

In USC units:

$$\sigma_{\text{el}} = 16,980 \text{ psi}$$

$$\delta_{\sigma} = \frac{(840)(6.625)}{2(16,980) + 840} = 0.16 \text{ in.}$$

$$\delta_{\min} = 0.16 + 0.125 = 0.285 \text{ in.}$$

Since $\delta_{\min}$ based on rupture design is greater, it governs the design. This design calculation is summarized on the calculation sheet in Figure 5.

CALCULATION SHEET SI Units (USC Units)		
Heater _____	Plant _____	Refinery _____
Coil _____	Material Type 347	ASTM Spec A 213/A 213M
Calculation of Minimum Thickness	Elastic Design	Rupture Design
Outside diameter, mm (in.)	$D_o = 168.3 (6.625)$	$D_o = 168.3 (6.625)$
Design pressure, gauge, MPa (psi)	$p_{\text{el}} = 6.2 (900)$	$p_r = 5.8 (840)$
Maximum or equivalent metal temperature, °C (°F)	$T_{\text{max}} =$	$T_{\text{max}} =$
Temperature allowance, °C (°F)	$T_A =$	$T_A =$
Design metal temperature, °C (°F)	$T_d = 705 (1300)$	$T_d = 705 (1300)$
Design life, h	—	$t_{\text{DL}} = 100,000$
Allowable stress at T_d , Figure E.49 (Figure F.49), MPa (psi)	$\sigma_{\text{el}} = 117 (16980)$	$\sigma_r = 20.7 (3000)$
Stress thickness, Equation (2) or (4), mm (in.)	$\delta_{\sigma} = 4.34 (0.171)$	$\delta_{\sigma} = 20.7 (0.81)$
Corrosion allowance, mm (in.)	$\delta_{\text{CA}} = 3.18 (0.125)$	$\delta_{\text{CA}} = 3.18 (0.125)$
Corrosion fraction, Figure 1, $n = 4.4$; $B = 0.264$	—	$f_{\text{corr}} = 0.53$
Minimum thickness, Equation (3) or (5), mm (in.)	$\delta_{\min} = 7.27 (0.285)$	$\delta_{\min} = 22.4 (0.88)$

Figure 5—Sample Calculation for Rupture Design (Constant Temperature)

7.4 Rupture Design with Linearly Changing Temperature

Suppose the tube described in 7.3 operates in a service for which the estimated tube metal temperature varies from 635 °C (1175 °F) at the start of run to 690 °C (1275 °F) at the end of run. Assume that the run lasts a year, during which the thickness changes by about 0.33 mm (0.013 in.).

Assume that the initial minimum thickness is 8.0 mm (0.315 in.); therefore, using Equation (1), the initial stress is as follows:

In SI units:

$$\sigma_o = \frac{p}{2} \left(\frac{D_o}{\delta} - 1 \right)$$

$$\sigma_o = \frac{5.8}{2} \left(\frac{168.3}{8.0} - 1 \right) = 58.1 \text{ MPa}$$

In USC units:

$$\sigma_o = \frac{840}{2} \left(\frac{6.625}{0.315} - 1 \right) = 8413 \text{ psi}$$

At the start-of-run temperature, $n_o = 4.96$. From Table 3, A is 3.74×10^5 MPa (5.43×10^7 psi). The parameters for the temperature fraction are, therefore, as follows:

In SI units:

$$V = n_o \left(\frac{\Delta T^*}{T_{sor}^*} \right) \ln \left(\frac{A}{\sigma_o} \right)$$

$$N = n_o \left(\frac{\Delta \delta}{\delta_o} \right)$$

$$V = 4.96 \left(\frac{55}{908} \right) \ln \left(\frac{3.74 \times 10^5}{58.1} \right) = 2.64$$

$$N = 4.96 \left(\frac{0.33}{8.0} \right) = 0.2$$

In USC units:

$$V = 4.96 \left(\frac{100}{1635} \right) \ln \left(\frac{5.43 \times 10^7}{8413} \right) = 2.64$$

$$N = 4.96 \left(\frac{0.013}{0.315} \right) = 0.2$$

From Figure 2, $f_T = 0.62$, and the equivalent temperature is calculated using Equation (6) as follows:

In SI units:

$$T_{eq} = 635 + (0.62 \times 55) = 669 \text{ }^{\circ}\text{C}$$

In USC units:

$$T_{eq} = 1175 + (0.62 \times 100) = 1237 \text{ }^{\circ}\text{F}$$

A temperature allowance of 15 °C (25 °F) is added to yield a design temperature of 684 °C (1262 °F), which is rounded up to 685 °C (1265 °F). Using this temperature to carry out the design procedure illustrated in 7.3 yields the following:

In SI units:

$$\delta_{\sigma} = 16.0 \text{ mm}$$

$$\delta_{min} = 16.0 + (0.54 \times 3.2)$$

$$\delta_{min} = 17.7 \text{ mm}$$

In USC units:

$$\delta_{\sigma} = 0.622 \text{ in.}$$

$$\delta_{min} = 0.622 + (0.54 \times 0.125)$$

$$\delta_{min} = 0.690 \text{ in.}$$

This thickness is different from the 8.0 mm (0.315 in.) thickness that was initially assumed. Using this thickness, the initial stress is calculated as follows:

In SI units:

$$\sigma_o = \frac{5.8}{2} \left(\frac{168.3}{17.7} - 1 \right) = 24.7 \text{ MPa}$$

In USC units:

$$\sigma_o = \frac{840}{2} \left(\frac{6.625}{0.690} - 1 \right) = 3613 \text{ psi}$$

With this stress, the temperature-fraction parameters V and N become the following:

In SI units:

$$V = 4.96 \left(\frac{55}{908} \right) \ln \left(\frac{3.74 \times 10^5}{24.7} \right) = 2.89$$

$$N = 4.96 \left(\frac{0.33}{17.7} \right) = 0.09$$

In USC units:

$$V = 4.96 \left(\frac{100}{1635} \right) \ln \left(\frac{5.43 \times 10^7}{3613} \right) = 2.92$$

$$N = 4.96 \left(\frac{0.013}{0.690} \right) = 0.09$$

Using these values in Figure 2, $f_T = 0.62$, the value that was determined in the first calculation. Since the temperature fraction did not change, further iteration is not necessary. This design calculation is summarized in the calculation sheet in Figure 6.

CALCULATION SHEET SI units (USC units)		
Heater _____	Plant _____	Refinery _____
Coil _____	Material Type 347	ASTM Spec. A 213/A 213M
Calculation of minimum thickness	Elastic design	Rupture design
Outside diameter, mm (in.)	$D_o =$	$D_o = 168.3 (6.625)$
Design pressure, gauge, MPa (psi)	$p_{el} =$	$p_r = 5.8 (840)$
Maximum or equivalent metal temperature, °C (°F)	$T_{eq} =$	$T_{eq} = 669 (1237)$
Temperature allowance, °C (°F)	$T_A =$	$T_A = 15 (25)$
Design metal temperature, °C (°F)	$T_d =$	$T_d = 685 (1265)$
Design life, h	—	$t_{DL} = 100,000$
Allowable stress at T_d , Figure E17.1 (Figures F17.1) MPa (psi)	$\sigma_{el} =$	$\sigma_r = 27.7 (4050)$
Stress thickness, Equation (2) or (4), mm (in.)	$\delta_\sigma =$	$\delta_\sigma = 16.0 (0.622)$
Corrosion allowance, mm (in.)	$\delta_{CA} =$	$\delta_{CA} = 3.2 (0.125)$
Corrosion fraction, Figure 1, $n = 4.5$; $B = 0.322$	—	$f_{corr} = 0.54$
Minimum thickness, Equation (3) or (5), mm (in.)	$\delta_{min} =$	$\delta_{min} = 17.7 (0.690)$
Calculation of equivalent tube metal temperature		
Duration of operating period, years	$t_{op} = 1.0$	
Metal temperature, start of run, °C (°F)	$T_{sor} = 635 (1175)$	
Metal temperature, end of run, °C (°F)	$T_{eor} = 690 (1275)$	
Temperature change during operating period, K (°R)	$\Delta T^* = 55 (100)$	
Metal absolute temperature, start of run, K (°R)	$T_{sor}^* = 908 (1635)$	
Thickness change during operating period, mm (in.)	$\Delta \delta = 0.33 (0.013)$	
Assumed initial thickness, mm (in.)	$\delta_0 = 8.00 (0.315)$	
Corresponding initial stress, Equation (1), MPa (psi)	$\sigma_0 = 58.1 (8,413)$	
Material constant, Table 3, MPa (psi)	$A = 3.74 \times 10^5 (5.43 \times 10^7)$	
Rupture exponent at T_{sor} , Figures E.1 to E.19 (Figures F.1 to F.19)	$n_0 = 4.96$	
Temperature fraction, Figure 2, $V = 2.64$; $N = 0.2$	$f_T = 0.62$	
Equivalent metal temperature, Equation (6), °C (°F)	$T_{eq} = 669 (1237)$	

Figure 6—Sample Calculation for Rupture Design (Changing Temperature)

Annex A

(informative)

Estimation of Allowable Skin Temperature, Tube Retirement Thickness, and Remaining Life

A.1 General

Figures E.1 to E.66 (in Annex E) and Figures F.1 to F.66 (in Annex F) have applications other than for the design of new tubes. They may also be used to help establish operating skin tube metal temperature (TMT) limits and answer retiring and retirement questions about operating tubes. This annex will first discuss how operating limits may be set that provide conservative upper bound on operating skin TMT. The second part of the annex will discuss how to estimate tube remaining life by determining an operating retirement wall thickness that may then be directly compared with measured thickness data. Finally, the third part of this annex will discuss in more detail how to estimate lifetime creep damage, including the considerations made in Annex G.

This annex describes how tube damage and remaining life may be estimated. This assessment of inspection data is collected in accordance with API 573 ^[10] and API 570 ^[11] and, assuming the normal or worst case conditions, may be used to quickly assess the fitness for service of individual tubes. It is recommended that tubes, return bends, or coil sections that fail the fitness for service assessment be further evaluated by performing a rigorous Level 1 or 2 assessment of metal loss and/or creep damage following the standard provided in Parts 4, 5, and 10 of API 579-1/ASME FFS-1 ^[12]. Tubes that pass this evaluation approach should also pass the rigorous API 579-1 assessment.

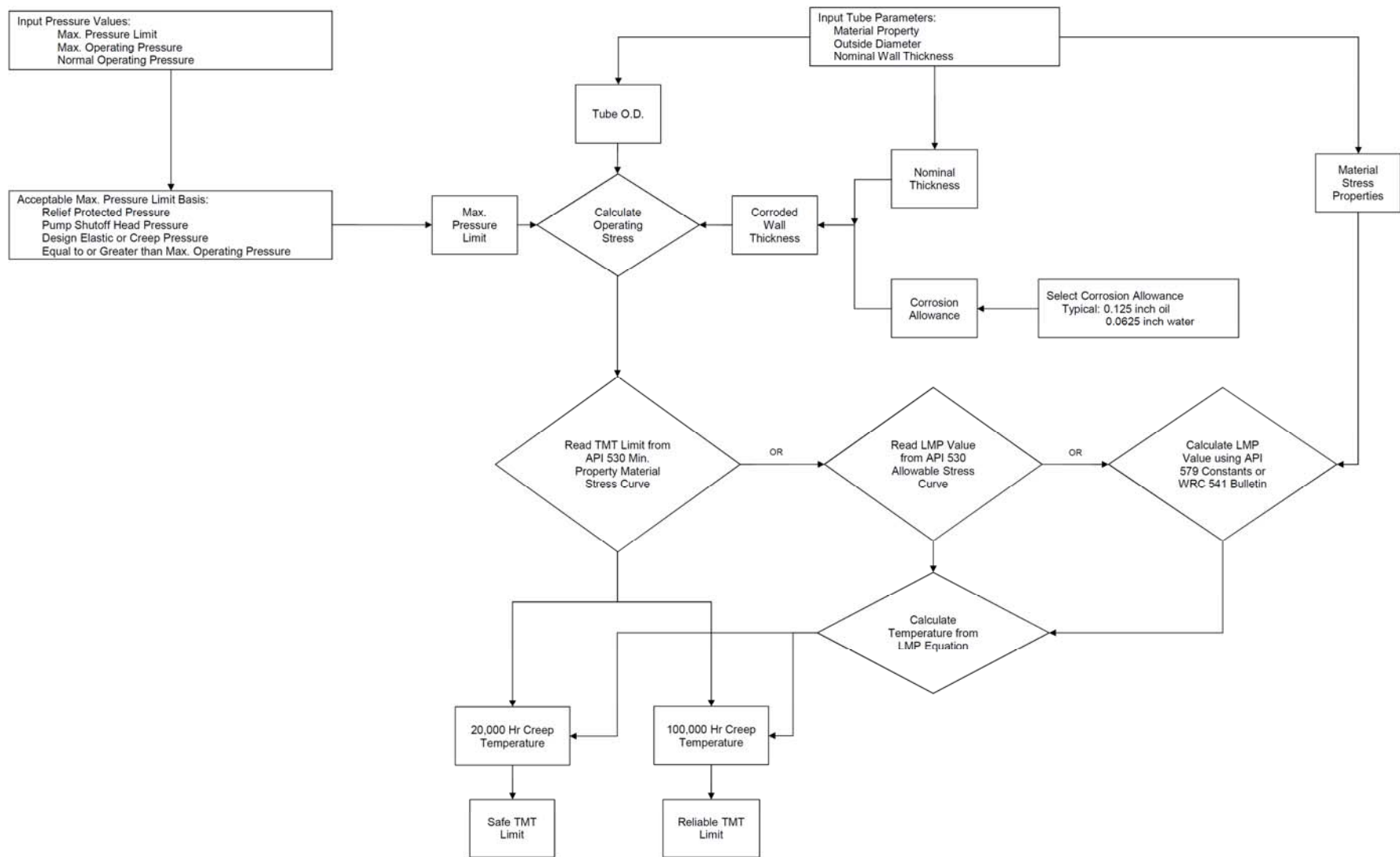
A.2 Establishment of Operating Skin TMT Limits

Once the fired heater is put into service, the design criteria may or may not apply to the actual operating conditions. However, the capability of the heater is limited by the design conditions. As discussed in API 584 ^[13], it is essential to define, monitor, and maintain Integrity Operating Windows (IOWs) as a vital component of mechanical equipment integrity. The essence of this section is to provide a process to establish IOW limits for fired heater tubes that will ensure the long-term reliability and short-term safe operation of the fired heater.

The following process may be used to set TMT operating limits. The operating stress based on the maximum pressure limit and the design corroded thickness is calculated using the standard equations for hoop stress. Using the material's creep properties and the calculated stress, the long-term and short-term TMT operating limit is selected. The recommended procedure is shown in the process logic diagram, Figure A.1, appearing on the next page.

The key point is establishing the IOWs and ensuring that the responsible parties understand the basis and are prepared to act if the limit is reached. For most heaters, these limits will not normally be reached without a change in operating conditions, e.g. internal fouling. The limits may be conservatively determined by selecting worst case conditions or less so, but still effective, by applying local knowledge of the operating process.

For fired heaters that routinely operate in the creep regime the selection of the creep material strength is an important consideration. It should be appropriate for these heaters to use the average creep material strength to provide sufficient operating margin between the normal condition and the limit. It may also be necessary to divide the heater into operating zones, e.g. high, medium, and low pressure, to provide further clarity to the operating limit.

**Figure A.1—Tube Metal Temperature Limit Process Logic Map**

A.3 Estimation of Retirement Thickness and Remaining Life

A fitness-for-service assessment for metal loss and creep damage should be performed utilizing the allowable stress properties provided in this standard. The essence of this assessment procedure may be outlined as follows. The allowable (or required) minimum wall thickness ($\delta_{\min}$) to handle the existing operating conditions is calculated using the standard equations for hoop stress. Based on expected operating time to the next inspection and measured damage rate, the allowable minimum wall thickness is increased to account for future metal loss, resulting in an estimate of retirement thickness. Finally, the remaining life, i.e. time to reach allowable minimum wall thickness, should be estimated based on the minimum measured wall thickness and measured damage rate. The assessment procedure is shown in the process logic diagram, Figures A.2a to A.2c, appearing on the next three pages.

As shown in Table A.1, a retirement wall thickness for a 40,000-hour (approximately five-year) run for the convection and radiant coils has been calculated. This approach is used to quickly assess the fitness for service of individual tubes in each coil section. The results of the assessment are reported as either pass or fail. Each tube is evaluated for fitness for service by comparing the minimum measured wall thickness (δ_{mm}) to the retirement wall thickness (δ_{retire}). The pass determination is based on satisfying the following criterion for minimum measured wall thickness:

$$\delta_{\text{mm}} > \delta_{\text{retire}} = \delta_{\min} + \text{FCA} \quad (\text{A.1})$$

Satisfying this criterion indicates that the tube is fit for service based on the observed damaged and provided heater specifications, operating conditions and scheduled turnaround time. The assumption being made is that future operating conditions will be consistent with the past conditions and future damage is adequately captured in the future corrosion allowance (FCA). The time to reach the minimum allowable wall thickness may be estimated as follows:

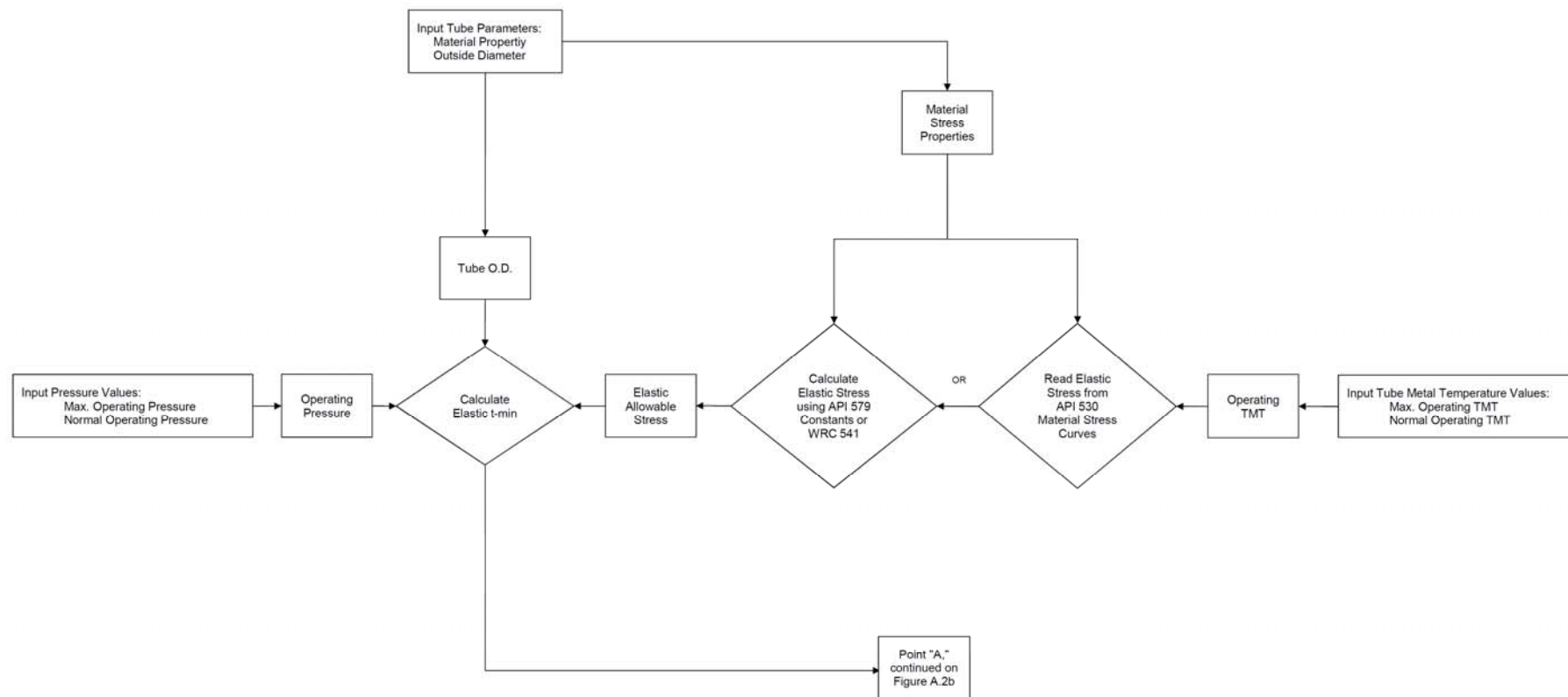
$$\text{Remaining life} = (\delta_{\text{mm}} - \delta_{\min}) / \text{corrosion damage rate} \quad (\text{A.2})$$

Note this assessment is based on heaters that have not operated in the creep regime, i.e. no existing creep damage. If creep damage (as indicated by measured strain damage) has been observed, further fitness for service assessment should be done. The extent of creep damage may be estimated as described in the next section of this annex.

The input conditions for this approach are broken into two basic operating regimes: normal average operation and normal maximum operation. “Normal” term refers to operation that follows defined best practice or typical practices. Transient, or other nontypical, events are not captured in the assessment, since these events are obviously not normal practice, not planned and impossible to predict. Note for this reason design maximum parameters are not used in the assessment, only actual maximum operations are considered relevant to the assessment. If a significant event does occur, such as hot-spot on an individual tube, the event would need to be accounted for, in a reassessment, to capture the impact on the individual tube’s remaining life.

In determining the allowable minimum wall thickness, possible combinations of (long-term and short-term) temperature and pressure should be defined and evaluated. For the most conservative assessment, the maximum operating conditions could be used, i.e. maximum pressure and tube metal temperature, to determine the elastic and creep allowable minimum wall thickness. For the least conservative assessment, the normal operating conditions could be used, i.e. normal pressure and tube metal temperature. For a moderately conservative assessment, the normal operating pressure and maximum tube metal temperature could be used for creep assessment and the maximum operating pressure and normal tube metal temperature could be used for elastic assessment.

For example, the most conservative assessment, i.e. maximum pressure and tube metal temperature, is used for Figure A.2 in determining allowable minimum wall thickness. A blank calculation sheet may be found in Annex D.

**Figure A.2a—Retirement Thickness Determination Process Logic Map**

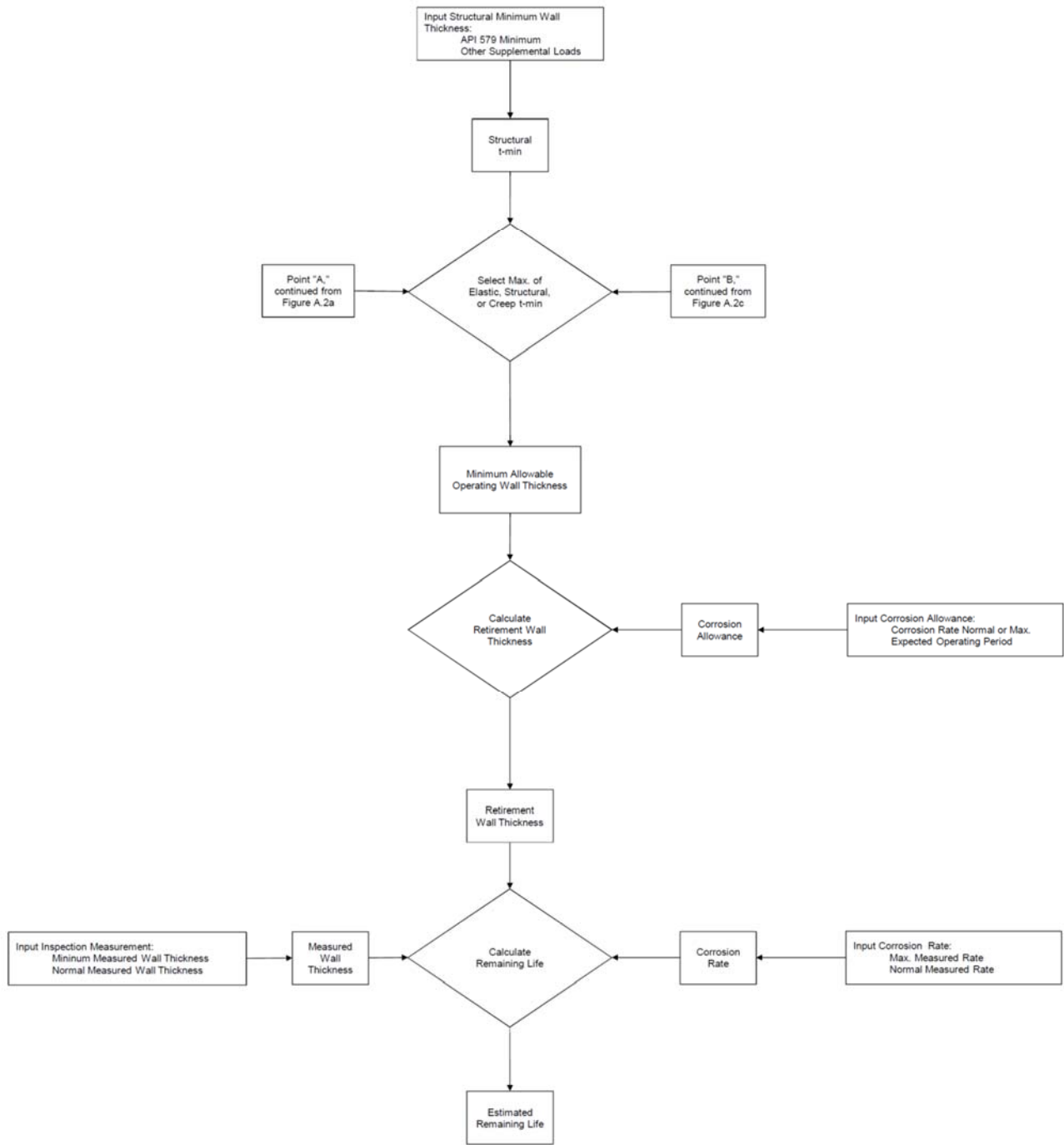


Figure A.2b—Retirement Thickness Determination Process Logic Map (Continued)

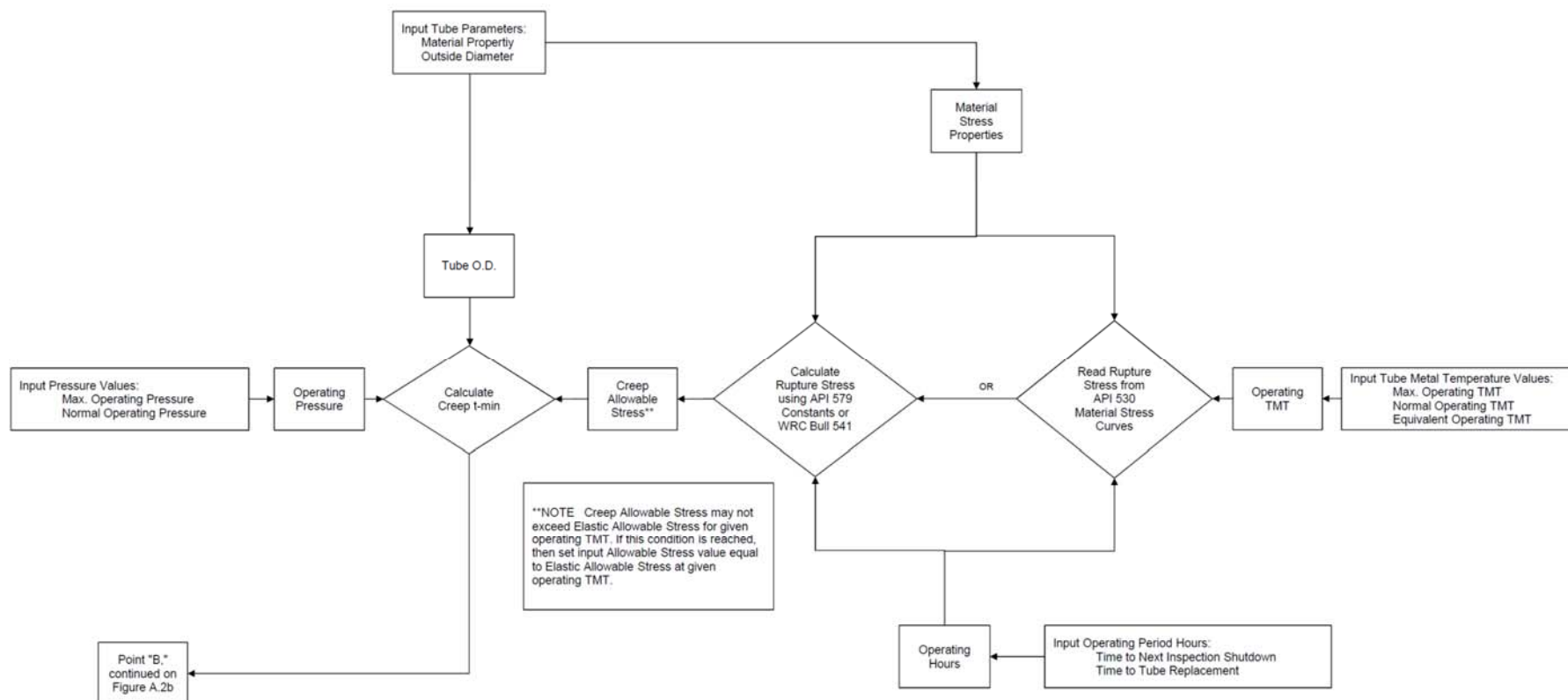
**Figure A.2c—Retirement Thickness Determination Process Logic Map (Continued)**

Table A.1—Retirement Wall Thickness

Parameter	Convection	Radiant	Unit	Reference
Pressure, P				
Normal	1.83 (265)	1.83 (265)	MPa.g (psig)	
Maximum	2.41 (350)	2.41 (350)	MPa.g (psig)	
Tube metal temperature, TMT				
Normal	303 (578)	414 (778)	°C (°F)	
Maximum	370 (698)	482 (900)	°C (°F)	
Operating plan				
Time to next inspection	40,000	40,000	hours	
Time to tube retirement	Unknown	Unknown	hours	
Future corrosion allowance, FCA	1.02 (0.040)	1.07 (0.042)	mm (inch)	
Allowance for supplemental load(s)	None	None	mm (inch)	
Tube parameters				
Outside diameter, D	127 (5.000)	127 (5.000)	mm (inch)	
Nominal wall thickness, δ_{nom}	9.52 (0.375)	9.52 (0.375)	mm (inch)	
Material specification	Medium carbon steel	Medium carbon steel	—	
Creep material strength property	Minimum	Minimum	—	
Creep life fraction consumed	None	None	—	
Allowable stress, S				
Elastic	109.0 (15,805)	89.4 (12,969)	MPa (psi)	API 530
Creep	109.0 (15,805)	55.6 (8,065)	MPa (psi)	API 530
Minimum required thickness, δ_{min}				
Value	2.54 (0.100)	2.69 (0.106)	mm (inch)	API 579
Basis	Structural	Creep	—	API 579
Retirement wall thickness, δ_{retire}	3.56 (0.140)	3.76 (0.148)	mm (inch)	Equation (1)
Minimum measured thickness, δ_{mm}	8.13 (0.320)	8.18 (0.322)	mm (inch)	
Remaining life	>20	>20	years	Equation (2)

A.4 Estimation of Accumulated Creep Damage

A.4.1 General

The information presented in this section and considerations made in Annex G may be used to estimate life-time creep damage for heaters operating in the creep regime. Because of the uncertainties involved in these calculations, decisions about tube retirement should not be based solely on the results of these calculations. Other factors such as tube thickness or diameter-strain measurements should be primary considerations in decisions about tube retirement.

The essence of this calculation procedure may be outlined as follows. The operating history is divided into periods of time during which the pressure, metal temperature, and corrosion rate are assumed constant. For each of these periods, the life fraction used up is calculated. The sum of these calculated life fractions is the total accumulated tube damage. The fraction remaining is calculated by subtracting this sum from unity. Finally, the remaining life fraction is transformed into an estimate of the expected life at specified operating conditions.

There are three primary areas of uncertainty in these calculations. First, it is necessary to estimate the accumulated tube damage (the life fraction used up) based on the operating history, i.e. the influence from the operating pressure, the tube-metal temperature, and the corrosion rate, of the tube. The uncertainties in these factors, particularly the temperature, may have a significant effect on the estimate. Second, knowledge of the actual rupture strength of a given tube is not precise. The example calculation in A.4 demonstrates the effects of this uncertainty. Finally, it is necessary to consider the tube-damage rule as described in G.2.

However, as mentioned in G.2, the limitations of this hypothesis are not well understood. In spite of all these uncertainties, the estimation that is made using the procedure described in this annex may provide information that assists in making decisions about tube rerating and retirement.

A more detailed life-assessment evaluation for heater tubes operating in the creep-rupture range may be found in API 579.

Since the concepts required to estimate damage are developed elsewhere in this standard, they are not repeated here. The calculation procedure may be explained by working through an example. For this example, the following conditions are assumed:

Material: 16Cr-12Ni-2Mo (type 316) stainless steel;

Outside diameter: 168.3 mm (6.625 in.);

Initial minimum thickness: 6.8 mm (0.268 in.).

It is also assumed that the operating history of the tube may be approximated as shown in Table A.2. (The SI conversions are approximate.)

It is not necessary that the operating periods be of uniform length. In an actual heater, neither the operating pressure nor the metal temperature is uniform. Nonetheless, for this calculation, they are assumed to be uniform during each period. The values chosen for each period should represent typical values. The choice of the length of the operating period depends on the extent of the variation of the pressure and temperature.

It is necessary to approximate the operating history for the tube thickness. This history may usually be developed from thickness measurements made before the initial start-up and during routine heater-tube inspections. For all of these estimates, it is assumed that the outside diameter remains constant.

Table A.2—Approximation of the Operating History

Operation Period	Duration	Operating Gauge Pressure		Tube Metal Temperature		Minimum Thickness			
						Beginning		End	
	a ^a	MPa.g	(psig)	°C	(°F)	mm	(in.)	mm	(in.)
1	1.3	3.96	(575)	649	(1200)	6.81	(0.268)	6.40	(0.252)
2	0.6	4.27	(620)	665	(1230)	6.40	(0.252)	6.20	(0.244)
3	2.1	4.07	(590)	660	(1220)	6.20	(0.244)	5.51	(0.217)
^a "a" is the international unit symbol for "year."									

This information may be used to calculate the life fractions shown in Table A.3.

For tubes undergoing corrosion, an equation similar to Equation (G.17) may be developed for the life fraction; however, this is not necessary since sufficient accuracy may be achieved for this calculation by using the average stress for each period (i.e. the average of the stress at the beginning and at the end of the operating period).

The minimum and average Larson-Miller values in Table A.3 are determined from the average stress using the Larson-Miller Parameter curves for minimum and average rupture strength in Figures E.3 to E.66 (SI units) or Figures F.3 to F.66 (USC units). For this example, Figure F.39 was used.

With these Larson-Miller values and the metal temperature for each period, the expression for the Larson-Miller Parameter was solved for the rupture time. These expressions are shown in Equations (H.2) (in USC units) and (H.3) (in SI units). Since this expression gives the rupture time in hours, the value needs converting to years. The resulting times based on the minimum rupture strength and the average rupture strength are shown in Table A.3.

The following example illustrates how to calculate the minimum-strength rupture time, t_{DL} , for the first operating period from the equations for $\delta_{\sigma,AVE}$, the average stress thickness, and σ_r , the rupture allowable stress. The equations to be solved are as follows:

In SI units:

$$\delta_{\sigma,AVE} = \frac{6.81 + 6.40}{2} = 6.605 \text{ mm}$$

In USC units:

$$\delta_{\sigma,AVE} = \frac{0.268 + 0.252}{2} = 0.260 \text{ in.}$$

In SI units:

$$\sigma_r = \frac{1}{2} \left(\frac{p_r D_o}{\delta_{\sigma,AVE}} - p_r \right) = \frac{1}{2} \left(\frac{3.96 \times 168.3}{6.605} - 3.96 \right) = 48.47 \text{ MPa}$$

In USC units:

$$\sigma_r = \frac{1}{2} \left(\frac{p_r D_o}{\delta_{\sigma,AVE}} - p_r \right) = \frac{1}{2} \left(\frac{575 \times 6.625}{0.260} - 575 \right) = 7038 \text{ psi}$$

At 48.47 MPa, using the minimum rupture strength, the Larson-Miller Parameter, C_{LM} , equals 20.53 in SI units.

At 7038 psi, using the minimum rupture strength, the Larson-Miller Parameter, C_{LM} , equals 36.95 in USC units.

To determine the rupture time using minimum strength, in USC units:

$$C_{LM} = (T_d + 460) (16.76 + \lg t_{DL}) \times 10^{-3}$$

Therefore:

$$36.95 = (1200 + 460) (16.76 + \lg t_{DL}) \times 10^{-3}$$

$$\lg t_{DL} = 5.5$$

$$t_{DL} = 316,225 \text{ hours}$$

$$t_{DL} = 36.1 \text{ years}$$

To determine the rupture time using average strength, in USC units:

$$C_{LM} = (T_d + 460) (16.31 + \lg t_{DL}) \times 10^{-3}$$

Therefore:

$$36.95 = (1200 + 460) (16.31 + \lg t_{DL}) \times 10^{-3}$$

$$\lg t_{DL} = 5.95$$

$$t_{DL} = 891,250 \text{ hours}$$

$$t_{DL} = 101.7 \text{ years}$$

The life fractions are the duration of the operating period divided by the rupture time that corresponds to that period. Using the minimum-strength rupture time calculated above, the fraction for the first line in Table A.3 is 1.3/36.1, which equals 0.04. The accumulated damage is the sum of the fractions.

The effect of the uncertainty about the rupture strength is evident as shown in the example in Table A.3. If the actual rupture strength of this tube is in the lower part of the scatter band (near the minimum rupture strength), then 37 % of the tube life has been used. If the actual strength is in the middle of the scatter band (near the average rupture strength), then only 12 % of the tube life has been used. If the actual rupture strength is higher, even less of the tube life has been used.

The effect of the uncertainty about the operating temperature may also be evaluated. Suppose the actual metal temperature of this tube were 5 °C (9 °F) higher than that shown in Table A.2. To estimate the effect of this difference, the life-fraction calculations in Table A.3 have been made with the slightly higher temperature. The corresponding accumulated damage fractions are 0.51 and 0.17, respectively. These should be compared with the values 0.37 and 0.12 that were calculated first.

Table A.3—Life Fractions for Each Period

Operating Period	Average Stress		Larson-Miller Values				Rupture Time Based on Minimum Strength		Rupture Time Based on Average Strength	
			minimum		average					
	MPa	psi	°C	(°F)	°C	(°F)	years	life fraction	years	life fraction
1	48.47	(7038)	20.53	(36.95)	20.53	(36.95)	36.1	0.04	101.7	0.01
2	54.90	(7970)	20.25	(36.43)	20.25	(36.43)	7.2	0.08	20.3	0.03
3	56.46	(8183)	20.18	(36.34)	20.18	(36.34)	8.5	0.25	23.9	0.08
					Accumulated damage =			0.37		0.12

A.4.2 Estimation of Remaining Tube Life

As in A.4, this calculation procedure is best explained using an example. The example used is summarized in Tables A.4 and A.5. The life fraction remaining for this tube is as follows:

Minimum rupture strength: equals 1 minus 0.37, or 0.63;

Average rupture strength: equals 1 minus 0.12, or 0.88.

These fractions should be converted to the expected life under the specified operating conditions.

The following related questions may be asked at this point.

- What is the estimated life at a given operating pressure, metal temperature, and corrosion rate?
- For a specified operating pressure and corrosion rate, what temperature limit should be imposed for the tube to last a minimum period of time?
- How much should the operating pressure or metal temperature be reduced to extend the expected life by a given percentage?

Not all of these questions are answered in this annex, but the method used to develop the answers should be clear from the following example.

For this example, the expected operating conditions are as follows:

Operating gauge pressure: 4.27 MPa (620 psi);

Metal temperature: 660 °C (1220 °F);

Corrosion rate: 0.33 mm/year (0.013 in./year).

From these values, a table of future-life fractions may be developed as shown in Table A.4 for the minimum rupture strength and in Table A.5 for the average rupture strength. As before, the average stress is the average of the stresses at the beginning and end of each operating period.

Since the tube in the example is undergoing corrosion, the life estimation should be calculated in steps. For this example, a 1-year step was used. As may be seen from the two tables, the estimated life of this tube is less than 1.2 years (for minimum rupture strength) and less than 3 years (for average rupture strength). If the rupture strength were in the upper part of the scatter band (above the average rupture strength), the estimated life would be even longer.

For tubes that are not undergoing corrosion, estimating the life is easier. The rupture life is calculated, as above, from the anticipated stress and temperature. The estimated remaining life is the fraction remaining multiplied by the rupture life. In these cases, tables such as Tables A.4 and A.5 are not required.

The example given above describes a way to answer Question a), posed at the beginning of this subsection: What is the estimated life for a specified set of operating conditions? Question b), concerning the temperature limit that should be imposed for a specified pressure, corrosion rate, and minimum life, may be answered as follows. The pressure and corrosion rate may be used to calculate an average stress from which a Larson-Miller value may be found using the curves in Figures E.3 through E.66 and F.3 through F.66. With this value and a rupture life calculated by dividing the required life by the remaining life fraction, the Larson-Miller Parameter equation may be solved for the maximum temperature. The other questions may be answered in similar ways.

Table A.4—Future Life Fractions, Minimum Rupture Strength

Time	Minimum Thickness		Average Stress		Minimum Larson-Miller Value		Rupture Time	Fraction	Remaining Fraction
a	mm	(in.)	MPa	(psi)	°C	(°F)	a		
0	4.83	(0.190)	—	—	—	—	—	—	0.63
1	4.50	(0.177)	74.80	(10,850)	19.53	(35.17)	1.7	0.59	0.04
1.2	4.43	(0.174)	78.34	(11,392)	19.43	(34.97)	1.3	0.77	−0.73

Table A.5—Future Life Fractions, Average Rupture Strength

Time	Minimum Thickness		Average Stress		Minimum Larson-Miller Value		Rupture Time	Fraction	Remaining Fraction
							a		
a	mm	(in.)	MPa	(psi)	°C	(°F)	a		
0	4.83	(0.190)	—	—	—	—	—	—	0.88
1	4.50	(0.177)	74.80	(10,850)	19.53	(35.17)	4.8	0.21	0.67
2	4.17	(0.164)	80.66	(11,698)	19.15	(34.87)	3.2	0.31	0.35
3	3.84	(0.151)	87.47	(12,686)	19.18	(34.52)	2.0	0.50	−0.15

Annex B (informative)

Calculation of Maximum Radiant Section Tube Skin Temperature

B.1 General

This annex provides a procedure for calculating the maximum radiant section tube metal (skin) temperature. Correlations for estimating the fluid-film heat-transfer coefficient are given in B.2. A method for estimating the maximum local heat flux is given in B.3. The equations used to calculate the maximum tube skin temperature and the temperature distribution through the tube wall are described in B.4. The sample calculation in B.5 demonstrates the use of these equations.

The maximum tube metal temperature (TMT) might or might not be located towards the process outlet of a fired heater. Factors including inside film coefficient, radiant heat flux, heater/tube geometry, internal fouling, and fluid flow regime all influence the maximum TMT calculation. In some cases, such as with vacuum heaters, a tube-by-tube analysis from the fluid outlet to before the initial boiling point (IBP) should be performed.

B.2 Heat-transfer Coefficient

A value necessary for calculating the maximum tube metal temperature is the fluid heat-transfer coefficient at the inside wall of the tube. Although the following correlations are extensively used and accepted in heater design, they have inherent inaccuracies associated with all simplified correlations that are used to describe complex relationships.

For single-phase fluids, the heat-transfer coefficient is calculated by one of the two equations below, where Re is the Reynolds number and Pr is the Prandtl number. No correlation is included for the heat-transfer coefficient in laminar flow, since this flow regime is rare in process heaters. There is inadequate information for reliably determining the inside coefficient in laminar flow for oil in tube sizes that are normally used in process heaters.

The heat-transfer coefficient, K_i , expressed in $W/(m^2 \cdot K)$ [$Btu/(h \cdot ft^2 \cdot ^\circ F)$], for the liquid flow with $Re > 10,000$ is calculated using Equation (B.1) from Reference [14]:

$$K_i = 0.023 \left(\frac{\lambda_{f,Tb}}{D_i} \right) Re^{0.8} Pr^{0.33} \left(\frac{\mu_{f,Tb}}{\mu_{f,Tw}} \right)^{0.14} \quad (B.1)$$

where

$$Re = \frac{D_i q_{mA}}{\mu_{f,Tb}} \quad (B.2)$$

$$Pr = \frac{c_p \mu_{f,Tb}}{\lambda_{f,Tb}} \quad (B.3)$$

q_{mA} is the mass flow rate, in $kg/(m^2 \cdot s)$ [$lb/(ft^2 \cdot h)$], of the fluid;

c_p is the specific heat capacity, in $J/(kg \cdot K)$ [$Btu/(lb \cdot ^\circ R)$], of the fluid at bulk temperature;

$\lambda_{f,Tb}$ is the thermal conductivity, expressed in W/(m·K) [Btu/(h·ft·°F)], of the fluid at bulk temperature;

D_i is the inside diameter, expressed in meters (feet), of the tube;

$\mu_{f,Tb}$ is the absolute viscosity, in Pa·s [lb/(ft·h)], of the fluid at bulk temperature;

$\mu_{f,Tw}$ is the absolute viscosity, in Pa·s [lb/(ft·h)], of the fluid at wall temperature.

The heat-transfer coefficient, K_v , expressed in W/(m²·K) [Btu/(h·ft²·°F)], for the vapor flow with $Re > 15,000$ is calculated using Equation (B.4) from Reference [15]:

$$K_v = 0.021 \left(\frac{\lambda_{f,Tb}}{D_i} \right) Re^{0.8} Pr^{0.4} \left(\frac{T_b}{T_w} \right)^{0.5} \quad (B.4)$$

where

T_b is the absolute bulk temperature, expressed in Kelvin (degrees Rankine), of the vapor;

T_w is the absolute wall temperature, expressed in Kelvin (degrees Rankine), of the vapor.

All of the material properties except $\mu_{f,Tw}$ are evaluated at the bulk fluid temperature. To convert absolute viscosity in millipascal-seconds or centipoise to pounds per foot per hour, multiply $\mu_{f,Tw}$ by 2.42.

For two-phase flows, the heat-transfer coefficient may be approximated using Equation (B.5):

$$K_{2p} = K_l w_l + K_v w_v \quad (B.5)$$

where

K_{2p} is the heat-transfer coefficient, expressed in W/(m²·K) [Btu/(h·ft²·°F)], for two phases;

w_l is the mass fraction of the liquid;

w_v is the mass fraction of the vapor.

The liquid and vapor heat-transfer coefficients, K_l and K_v , should be calculated using the mixed-phase mass flow rate and using the liquid and the vapor material properties, respectively.

NOTE In two-phase flow applications where dispersed-flow or mist-flow regimes occur due to entrainment of tiny liquid droplets in the vapor (e.g. towards the outlet of vacuum heaters), the heat-transfer coefficient may be calculated using the correlation for the vapor phase using Equation (B.4), based on the total flow rate, rather than being approximated by Equation (B.5). In vertical tube two-phase flow applications where annular flow regimes occur upflow and downflow have been noted as having different heat transfer coefficients. The downflow coefficient tends to be lower than upflow. Many default calculations methods are good at predicting upflow coefficients.

B.3 Maximum Local Heat Flux

The average heat flux in the radiant section of a heater (or in a zone of the radiant section) is equal to the duty in the section or zone divided by the total outside surface area of the coil in the section or zone. The maximum local heat flux at any point in the coil may be estimated from the average heat flux. The maximum local heat flux is used with the equations in B.4 to calculate the maximum tube metal temperature.

Local heat fluxes vary considerably throughout a heater because of nonuniformities around and along each tube. Circumferential variations result from variations in the radiant heat flux produced by shadings of other tubes or from the placement of the tubes next to a wall. Conduction around the tubes and convection flows of flue gases tend to reduce the circumferential variations in the heat flux. The longitudinal variations result from the proximity to burners and variations in the radiant firebox and the bulk fluid temperatures. In addition to variations in the radiant section, the tubes in the shock section of a heater may have a high convective heat flux.

The maximum radiant heat flux, $q_{R,max}$, expressed in W/m^2 [$Btu/(h \cdot ft^2)$], for the outside surface at any point in a coil may be estimated from Equation (B.6):

$$q_{R,max} = F_{cir} F_L F_T q_{R,ave} + q_{conv} \quad (B.6)$$

where

F_{cir} is the factor accounting for circumferential heat flux variations;

F_L is the factor accounting for longitudinal heat flux variations;

F_T is the factor accounting for the effect of tube metal temperature on the radiant heat flux;

$q_{R,ave}$ is the average radiant heat flux, in W/m^2 [$Btu/(h \cdot ft^2)$], for the outside surface;

q_{conv} is the average convective heat flux, in W/m^2 [$Btu/(h \cdot ft^2)$], for the outside surface.

The circumferential variation factor, F_{cir} , is given as a function of tube spacing and coil geometry in Figure B.1. The factor given by this figure is the ratio of the maximum local heat flux at the fully exposed face of a tube to the average heat flux around the tube. This figure was developed from considerations of radiant heat transfer only. As mentioned above, influences such as conduction around the tube and flue-gas convection act to reduce this factor. Since these influences are not included in this calculation, the calculated value is somewhat higher than the actual maximum heat flux.

The longitudinal variation factor, F_L is used to account for the variation in heat flux along the flame path, from the burner to the firebox exit. The longitudinal variation factor, is not easy to quantify. Values between 1.0 and 1.5 are most often used. In a firebox that has a very uniform distribution of heat flux, a value of 1.0 may be appropriate. Depending on firebox and flame aspect ratios, this factor may be higher than 1.5 at the peak heat flux elevation (typically 2/3 of flame length) and as low as 0.7 at the floor and 0.5 at the roof. For new or existing heaters, this factor may be estimated with CFD modeling methods that have been field checked for burner type, fuels and heater configuration. In existing heaters, infrared measurement of tubes or tube supports along the flame path may be used to estimate the heat flux profile.

The tube metal temperature factor, F_T , is less than 1.0 near the coil outlet or in areas of maximum tube metal temperature. It is greater than 1.0 in areas of lower tube metal temperatures. For most applications, the factor may be approximated as given in Equation (B.7):

$$F_T = \left(\frac{T_{g,ave}^{*4} - T_{tm}^{*4}}{T_{g,ave}^{*4} - T_{tm,ave}^{*4}} \right) \quad (B.7)$$

where

$T_{g,ave}^*$ is the average flue-gas temperature, expressed in Kelvin (degrees Rankine), in the radiant section;

T_{tm}^* is the tube metal temperature, expressed in Kelvin (degrees Rankine), at the point under consideration;

$T_{tm,ave}^*$ is the average tube metal temperature, expressed in Kelvin (degrees Rankine), in the radiant section.

The convective heat flux in most parts of a radiant section is usually small compared with the radiant heat flux. In the shock section, however, the convective heat flux may be significant; it should therefore be added to the radiant heat flux when the maximum heat flux in the shock section is estimated. Note that frequently the location of maximum convective heat flux does not coincide with maximum radiant heat flux.

B.4 Maximum Tube Metal Temperature

In addition to the heat-transfer coefficient and the maximum heat flux, the temperature profile of the fluid in the coil is necessary for calculating the maximum tube metal temperature in the radiant section of the heater. This profile, which is often calculated by the heater supplier, defines the variation of the bulk fluid temperature through the heater coil. For operation at or near design, the design profile may be used. For operation significantly different from design, a bulk temperature profile may be developed.

Once the bulk fluid temperature is known at any point in the coil, the maximum tube metal temperature, T_{max} , expressed in degrees Celsius (Fahrenheit), can be calculated from Equations (B.8) to (B.12):

$$T_{max} = T_{bf} + \Delta T_{ff} + \Delta T_f + \Delta T_{tw} \quad (B.8)$$

where

T_{bf} is the bulk fluid temperature, expressed in degrees Celsius (Fahrenheit);

ΔT_f is the temperature difference across any internal fouling, expressed in degrees Celsius (Fahrenheit);

ΔT_{ff} is the temperature difference across the fluid film, expressed in degrees Celsius (Fahrenheit);

ΔT_{tw} is the temperature difference across the tube wall, expressed in degrees Celsius (Fahrenheit).

$$\Delta T_{ff} = \frac{q_{R,max}}{K_{ff}} \left(\frac{D_o}{D_i} \right) \quad (B.9)$$

where

K_{ff} is the fluid-film heat-transfer coefficient, expressed in $W/(m^2)$ [$Btu/(h \cdot ft^2)$];

$q_{R,max}$ is the maximum radiant heat flux, expressed in W/m^2 [$Btu/h \cdot ft^2$], for the outside surface;

D_o is the outside diameter, expressed in meters (feet), of the tube;

D_i is the inside diameter, expressed in meters (feet), of the tube.

$$\Delta T_f = q_{R,max} R_f \left(\frac{D_o}{D_i - \delta_f} \right) \quad (B.10)$$

where

δ_f is the coke and/or scale thickness, expressed in meters (feet);

R_f is the fouling factor inside the tube due to the presence of any internal fouling, coke or scale, expressed in $\text{m}^2\cdot\text{K}/\text{W}$ ($\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$).

$$\Delta T_{tw} = q_{R,\max} \left(\frac{D_o \ln \left(\frac{D_o}{D_i} \right)}{2\lambda_{tm}} \right) \quad (\text{B.11})$$

where

λ_{tm} is the thermal conductivity, expressed in $\text{W}/(\text{m}\cdot\text{K})$ [$\text{Btu}/(\text{h}\cdot\text{ft}\cdot^\circ\text{F})$], of the tube metal.

The effect of internal fouling on the tube metal temperature can be calculated if a fouling factor rather than coke thickness has been provided on the fired heater datasheets (see API 560). The fouling factor, R_f , may also be expressed as a function of coke or scale thickness and thermal conductivity, as given in Equation (B.12), if only coke or scale thickness is provided:

$$R_f = \frac{\delta_f}{\lambda_f} \quad (\text{B.12})$$

where

δ_f is the coke and/or scale thickness, expressed in meters (feet);

λ_f is the thermal conductivity of coke or scale, expressed in $\text{W}/(\text{m}^2\cdot\text{K})$ [$\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$].

If a thickness for a layer of coke or scale is specified, the effective inside diameter of the tube is adjusted as noted in Equation (B.10). The effects of internal fouling, coke or scale on tube metal temperature can be calculated using Equations (B.8) and (B.10).

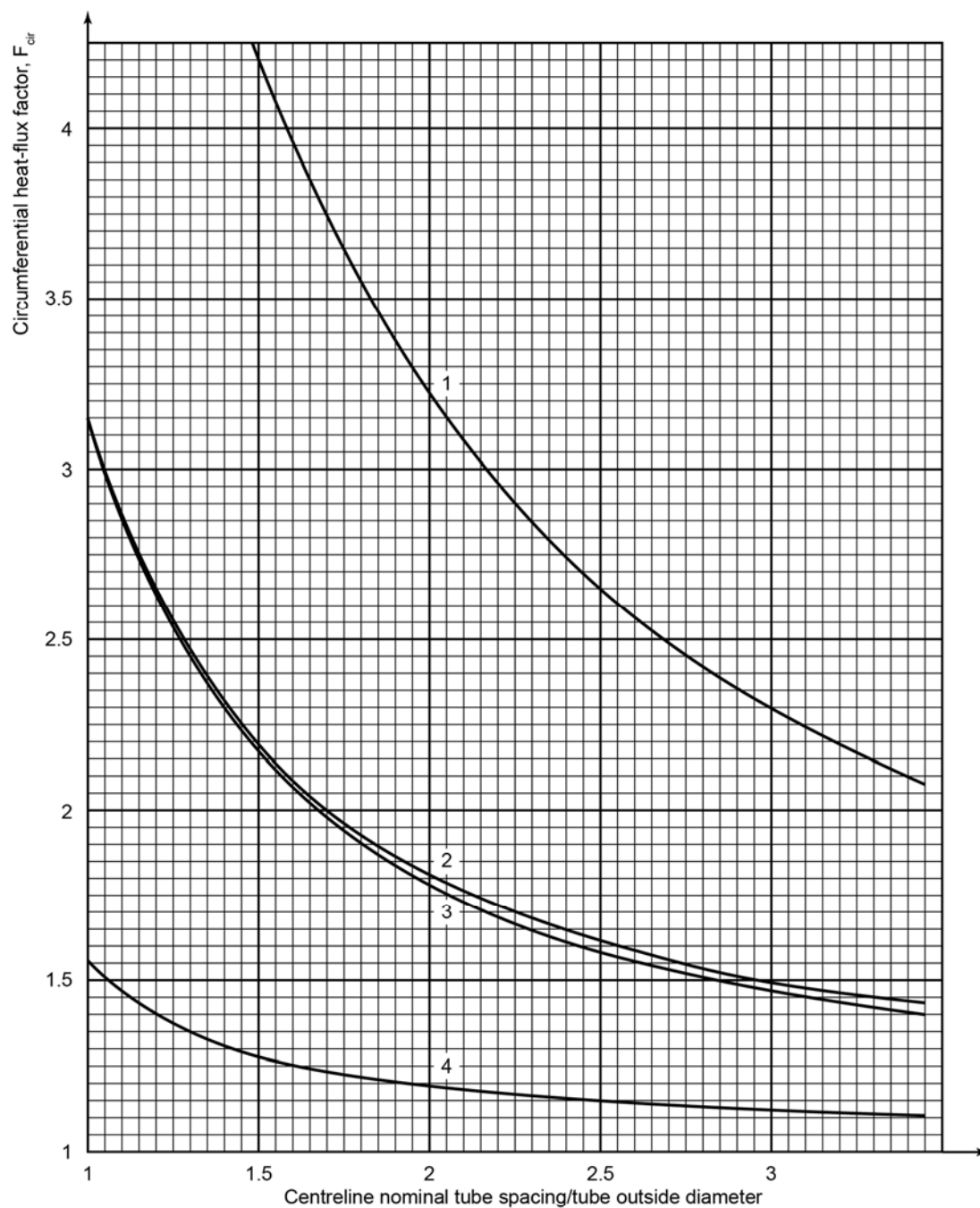
Equation (B.13) should be used to calculate the maximum fluid-film temperature coincident with maximum radiant heat flux, T_{fm} , expressed in degrees Celsius (Fahrenheit).

$$T_{fm} = T_{bf} + \Delta T_{ff} \quad (\text{B.13})$$

In the absence of thermal conductivity data provided by the Purchaser, the following range of values may be used. Petroleum coke: 4.91 $\text{W}/\text{m}\cdot\text{K}$ to 5.89 $\text{W}/\text{m}\cdot\text{K}$ (2.8 $\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$ to 3.4 $\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$) and iron oxide scale: 0.87 $\text{W}/\text{m}\cdot\text{K}$ to 1.05 $\text{W}/\text{m}\cdot\text{K}$ (0.5 $\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$ to 0.6 $\text{Btu}/\text{h}\cdot\text{ft}\cdot^\circ\text{F}$).

The thermal conductivity of the tube material, λ_{tm} , used in Equation (B.11), should be evaluated at the average tube wall temperature.

See Figure B.1 depicting the ratio of maximum local to average heat flux based on centerline nominal tube spacing and tube diameter.

**Key**

- 1 Curve 1 for a double row against a wall, triangular spacing
- 2 Curve 2 for a double row with equal radiation from both sides and two diameters between rows, triangular spacing
- 3 Curve 3 for a single row against a wall
- 4 Curve 4 for a single row with equal radiation from both sides

These curves are valid when used with a tube-center-to-refractory-wall spacing of 1.5 times the nominal tube diameter. Any appreciable variation from this spacing should be given special consideration.

NOTE 1 These curves do not take into consideration the convection heat transfer to the tubes, circumferential heat transfer by conduction through the tube wall, or variations in heat flux in different zones of the radiant section.

NOTE 2 These curves are based on the work of H. C. Hottel. Applicable papers are identified in Reference [14].

Figure B.1—Ratio of Maximum Local to Average Heat Flux

B.5 Sample Calculation

The following sample calculation demonstrates how to use the equations given in B.2 to B.4.

NOTE Differences in results between calculations in SI and USC units for dimensionless numbers are due to the significant figures used in the dimension conversions.

In the heater under consideration, the medium-carbon-steel tubes are in a single row against the wall. Other aspects of the heater configuration are as follows:

Tube spacing is 203.2 mm (= 0.667 ft = 8.0 in.).

$D_o = 114.3 \text{ mm}$ (= 0.375 ft = 4.5 in.);

$\delta_{t,ave} = 6.4 \text{ mm}$ (= 0.0208 ft = 0.25 in.);

$D_i = 101.6 \text{ mm}$ (= 0.333 ft = 4.0 in.);

$\delta_f = 0 \text{ mm}$ (0 in);

$\lambda_{tm} = 42.2 \text{ W/(m}\cdot\text{K)}$ [24.4 Btu/(h·ft·°F)] at an assumed tube metal temperature of 380 °C (720 °F).

The flow in the tubes is two-phase with 10 % mass vapor. Other operating conditions are as follows:

Flow rate (total liquid plus vapor) is 6.3 kg/s (50,000 lb/h).

$T_b = 271 \text{ °C}$ (520 °F);

$q_{R,ave} = 31,546 \text{ W/m}^2$ [10,000 Btu/(h·ft²)].

The properties of the liquid at the bulk temperature are as follows:

$\mu_{f,Tb} = 2.0 \times 10^{-3} \text{ Pa}\cdot\text{s}$ [4.84 lb/(h·ft)];

$\lambda_{f,Tb} = 0.1163 \text{ W/(m}\cdot\text{K)}$ [0.0672 Btu/(h·ft·°F)];

$c_{p,f} = 2.847 \text{ J/(kg}\cdot\text{K)}$ [0.68 Btu/(lb·°F)].

The properties of the vapor at the bulk temperature are as follows:

$\mu_{v,Tb} = 7.0 \times 10^{-6} \text{ Pa}\cdot\text{s}$ [0.017 lb/(ft·h)];

$\lambda_{v,Tb} = 0.0346 \text{ W/(m}\cdot\text{K)}$ [0.020 Btu/(h·ft·°F)];

$c_{p,v} = 2.394 \text{ J/(kg}\cdot\text{K)}$ [0.572 Btu/(lb·°F)].

From the inside diameter, the flow area is equal to $8.107 \times 10^{-3} \text{ m}^2$ (0.0873 ft²). Using the total flow rate:

$q_{mA} = 6.3 / (8.107 \times 10^{-3}),$

$q_{mA} = 777.1 \text{ kg/(m}^2\cdot\text{s)}.$

In USC units:

$$q_{mA} = (50,000/0.0873),$$

$$q_{mA} = 5.73 \times 10^5 \text{ lb}/(\text{h}\cdot\text{ft}^2).$$

The Reynolds number [Equation (B.2)] is calculated as follows:

For liquid:

In SI units:

$$\text{Re} = \frac{(0.1016)(777.1)}{0.002} = 3.95 \times 10^4$$

In USC units:

$$\text{Re} = \frac{(0.333)(5.73 \times 10^5)}{4.84} = 3.94 \times 10^4$$

For vapor:

In SI units:

$$\text{Re} = \frac{(0.1016)(777.1)}{7.0 \times 10^{-6}} = 1.13 \times 10^7$$

In USC units:

$$\text{Re} = \frac{(0.333)(5.73 \times 10^5)}{0.017} = 1.12 \times 10^7$$

The Prandtl number [Equation (B.3)] is calculated as follows:

For liquid:

In SI units:

$$\text{Pr} = \frac{(2847)(0.002)}{0.1163} = 49.0$$

In USC units:

$$\text{Pr} = \frac{(0.68)(4.84)}{0.0672} = 49.0$$

For vapor:

In SI units:

$$\text{Pr} = \frac{(2395)(7.0 \times 10^{-6})}{0.0346} = 0.485$$

In USC units:

$$Pr = \frac{(0.572)(0.017)}{0.020} = 0.486$$

Assume that for the liquid:

$$\left(\frac{\mu_{f, Tb}}{\mu_{f, Tw}} \right)^{0.14} = 1.1$$

Assume that for the vapor:

$$\left(\frac{T_b}{T_w} \right)^{0.5} = 0.91$$

These assumptions will be checked later. Using Equation (B.1):

$$\begin{aligned} K_l &= 0.023 \left(\frac{\mu_{f, Tb}}{D_i} \right) (3.94 \times 10^4)^{0.8} (49.0)^{0.33} (1.1) \\ &= 433.8 \left(\frac{\mu_{f, Tb}}{D_i} \right) \end{aligned}$$

Using Equation (B.4):

$$\begin{aligned} K_v &= 0.021 \left(\frac{\mu_{f, Tb}}{D_i} \right) (1.12 \times 10^7)^{0.8} (0.486)^{0.4} (0.91) \\ &= 6242 \left(\frac{\mu_{f, Tb}}{D_i} \right) \end{aligned}$$

Hence:

In SI units:

$$K_l = 433.8 \left(\frac{0.1163}{0.1016} \right) = 497 \text{ W/m}^2 \cdot \text{K}$$

$$K_v = 6242 \left(\frac{0.0346}{0.1016} \right) = 2126 \text{ W/m}^2 \cdot \text{K}$$

In USC units:

$$K_l = 433.8 \left(\frac{0.0672}{0.333} \right) = 87.5 \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{F}$$

$$K_v = 6242 \left(\frac{0.020}{0.333} \right) = 375 \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{F}$$

The two-phase heat-transfer coefficient can then be calculated using Equation (B.5):

In SI units:

$$\begin{aligned} K_{2p} &= (0.90)K_l + (0.10)K_v \\ &= (0.90)(497) + (0.10)(2126) \\ &= 659.9 \text{ W/(m}^2\cdot\text{K)} \end{aligned}$$

In USC units:

$$\begin{aligned} K_{2p} &= (0.90)(87.5) + (0.10)(375) \\ &= 116.3 \text{ Btu/(h}\cdot\text{ft}^2 \cdot ^\circ\text{F)} \end{aligned}$$

The ratio of tube spacing to tube diameter is as follows:

In SI units:

$$\frac{203.2}{114.3} = 1.78$$

In USC units:

$$\frac{8.0}{4.5} = 1.78$$

From Figure B.1, $F_{\text{cir}} = 1.91$. Assume that for this heater, $F_L = 1.1$, $F_T = 1.0$, and $q_{\text{conv}} = 0$ (i.e., there is no convective heat flux at this point). Using Equation (B.6):

In SI units:

$$\begin{aligned} q_{R,\text{max}} &= (1.91)(1.1)(1.0)(31,546) \\ &= 66,278 \text{ W/m}^2 \end{aligned}$$

In USC units:

$$\begin{aligned} q_{R,\text{max}} &= (1.91)(1.1)(1.0)(10,000) \\ &= 21,010 \text{ Btu/(h}\cdot\text{ft}^2) \end{aligned}$$

The temperature difference through each part of the system can now be calculated from Equation (B.9) for the fluid film:

In SI units:

$$\Delta T_{\text{ff}} = \left(\frac{66,278}{659.9} \right) \left(\frac{114.3}{101.6} \right) = 113 \text{ K}$$

In USC units:

$$\Delta T_{\text{ff}} = \left(\frac{21,010}{116.3} \right) \left(\frac{0.375}{0.333} \right) = 203 \text{ } ^\circ\text{R}$$

From Equation (B.11) for the tube wall:

In SI units:

$$\Delta T_{tw} = 66,278 \left[\frac{114.3 \ln \left(\frac{114.3}{101.6} \right)}{2(42.2)} \right] \times 10^{-3} = 11 \text{ K}$$

In USC units:

$$\Delta T_{tw} = 21,028 \left[\frac{0.375 \ln \left(\frac{0.375}{0.333} \right)}{2(24.4)} \right] = 19 \text{ }^{\circ}\text{R}$$

Using Equation (B.8), the maximum tube metal temperature is as follows:

In SI units:

$$T_{\max} = 271 + 113 + 11 = 395 \text{ }^{\circ}\text{C}$$

In USC units:

$$T_{\max} = 520 + 203 + 19 = 742 \text{ }^{\circ}\text{F}$$

Checking the assumed viscosity ratio, at the oil-film temperature calculated above, $271 + 113 = 384 \text{ }^{\circ}\text{C}$ ($520 + 203 = 723 \text{ }^{\circ}\text{F}$), the viscosity is 1.1 mPa·s (2.66 lb/ft·h). So, for the liquid:

In SI units:

$$\left(\frac{\mu_{f, Tb}}{\mu_{f, Tw}} \right)^{0.14} = \left(\frac{0.002}{0.0011} \right)^{0.14} = (1.82)^{0.14} = 1.09$$

In USC units:

$$\left(\frac{\mu_{f, Tb}}{\mu_{f, Tw}} \right)^{0.14} = \left(\frac{4.84}{2.66} \right)^{0.14} = (1.82)^{0.14} = 1.09$$

For the vapor:

In SI units:

$$\left(\frac{T_b}{T_w} \right)^{0.5} = \left(\frac{270 + 273}{384 + 273} \right)^{0.5} = (0.83)^{0.5} = 0.91$$

In USC units:

$$\left(\frac{T_b}{T_w} \right)^{0.5} = \left(\frac{520 + 460}{723 + 460} \right)^{0.5} = (0.83)^{0.5} = 0.91$$

Both values are close to the values assumed for the calculation of K_l and K_v , so no additional work is needed.

The mean tube wall temperature is as follows:

In SI units:

$$270 + 113 + \frac{11}{2} = 388 \text{ }^{\circ}\text{C}$$

In USC units:

$$520 + 203 + \frac{19}{2} = 732 \text{ }^{\circ}\text{F}$$

This is close to the temperature assumed for the tube conductivity, so no additional work is required.

Annex C (normative)

Thermal-stress Limitations (Elastic Range)

C.1 General

In heater tubes, the thermal stress of greatest concern is the one developed by the radial distribution of temperature through the thickness. This stress can become particularly significant in thick stainless steel tubes exposed to high heat fluxes.

There are two limits for thermal stress; both are described in Section 5.5.6 of ASME Section VIII, Division 2 Code. These limits apply only in the elastic range; in the rupture range, an appropriate limit for thermal stress has not been established.

In addition to the above limitations, it should be noted that the applicability of the following thermal stress methodologies are limited to “thin wall” tubes (e.g. tubes with a thickness-to-outside diameter ratio of less than 0.15).

C.2 Equation for Thermal Stress

The following equation gives the maximum thermal stress, $\sigma_{T\max}$, in a tube:

$$\sigma_{T\max} = X \left[\left(\frac{2y^2}{y^2 - 1} \right) \ln y - 1 \right] \quad (C.1)$$

where

$$X = \left[\frac{\alpha E}{2(1-\nu)} \right] \left[\frac{\Delta T}{\ln y} \right] = \left[\frac{\alpha E}{4(1-\nu)} \right] \left[\frac{q_o D_o}{\lambda_s} \right] \quad (C.2)$$

α is the coefficient of thermal expansion;

E is the modulus of elasticity;

ν is Poisson's ratio;

ΔT is the temperature difference across the tube wall;

y is D_o/D_i , ratio of outside diameter to actual inside diameter;

q_o is the heat flux on the outside surface of the tube;

λ_s is the thermal conductivity of the steel.

The material properties α , E , ν , and λ_s shall be evaluated at the mean temperature of the tube wall. The average wall thickness shall also be used in this equation (see 5.7). Poisson's ratio at elevated temperature is not readily available. However, E and G (modulus of rigidity) at high temperature can be found in numerous references and used to calculate ν with the equation: $\nu = (E/2G) - 1$.

C.3 Limits on Thermal Stress

The limitation, $\sigma_{T,lim1}$, on primary plus secondary stress intensity of Mandatory Appendix 4 of ASME Section VIII, Division 2 Code (2004 Edition), Paragraph 4-134, can be approximated for thermal stress as given in Equations (C.3) and (C.4) (see Section C.4 for the derivation).

For ferritic steels:

$$\sigma_{T,lim1} = (2.0 - 0.67y) \sigma_y \quad (C.3)$$

For austenitic steels:

$$\sigma_{T,lim1} = (2.7 - 0.90y) \sigma_y \quad (C.4)$$

where σ_y is the yield strength.

The thermal-stress ratchet limit, $\sigma_{T,lim2}$, of Mandatory Appendix 5 of ASME Section VIII, Division 2 Code (2004 Edition), Paragraph 5-130, can be approximated for thermal stress as given in Equations (C.5) and (C.6) (see Section C.5 for derivation).

For ferritic steels:

$$\sigma_{T,lim2} = 1.33\sigma_y \quad (C.5)$$

For austenitic steels:

$$\sigma_{T,lim2} = 1.8\sigma_y \quad (C.6)$$

Both the primary plus secondary stress limit ($\sigma_{T,lim1}$) and the thermal-stress ratchet limit ($\sigma_{T,lim2}$) shall be met if the tube is designed for the elastic range.

C.4 Derivation of Limits on Primary Plus Secondary Stress Intensity

The limit on primary plus secondary stress intensity can be expressed symbolically as given by the inequality in Equation (C.7):

$$\sigma_{pl} + \sigma_{pb} + \sigma_{cir,max} < 3 \sigma_m \quad (C.7)$$

where

$\sigma_{cir,max}$ is the maximum circumferential thermal stress which, for this application, is the maximum thermal stress given by equation (C.1);

σ_{pl} is the local primary membrane stress;

σ_{pb} is the primary bending stress.

From ASME *BPVC* Section VIII, Division 2, for tubes with an internal pressure:

$$\sigma_{pl} + \sigma_{pb} = p_{el} \left(\frac{2y^2}{y^2 - 1} \right) \quad (C.8)$$

where

p_{el} is the elastic design pressure;

y is the ratio of outside to actual inside diameter, equal to D_o/D_i .

If the primary membrane stress intensity, σ_{pm} , is given by Equation (C.9),

$$\sigma_{pm} = \frac{p_{el}}{2} \left(\frac{D_o}{\delta} - 1 \right) = \frac{p_{el}}{2} \left(\frac{y+1}{y-1} \right) \quad (C.9)$$

it can, then, be easily shown that Equation (C.10) gives a first approximation and provides an upper bound:

$$\sigma_{pl} + \sigma_{pb} \cong y\sigma_{pm} \quad (C.10)$$

In ASME Section VIII, Division 2 *Pressure Vessel Code* (2004 Edition)], σ_m is the allowable membrane stress intensity. For ferritic steels above about 340 °C (650 °F), σ_m is equal to two-thirds of the yield strength, σ_y , as given in Equation (C.11):

$$3 \sigma_m = 2 \sigma_y \quad (C.11)$$

For austenitic steels above about 260 °C (500 °F), σ_m is 90 % of σ_y , as given in Equation (C.12):

$$3 \sigma_m = 2.7 \sigma_y \quad (C.12)$$

Heater tubes usually operate above these temperatures.

Combining all of this, the primary plus secondary stress intensity limit on thermal stress can be expressed as given in Equations (C.13) and (C.14):

For ferritic steels:

$$\sigma_{T,lim1} = 2\sigma_y - y\sigma_{pm} \quad (C.13)$$

For austenitic steels:

$$\sigma_{T,lim1} = 2.7\sigma_y - y\sigma_{pm} \quad (C.14)$$

where $\sigma_{T,lim1}$ is the maximum value permitted for the thermal stress, σ_T .

For ferritic-steel and austenitic-steel heater tubes designed according to this standard, the inequalities in Equations (C.15) and (C.16), respectively, hold:

$$\sigma_{pm} < 0.67\sigma_y \quad (C.15)$$

$$\sigma_{pm} < 0.90\sigma_y \quad (C.16)$$

The thermal-stress limit, $\sigma_{T,lim1}$, can therefore be approximated as given in Equations (C.17) and (C.18):

For ferritic steels:

$$\sigma_{T,lim1} = (2.0 - 0.67y)\sigma_y \quad (C.17)$$

For austenitic steels:

$$\sigma_{T,lim1} = (2.7 - 0.90y)\sigma_y \quad (C.18)$$

The limits expressed by these equations are simple and appropriate. If the thermal stress is less than this limit, the design is appropriate. If the thermal stress exceeds the limit given by these equations, then, the more exact form of Equation (C.13) or (C.14) shall be used with the primary membrane stress intensity given by Equation (C.9). Also, if the tube thickness is arbitrarily increased over the thickness calculated in 5.3, then the primary membrane stress intensity shall be calculated using the actual average thickness, and Equation (C.13) or Equation (C.14) shall be used to calculate the thermal-stress limit.

C.5 Derivation of Limits on Thermal-stress Ratchet

The limit, $\sigma_{T,lim2}$, set to avoid thermal-stress ratchet can be expressed as given in Equation (C.19):

$$\sigma_{T,lim2} = 4(\sigma - \sigma_{pm}) \quad (C.19)$$

For ferritic steels:

$$\sigma = \sigma_y \quad (C.20)$$

For austenitic steels above about 260 °C (500 °F):

$$\sigma = 1.5 (0.9 \sigma_y) = 1.35 \sigma_y \quad (C.21)$$

As before, σ_{pm} is derived from Equation (C.9). Using the inequalities in Equation (C.15) or Equation (C.16), this limit can be approximated as given in Equations (C.22) and (C.23):

For ferritic steels:

$$\sigma_{T,lim2} = 1.33 \sigma_y \quad (C.22)$$

For austenitic steels:

$$\sigma_{T,lim2} = 1.8 \sigma_y \quad (C.23)$$

As with the limits developed in Section C.4, these limits are approximate. If the thermal stress exceeds this limit or if the tube thickness is arbitrarily increased, the exact limit expressed by Equation (C.19) shall be used with the primary membrane stress intensity given by Equation (C.9).

Annex D (informative)

Calculation Sheets

This annex contains calculation sheets that are useful in aiding and documenting the calculation of minimum thickness and equivalent tube metal temperature. Individual sheets are provided for calculations in SI units or in USC units. These calculation sheets may be reproduced.

API Std 530 CALCULATION SHEET SI Units				
Heater _____ Unit _____ Item No. _____				
Coil _____ Material _____ ASTM Spec _____				
Calculation of Minimum Thickness	Elastic Design		Rupture Design	
Outside diameter, mm	$D_o =$		$D_o =$	
Design pressure, MPa (gauge)	$p_{el} =$		$p_r =$	
Maximum or equivalent metal temperature, °C	$T_{max} =$		$T_{max} =$	
Temperature allowance, °C	$T_A =$		$T_A =$	
Design metal temperature, °C	$T_d =$		$T_d =$	
Design life, h	—		$t_{DL} =$	
Allowable stress at T_d , Figures E.1 to E.64, MPa	$\sigma_{el} =$		$\sigma_r =$	
Stress thickness, Equation (2) or (4), mm	$\delta_\sigma =$		$\delta_\sigma =$	
Corrosion allowance, mm	$\delta_{CA} =$		$\delta_{CA} =$	
Corrosion fraction, Figure 1, $n =$; $B =$	—		$f_{corr} =$	
Minimum thickness, Equation (3) or (5), mm	$\delta_{min} =$		$\delta_{min} =$	
Calculation of Equivalent Tube Metal Temperature				
Duration of operating period, years			$t_{op} =$	
Metal temperature, start of run, °C			$T_{sor} =$	
Metal temperature, end of run, °C			$T_{eor} =$	
Temperature change during operating period, K			$\Delta T =$	
Metal absolute temperature, start of run, K			$T_{sor}^* =$	
Thickness change during operating period, mm			$\Delta \delta =$	
Assumed initial thickness, mm			$\delta_0 =$	
Corresponding initial stress, Equation (1), MPa			$\sigma_0 =$	
Material constant, Table 3, MPa			$A =$	
Rupture exponent at T_{sor1} , Figures E.2 to E.65			$n_0 =$	
Temperature fraction, Figure 2, $V =$; $N =$			$f_T =$	
Equivalent tube metal temperature, Equation (6), °C			$T_{eq} =$	

Std 530 CALCULATION SHEET (USC Units)				
Heater _____ Unit _____ Item No. _____				
Coil _____ Material _____ ASTM Spec _____				
Calculation of Minimum Thickness	Elastic Design		Rupture Design	
Outside diameter, in.	$D_o =$		$D_o =$	
Design pressure, psi (gauge)	$p_{el} =$		$p_r =$	
Maximum or equivalent metal temperature, °F	$T_{max} =$		$T_{max} =$	
Temperature allowance, °F	$T_A =$		$T_A =$	
Design metal temperature, °F	$T_d =$		$T_d =$	
Design life, h	—		$t_{DL} =$	
Allowable stress at T_d , Figures F.1 to F.64, psi	$\sigma_{el} =$		$\sigma_r =$	
Stress thickness, Equation (2) or (4), in.	$\delta_\sigma =$		$\delta_\sigma =$	
Corrosion allowance, in.	$\delta_{CA} =$		$\delta_{CA} =$	
Corrosion fraction, Figure 1, $n =$; $B =$	—		$f_{corr} =$	
Minimum thickness, Equation (3) or (5), in.	$\delta_{min} =$		$\delta_{min} =$	
Calculation of Equivalent Tube Metal Temperature				
Duration of operating period, years			$t_{op} =$	
Metal temperature, start of run, °F			$T_{sor} =$	
Metal temperature, end of run, °F			$T_{eor} =$	
Temperature change during operating period, °R			$\Delta T =$	
Metal absolute temperature, start of run, °R			$T_{sor}^* =$	
Thickness change during operating period, in.			$\Delta \delta =$	
Assumed initial thickness, in.			$\delta_0 =$	
Corresponding initial stress, Equation (1), psi			$\sigma_0 =$	
Material constant, Table 3, psi			$A =$	
Rupture exponent at T_{sor1} , Figures F.2 to F.65			$n_0 =$	
Temperature fraction, Figure 2, $V =$; $N =$			$f_T =$	
Equivalent tube metal temperature, Equation (6), °F			$T_{eq} =$	

API Std 530—Retirement Wall Thickness CALCULATION SHEET				
Parameter	Convection	Radiant	Unit	Reference
Pressure, P				
Normal				
Maximum				
Tube metal temperature, TMT				
Normal				
Maximum				
Operating plan				
Time to next inspection				
Time to tube retirement				
Future corrosion allowance, FCA				
Allowance for supplemental load(s)				
Tube parameters				
Outside diameter, D				
Nominal wall thickness, δ_{nom}				
Material specification				
Creep material strength property				
Creep life fraction consumed				
Allowable stress, S				
Elastic				
Creep				
Minimum required thickness, δ_{min}				
Value				
Basis				
Retirement wall thickness, δ_{retire}				Equation (1)
Minimum measured thickness, δ_{mm}				
Remaining life				Equation (2)

Annex E
(normative)

Stress Curves and Data Tables (SI Units)

Stress curves and data table (in SI units) are presented in Figures E.1 to E.66 and Tables E.1 to E.22.

List of Figures and Tables (SI Units)

Low Carbon Steels

- Figure E.1—Stress Curves (SI Units) for ASTM A192 Low-carbon Steels
- Figure E.2—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A192 Low-carbon Steels
- Figure E.3—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A192 Low-carbon Steels
- Table E.1—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A192 Low-carbon Steels

Medium Carbon Steels

- Figure E.4—Stress Curves (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
- Figure E.5—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
- Figure E.6—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
- Table E.2—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Carbon-1/2Moly Steels

- Figure E.7—Stress Curves (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels
- Figure E.8—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels
- Figure E.9—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels
- Table E.3—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

1-1/4Cr-1/2Moly Steels

- Figure E.10—Stress Curves (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels
- Figure E.11—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels
- Figure E.12—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels
- Table E.4—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

2-1/4Cr-1Moly Steels

- Figure E.13—Stress Curves (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels
- Figure E.14—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels
- Figure E.15—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels
- Table E.5—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

3Cr-1Moly Steels

Figure E.16—Stress Curves (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Figure E.17—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Figure E.18—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Table E.6—Elastic and Rupture Allowable Stresses (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

5Cr-1/2Moly Steels

Figure E.19—Stress Curves (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Figure E.20—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Figure E.21—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Table E.7—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

5Cr-1/2Moly-Si Steels

Figure E.22—Stress Curves (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Figure E.23—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Figure E.24—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Table E.8—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

9Cr-1Moly Steels

Figure E.25—Stress Curves (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Figure E.26—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Figure E.27—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Table E.9—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

9Cr-1Moly-V Steels

Figure E.28—Stress Curves (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Figure E.29—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Figure E.30—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Table E.10—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

TP 304-304H Stainless Steels

Figure E.31—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Figure E.32—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Figure E.33—Larson-Miller Parameter vs. Stress Curve (SI Units) for A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Table E.11—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

TP 304L Stainless Steels

Figure E.34—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

Figure E.35—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

Figure E.36—Larson-Miller Parameter vs. Stress Curve (SI Units) for A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

Table E.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

TP 316-316H Stainless Steels

Figure E.37—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Figure E.38—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Figure E.39—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Table E.13—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

TP 316L—317L Stainless Steels

Figure E.40—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

Figure E.41—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Figure E.42—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table E.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

TP 321 Stainless Steels

Figure E.43—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Figure E.44—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Figure E.45—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Table E.15—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

TP 321H Stainless Steels

Figure E.46—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Figure E.47—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Figure E.48—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Table E.16—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

TP 347 Stainless Steels

Figure E.49—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Figure E.50—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Figure E.51—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Table E.17—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

TP 347H Stainless Steels

Figure E.52—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Figure E.53—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Figure E.54—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Table E.18—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

TP 347LN Stainless Steels

Figure E.67—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.68—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure E.69—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table E.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Alloy 800 Steels

Figure E.55—Stress Curves (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Figure E.56—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Figure E.57—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Table E.19—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Alloy 800H Steels

Figure E.58—Stress Curves (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Figure E.59—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Figure E.60—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Table E.20—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Alloy 800HT Steels

Figure E.61—Stress Curves (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Figure E.62—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Figure E.63—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table E.21—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Alloy HK-40 Steels

Figure E.64—Stress Curves (SI Units) for ASTM A608 Grade HK-40 Steels

Figure E.65—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A608 Grade HK-40 Steels

Figure E.66—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A608 Grade HK-40 Steels

Table E.22—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A608 Grade HK-40 Steels

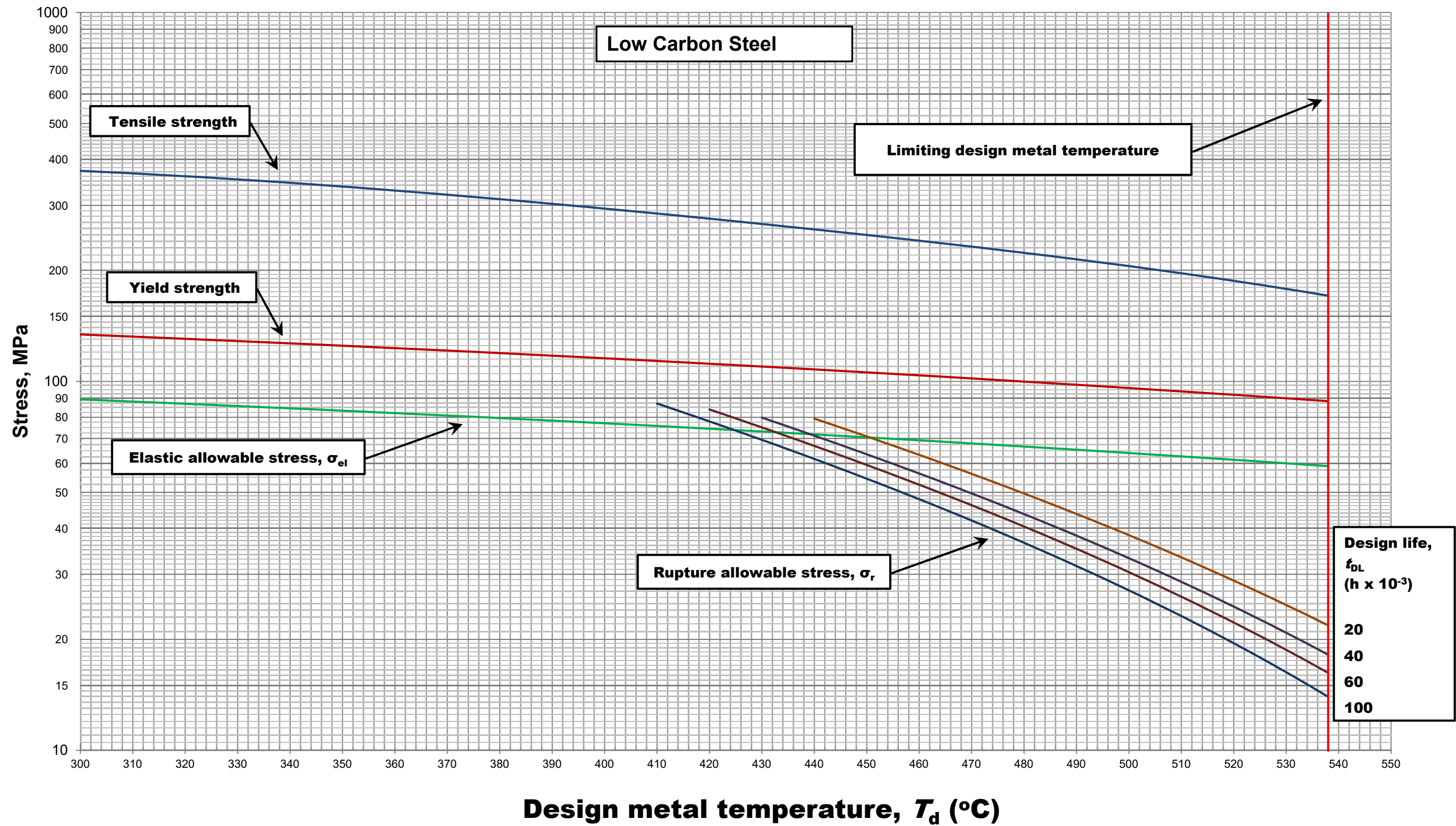


Figure E.1—Stress Curves (SI Units) for ASTM A192 Low-carbon Steels

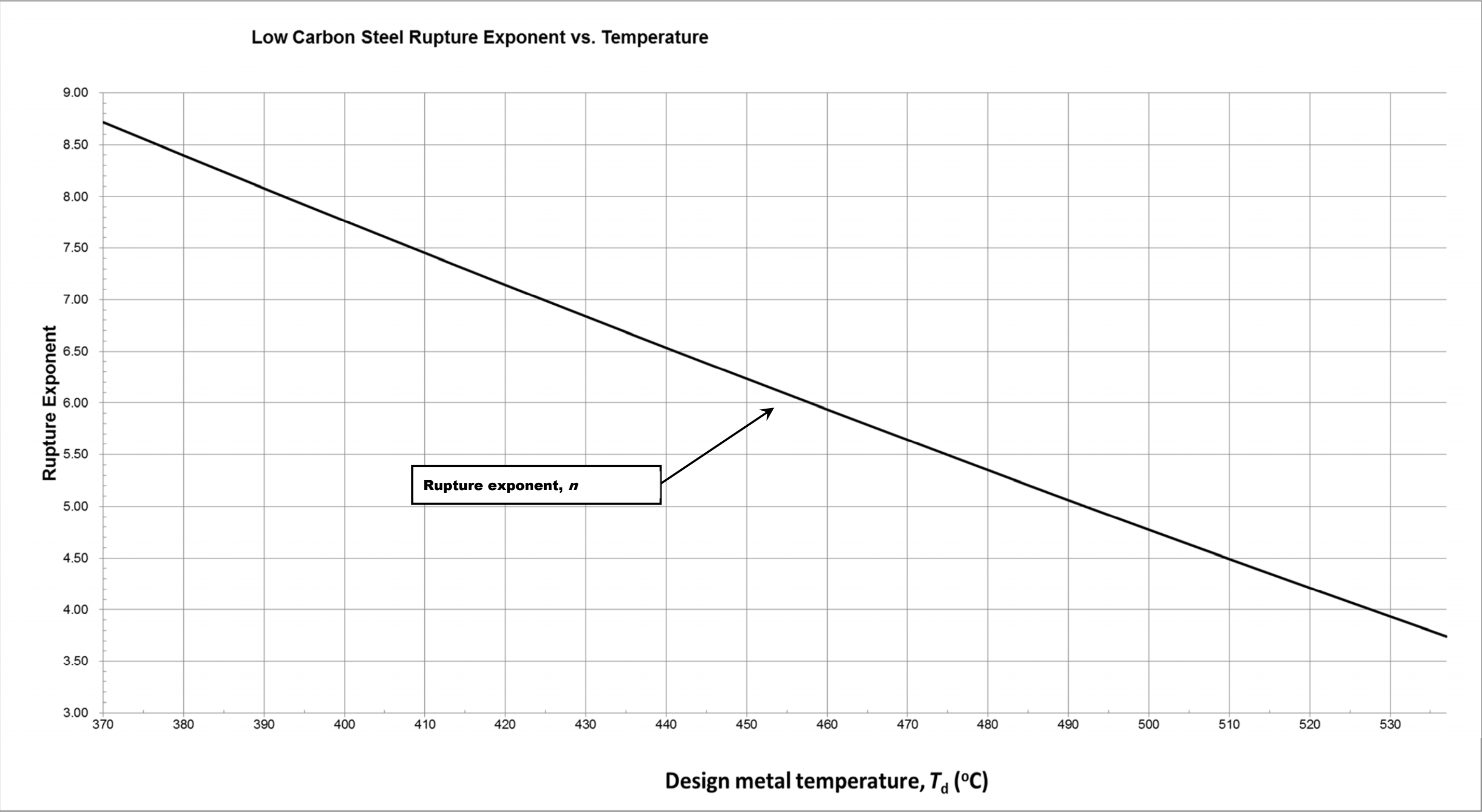


Figure E.2—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A192 Low-carbon Steels

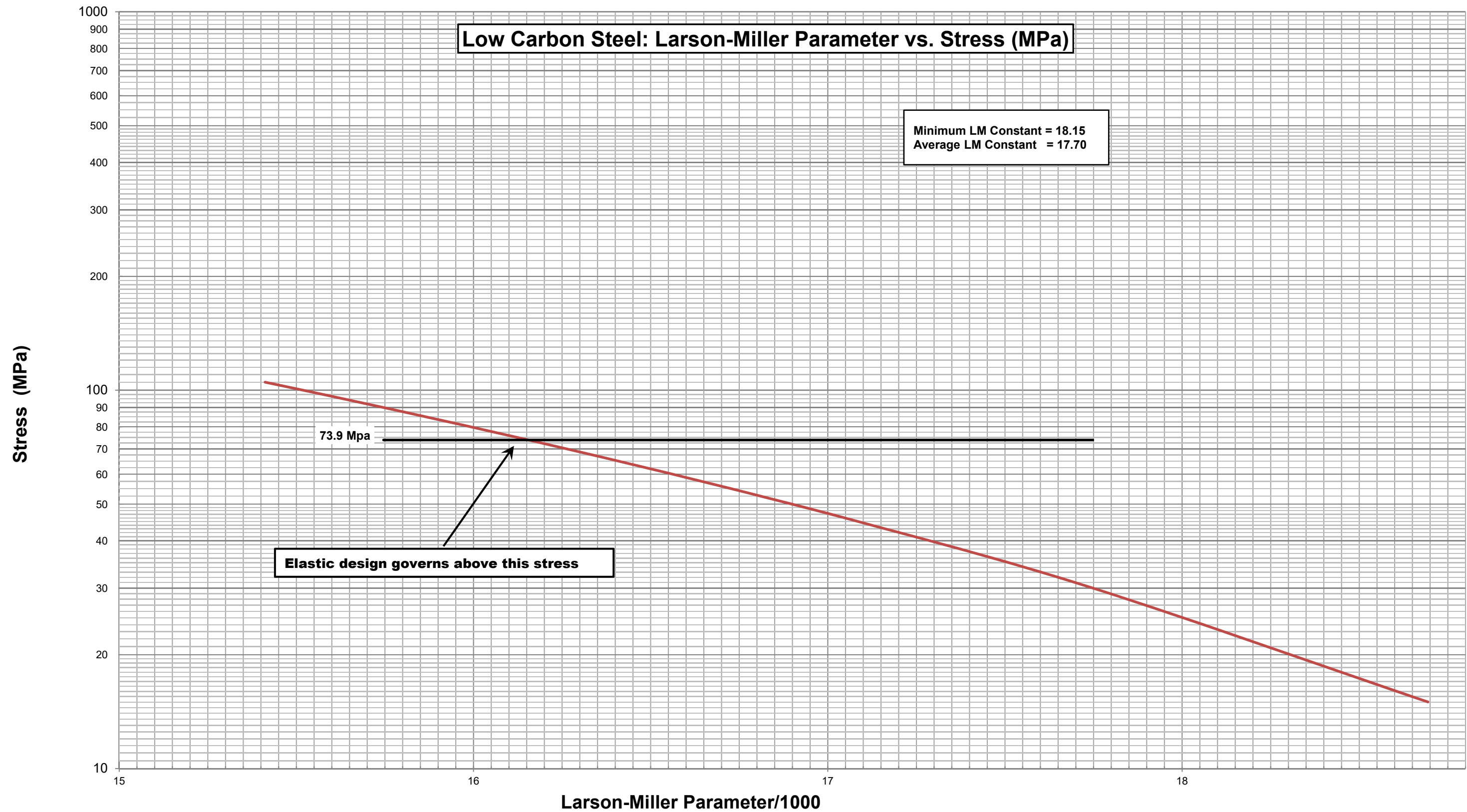


Figure E.3—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A192 Low-carbon Steels

Table E.1—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A192 Low-carbon Steels

Low Carbon Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	89.4					
310	88.2					
320	87.0					
330	85.8					
340	84.6					
350	83.3					
360	82.1					
370	80.8					
380	79.6					8.4
390	78.3					8.1
400	77.0	97.1	103.9	109.6	119.9	7.8
410	75.8	87.1	93.6	98.9	108.6	7.5
420	74.5	77.9	83.9	89.0	98.0	7.2
430	73.2	69.4	75.1	79.8	88.3	6.9
440	71.9	61.7	66.9	71.3	79.3	6.6
450	70.6	54.5	59.4	63.5	70.9	6.3
460	69.3	48.0	52.5	56.3	63.3	6.0
470	67.9	42.0	46.2	49.7	56.2	5.7
480	66.6	36.5	40.4	43.7	49.7	5.4
490	65.3	31.6	35.2	38.2	43.7	5.1
500	64.0	27.2	30.4	33.2	38.3	4.8
510	62.7	23.1	26.1	28.6	33.4	4.5
520	61.3	19.5	22.2	24.5	28.9	4.2
530	60.0	16.3	18.7	20.8	24.8	4.0
538	58.9	14.0	16.2	18.2	21.8	3.7

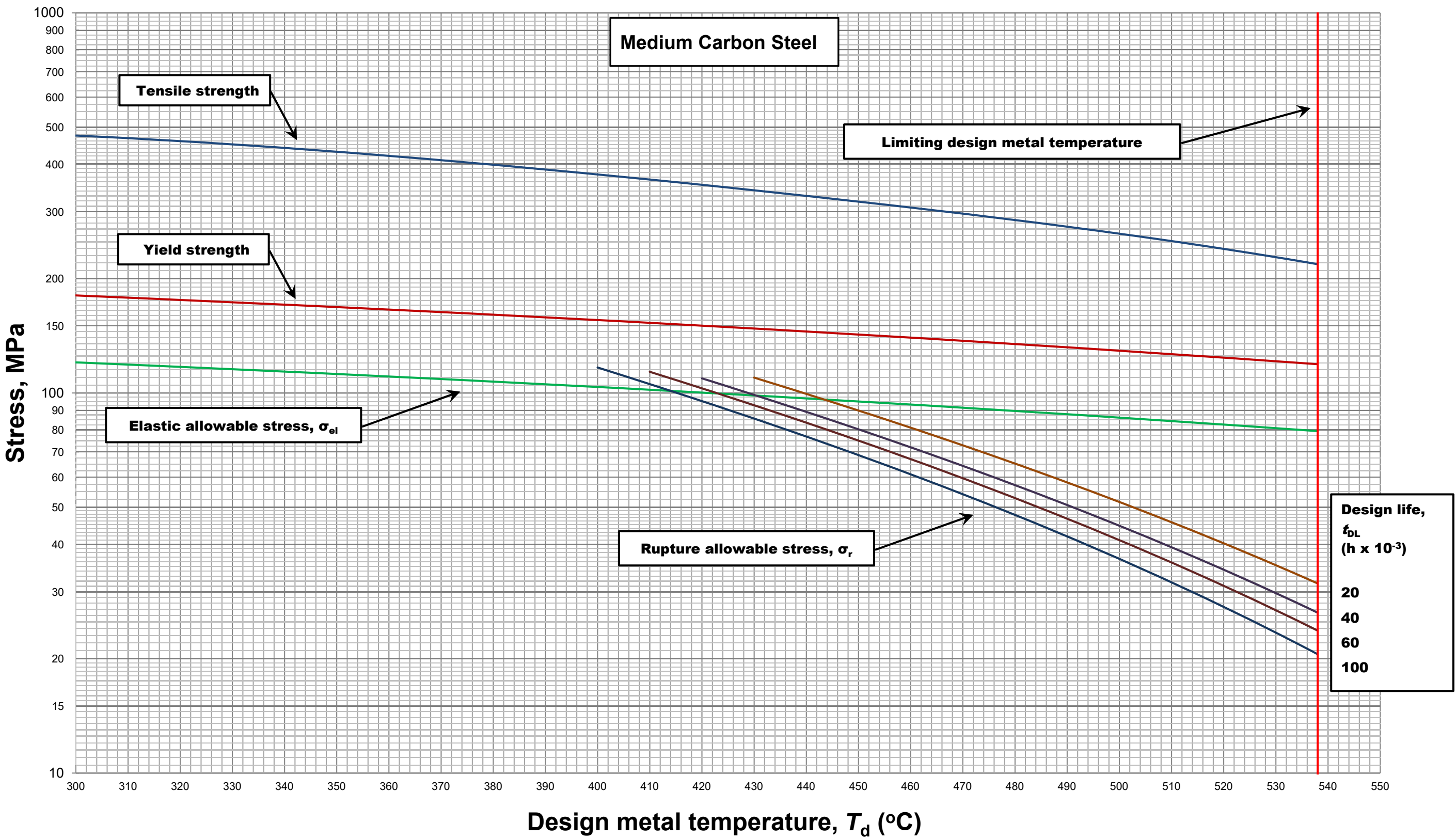


Figure E.4—Stress Curves (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

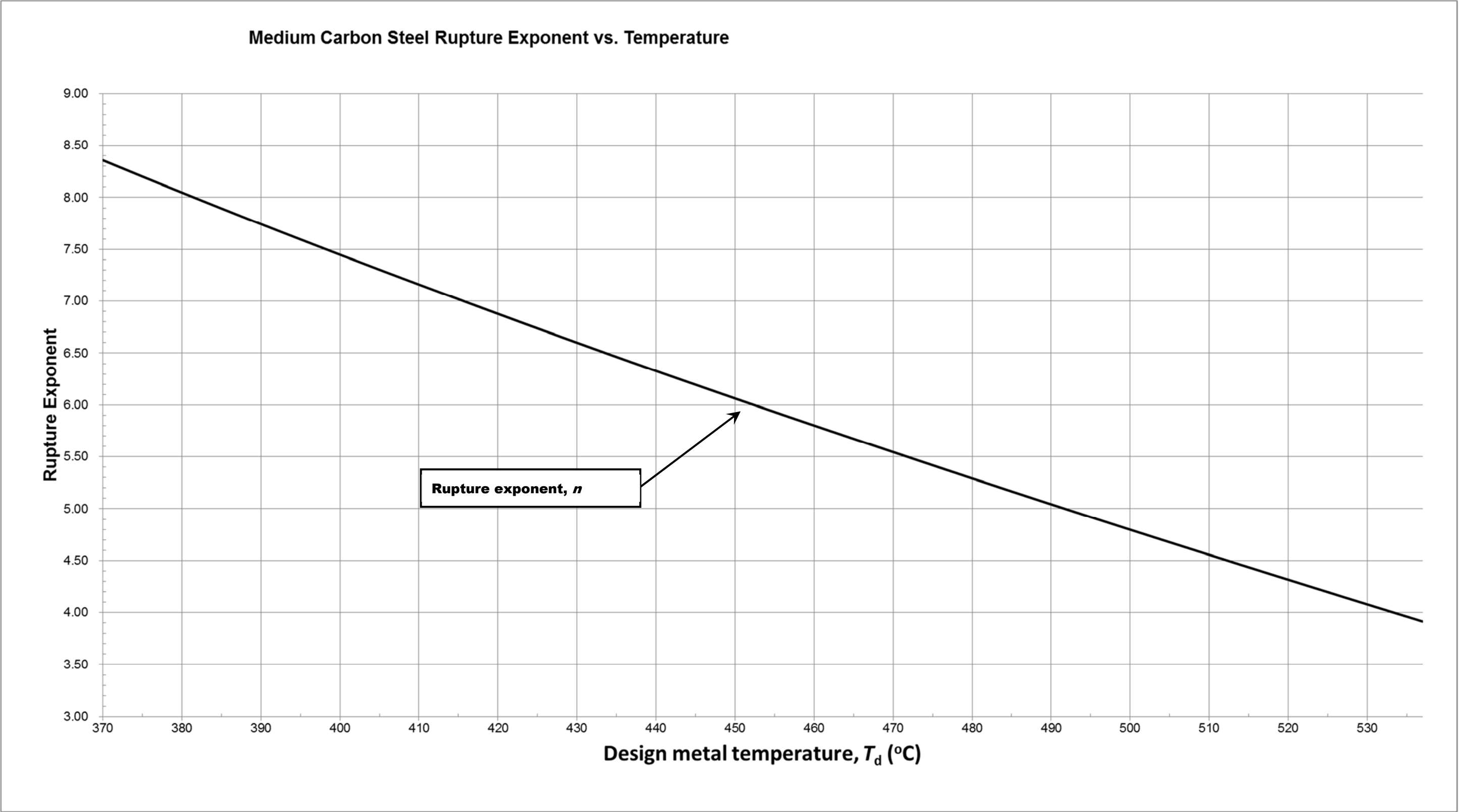


Figure E.5—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

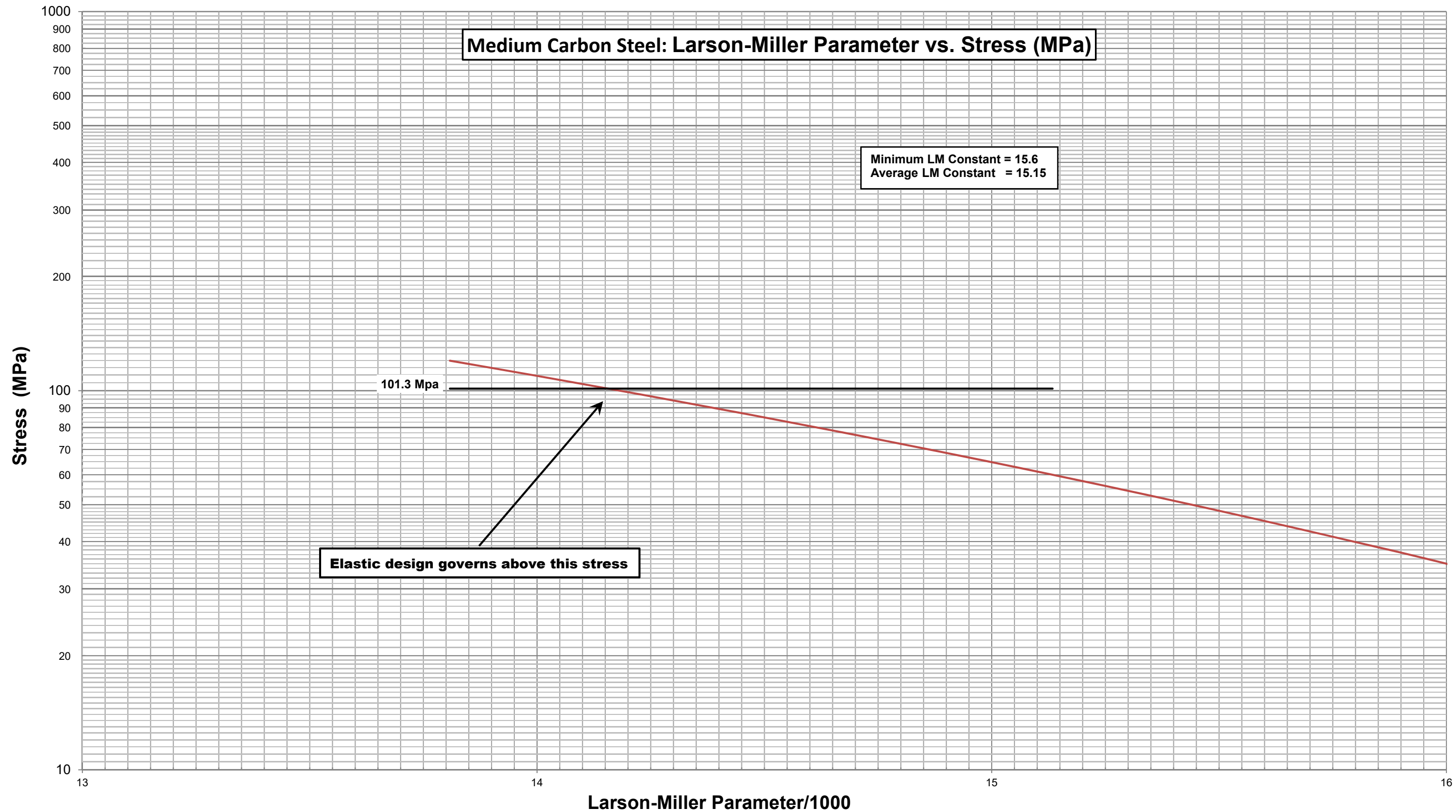


Figure E.6—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Table E.2—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Medium Carbon Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	120.4					
310	118.8					
320	117.1					
330	115.5					
340	113.8					
350	112.2					
360	110.5					
370	108.8					
380	107.1					
390	105.4	128.6	137.7	145.2	158.7	8.1
400	103.7	116.7	125.3	132.4	145.2	7.8
410	102.0	105.6	113.7	120.4	132.6	7.5
420	100.3	95.3	102.9	109.3	120.8	7.2
430	98.5	85.7	92.9	98.9	109.8	6.9
440	96.8	76.8	83.6	89.2	99.5	6.6
450	95.0	68.6	74.9	80.3	89.9	6.4
460	93.2	61.1	67.0	72.0	81.1	6.1
470	91.5	54.1	59.6	64.3	72.8	5.8
480	89.7	47.8	52.9	57.2	65.2	5.6
490	87.9	41.9	46.7	50.7	58.2	5.3
500	86.1	36.6	41.0	44.7	51.7	5.1
510	84.4	31.8	35.8	39.3	45.7	4.8
520	82.6	27.4	31.1	34.3	40.2	4.6
530	80.8	23.4	26.8	29.8	35.2	4.3
538	79.4	20.5	23.7	26.4	31.6	4.1
						3.9

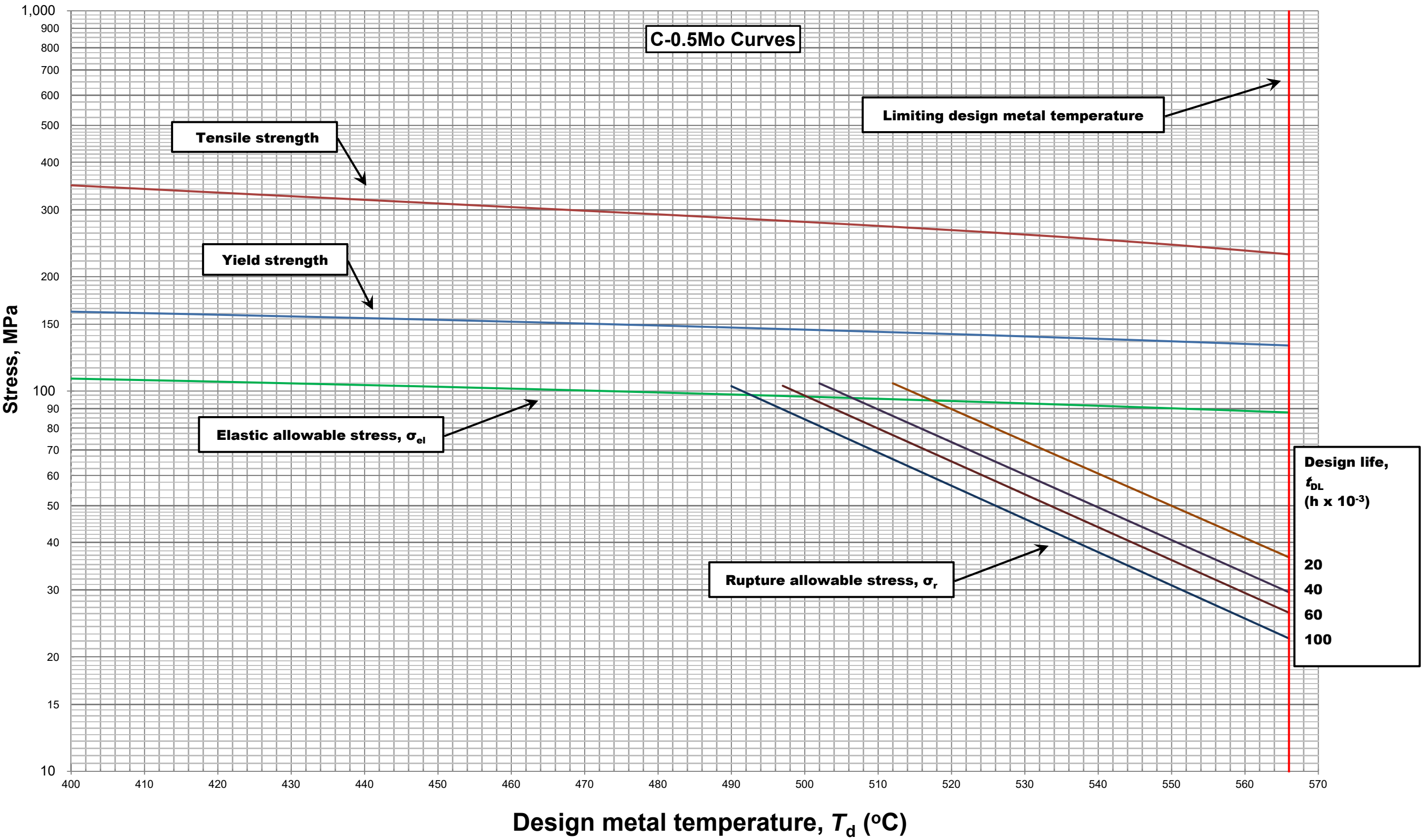


Figure E.7—Stress Curves (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

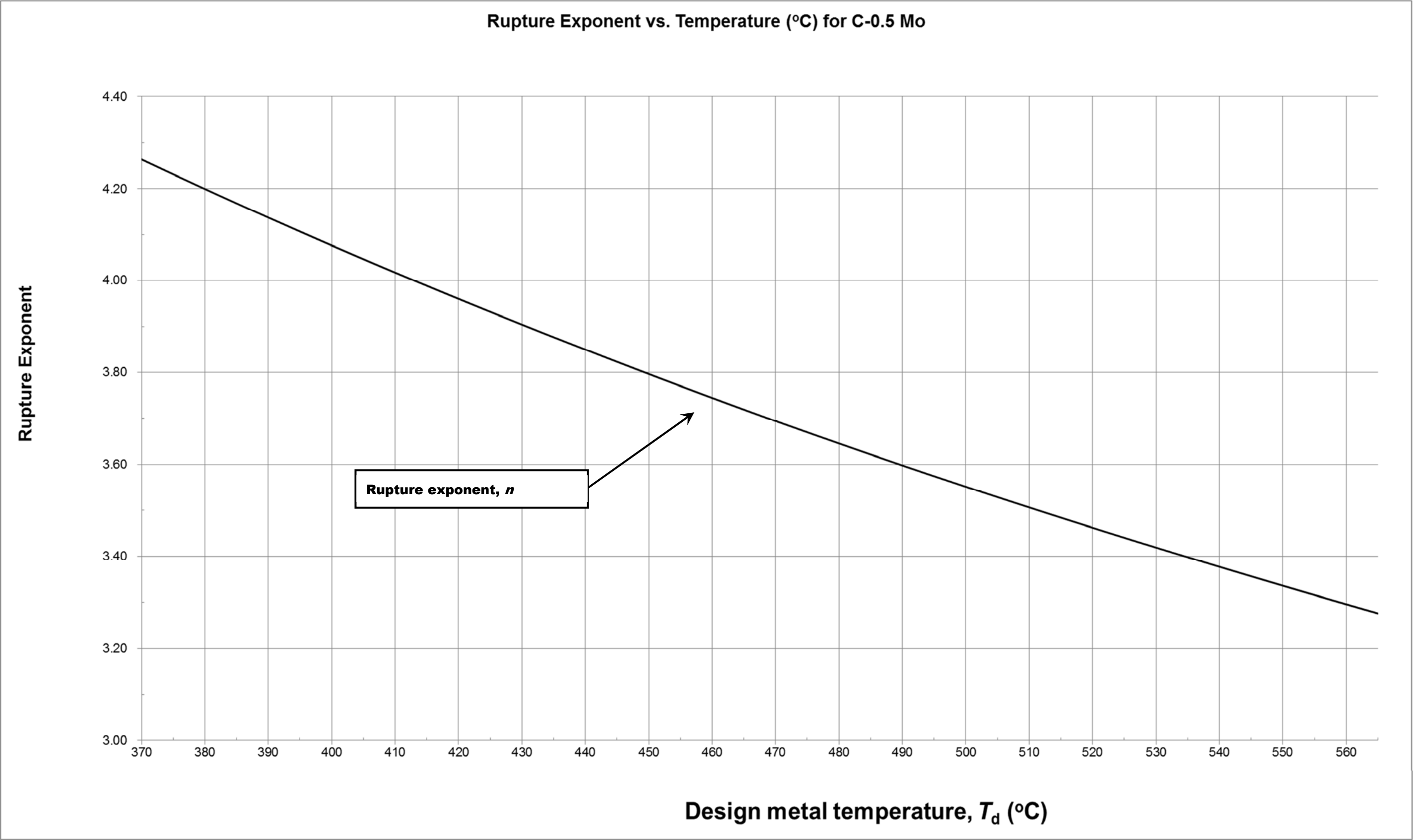


Figure E.8—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

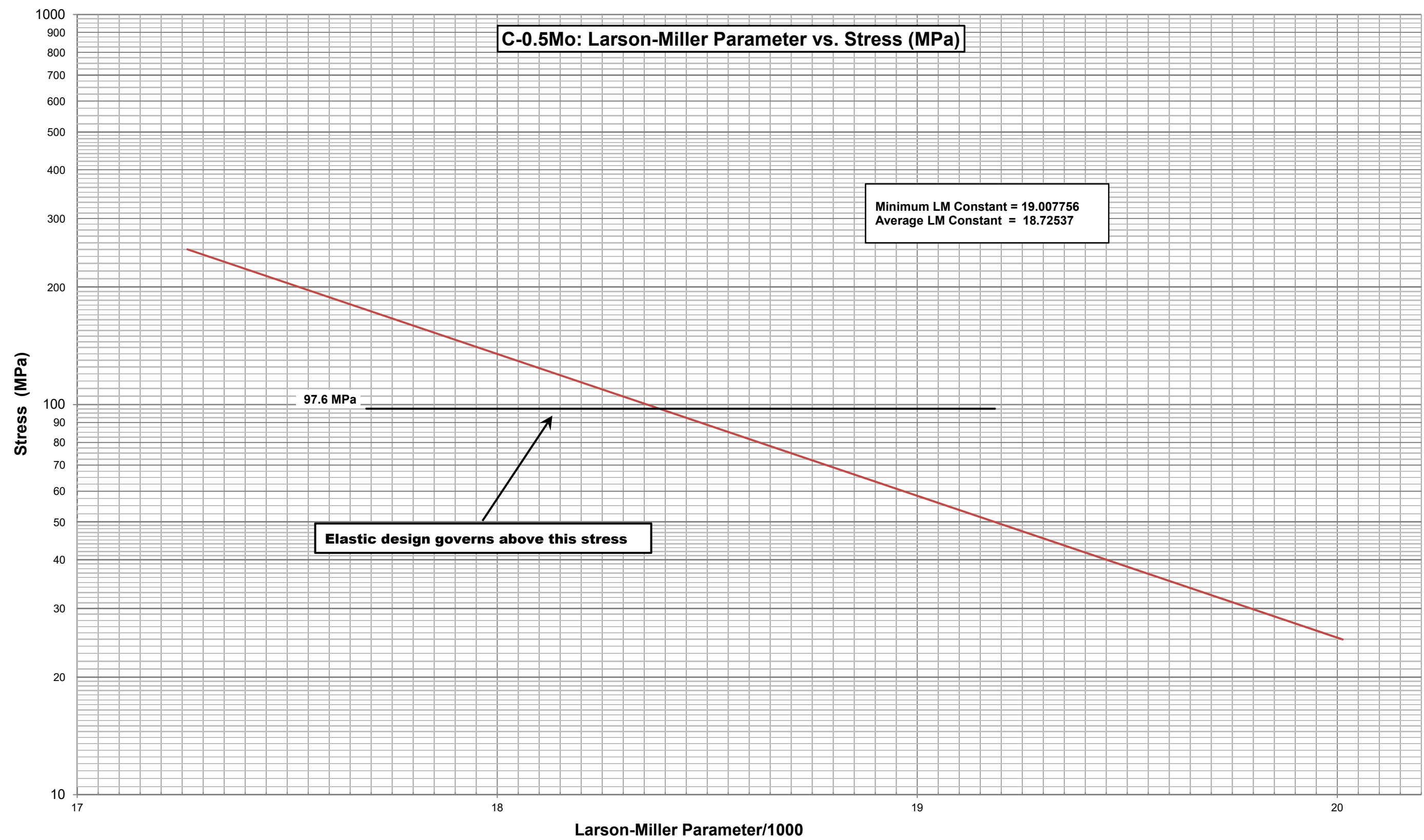


Figure E.9—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

Table E.3—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

C-0.5Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	116.6					
310	115.8					
320	115.0					
330	114.2					
340	113.3					
350	112.5					
360	111.6					
370	110.7					
380	109.8					4.2
390	108.8					4.1
400	107.9					4.1
410	106.9					4.0
420	105.9					4.0
430	104.8					3.9
440	103.7					3.9
450	102.6					3.8
460	101.5					3.8
470	100.4					3.7
480	99.2	125.9	144.9	161.9	195.7	3.7
490	98.0	103.0	118.7	132.8	161.0	3.6
500	96.7	84.3	97.3	109.0	132.5	3.6
510	95.4	68.9	79.7	89.5	109.0	3.5
520	94.2	56.4	65.3	73.4	89.7	3.5
530	92.8	46.1	53.5	60.2	73.8	3.4
540	91.5	37.7	43.9	49.4	60.7	3.4
550	90.1	30.8	35.9	40.6	49.9	3.3
560	88.7	25.2	29.4	33.3	41.1	3.3
566	87.8	22.4	26.1	29.6	36.5	3.3

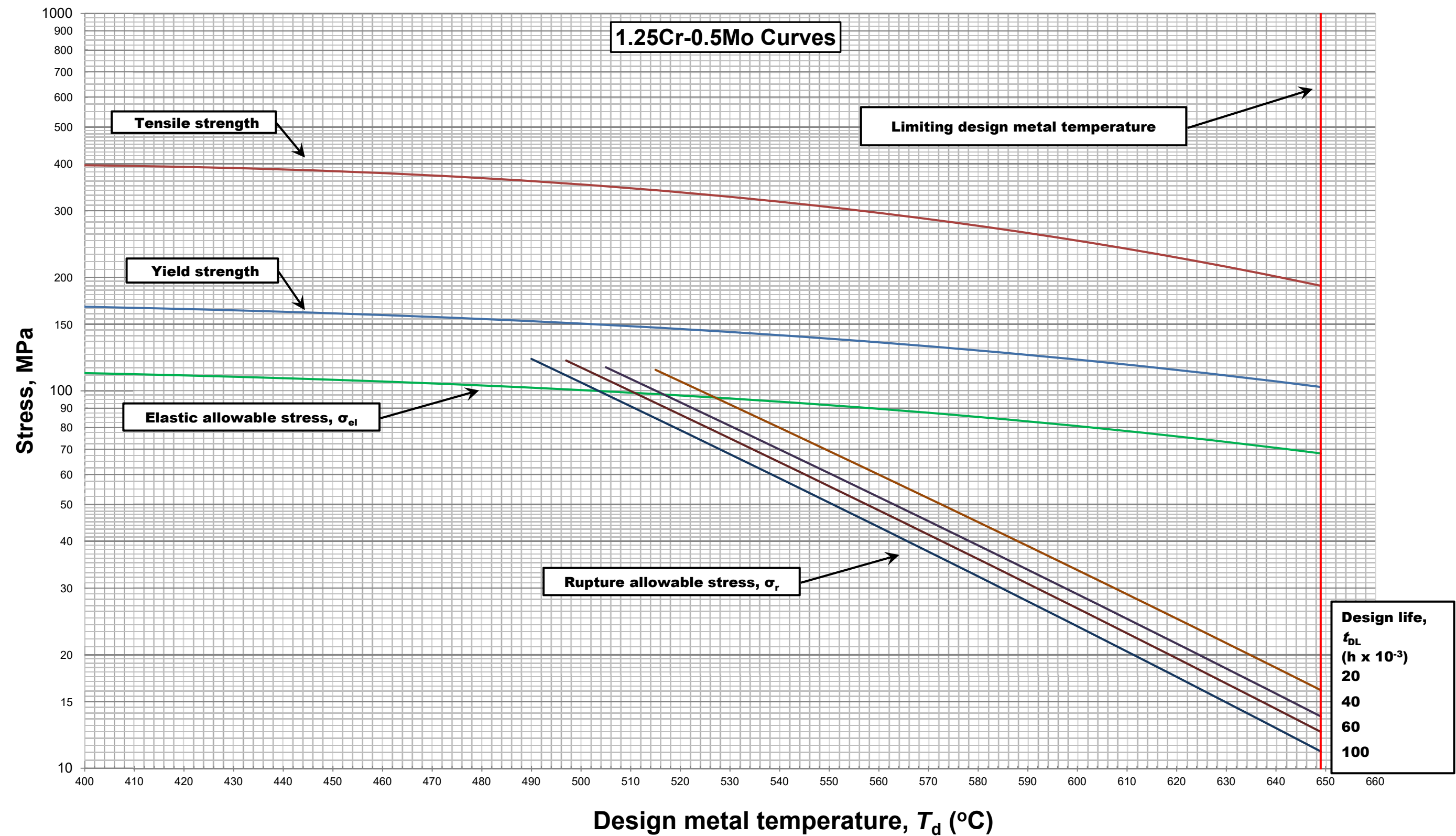


Figure E.10—Stress Curves (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

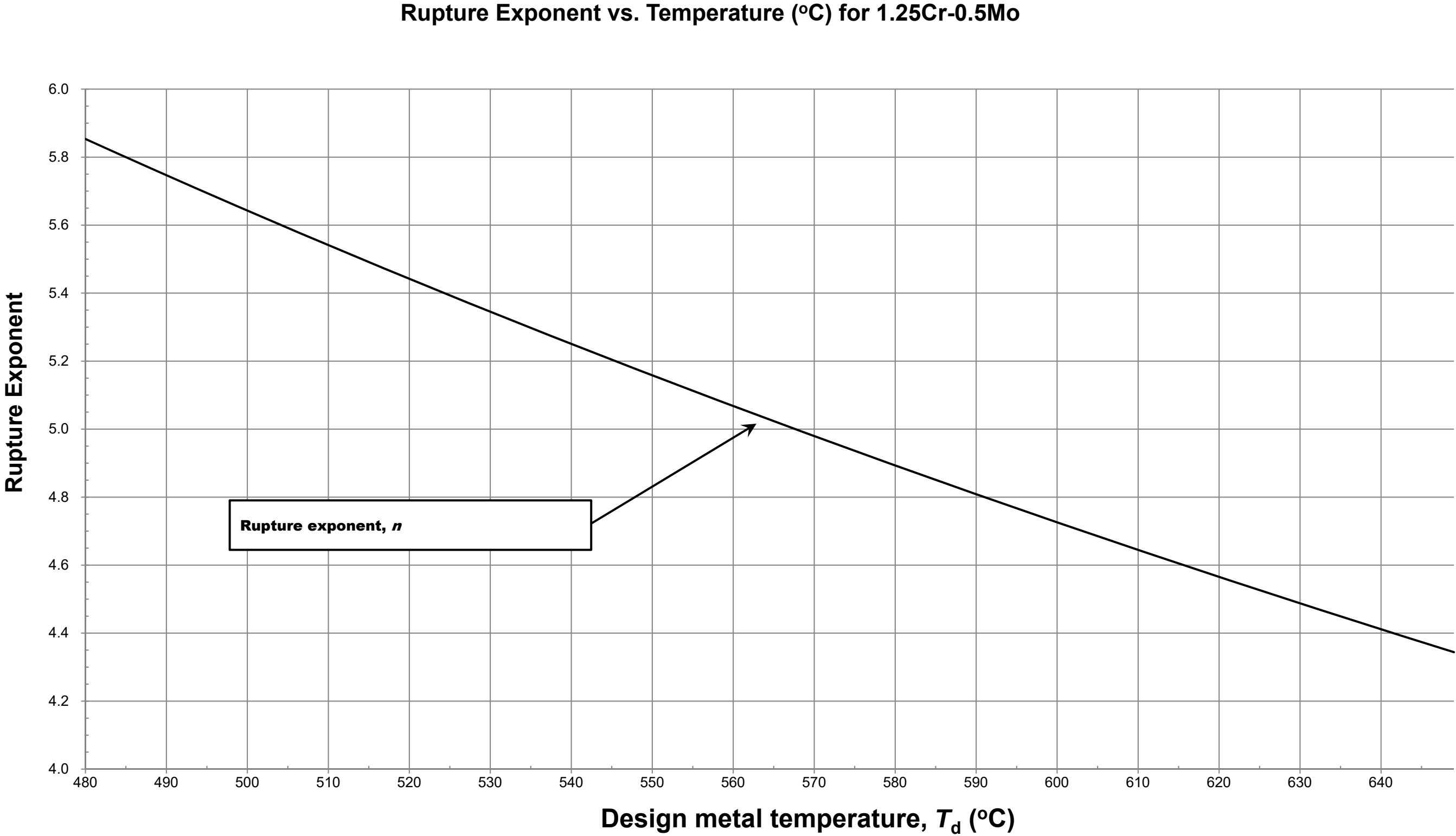


Figure E.11—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

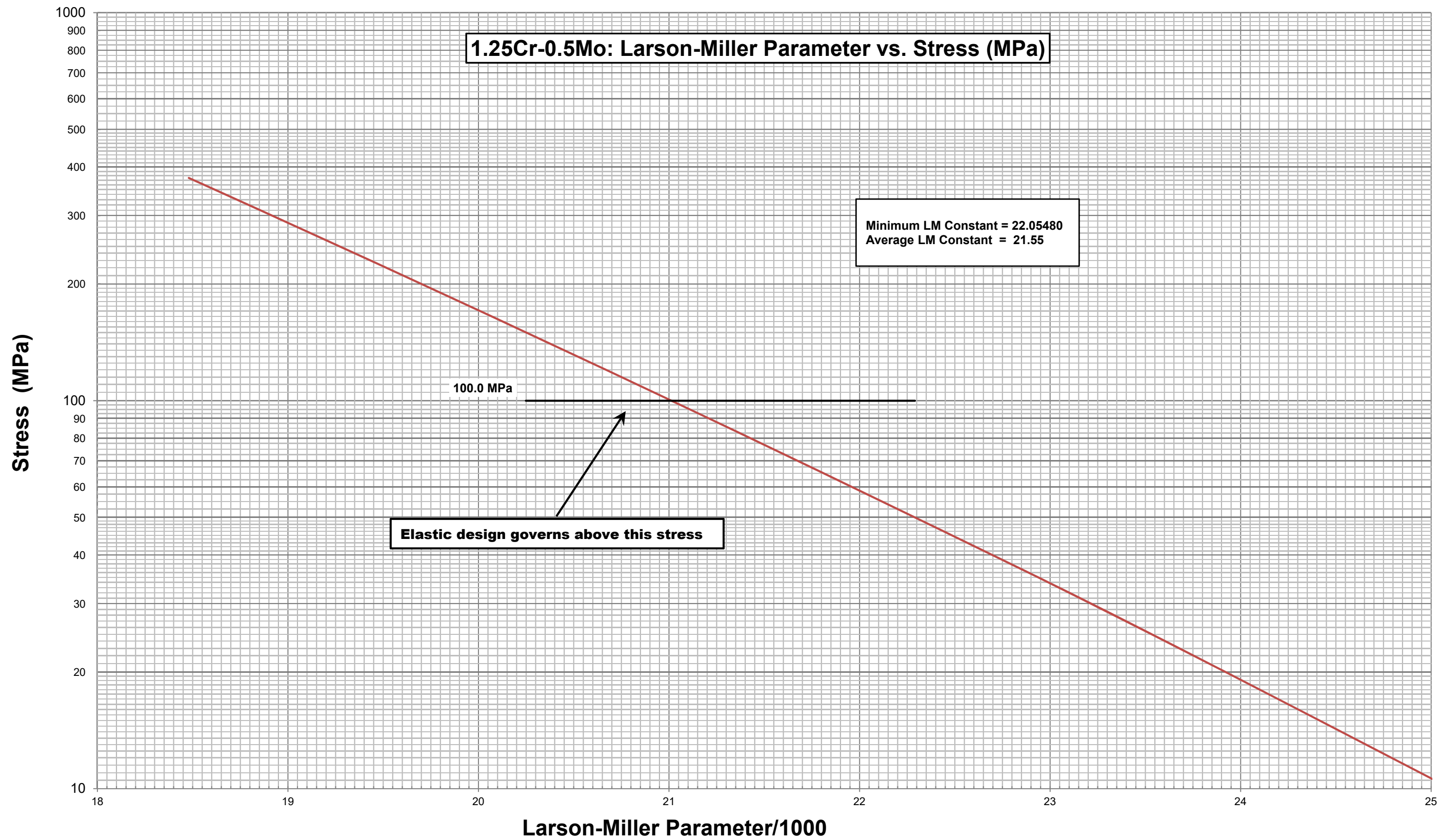


Figure E.12—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

Table E.4—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

1.25Cr-0.5Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	116.2					
310	115.8					
320	115.5					
330	115.1					
340	114.7					
350	114.3					
360	113.8					
370	113.3					
380	112.7					
390	112.1					
400	111.4					
410	110.7					
420	109.9					
430	109.0					
440	108.0					
450	107.0					
460	105.9					
470	104.7					
480	103.4	140.2	153.2	164.2	184.9	5.9
490	102.0	121.5	132.9	142.7	161.1	5.7
500	100.5	105.2	115.3	123.9	140.2	5.6
510	98.9	91.0	99.9	107.5	121.9	5.5
520	97.3	78.7	86.5	93.2	106.0	5.4
530	95.5	68.0	74.8	80.8	92.0	5.3
540	93.6	58.6	64.7	69.9	79.8	5.3
550	91.7	50.6	55.9	60.5	69.2	5.2
560	89.6	43.6	48.2	52.3	60.0	5.1
570	87.5	37.5	41.6	45.1	51.9	5.0
580	85.3	32.2	35.8	39.0	44.9	4.9
590	83.0	27.7	30.8	33.6	38.8	4.8
600	80.7	23.8	26.5	28.9	33.5	4.7
610	78.2	20.4	22.8	24.9	28.9	4.6
620	75.8	17.5	19.6	21.4	24.9	4.6
630	73.2	14.9	16.8	18.4	21.5	4.5
640	70.6	12.8	14.4	15.8	18.5	4.4
649	68.3	11.1	12.5	13.7	16.1	4.3

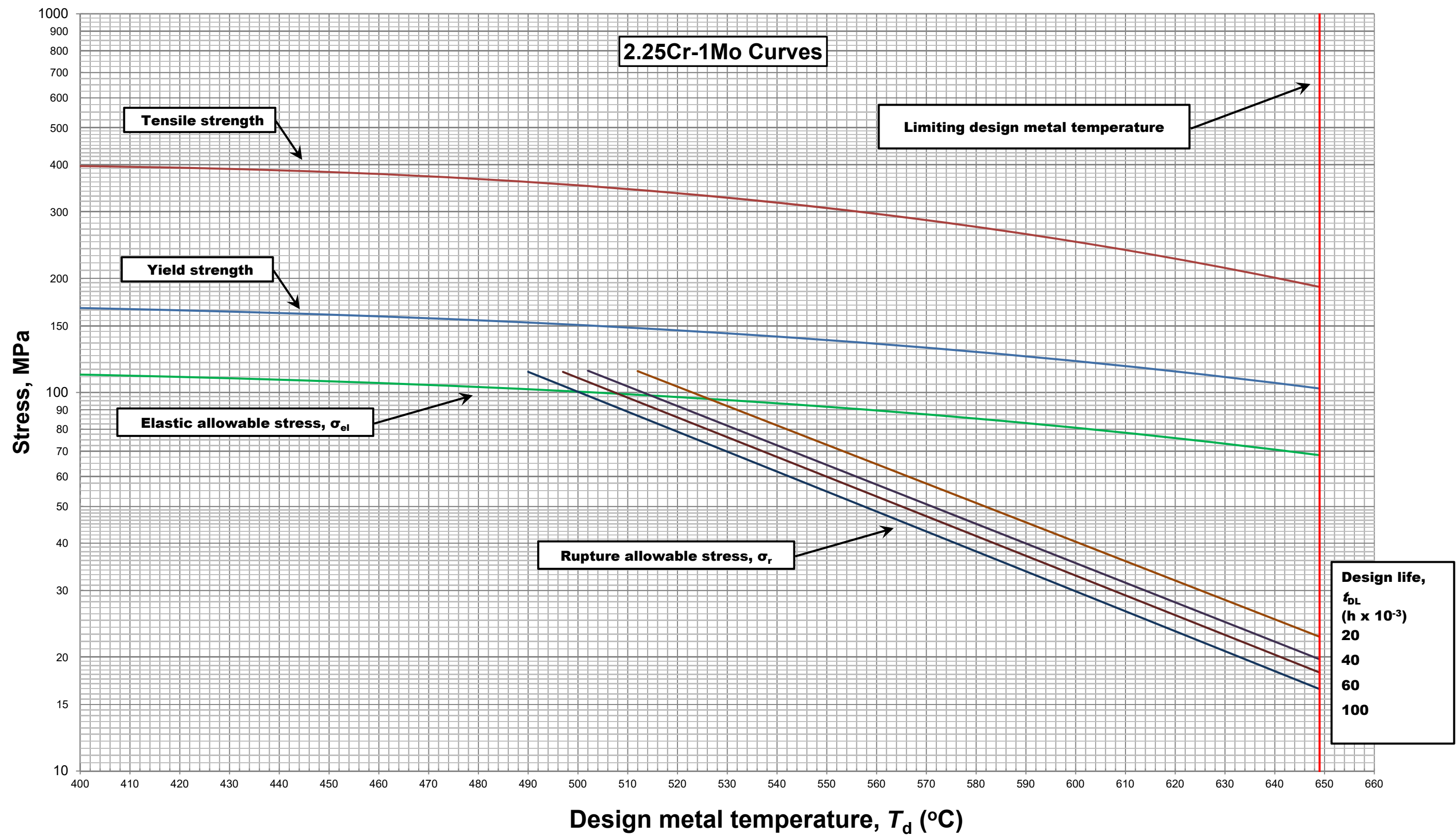


Figure E.13—Stress Curves (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

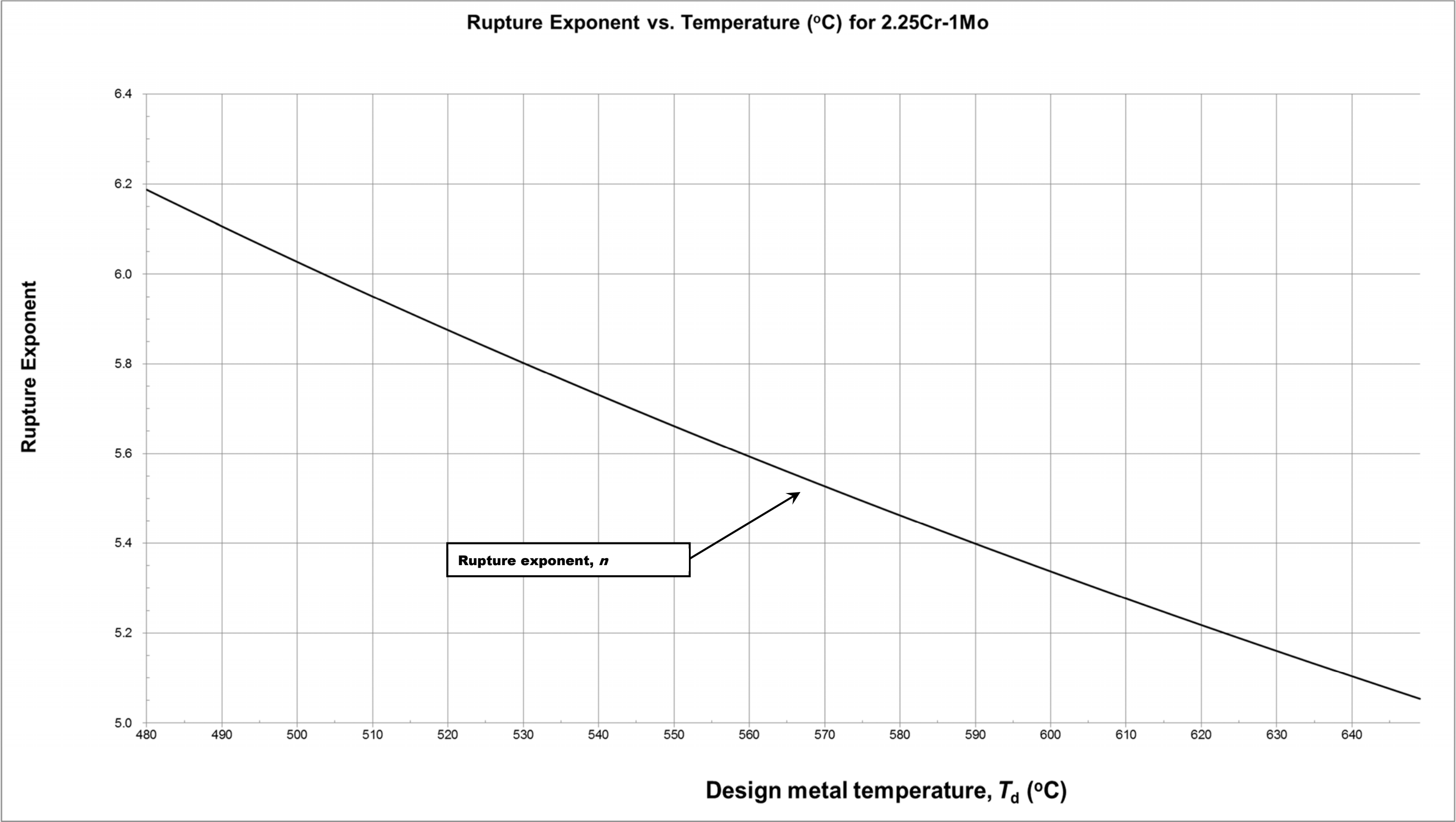


Figure E.14—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

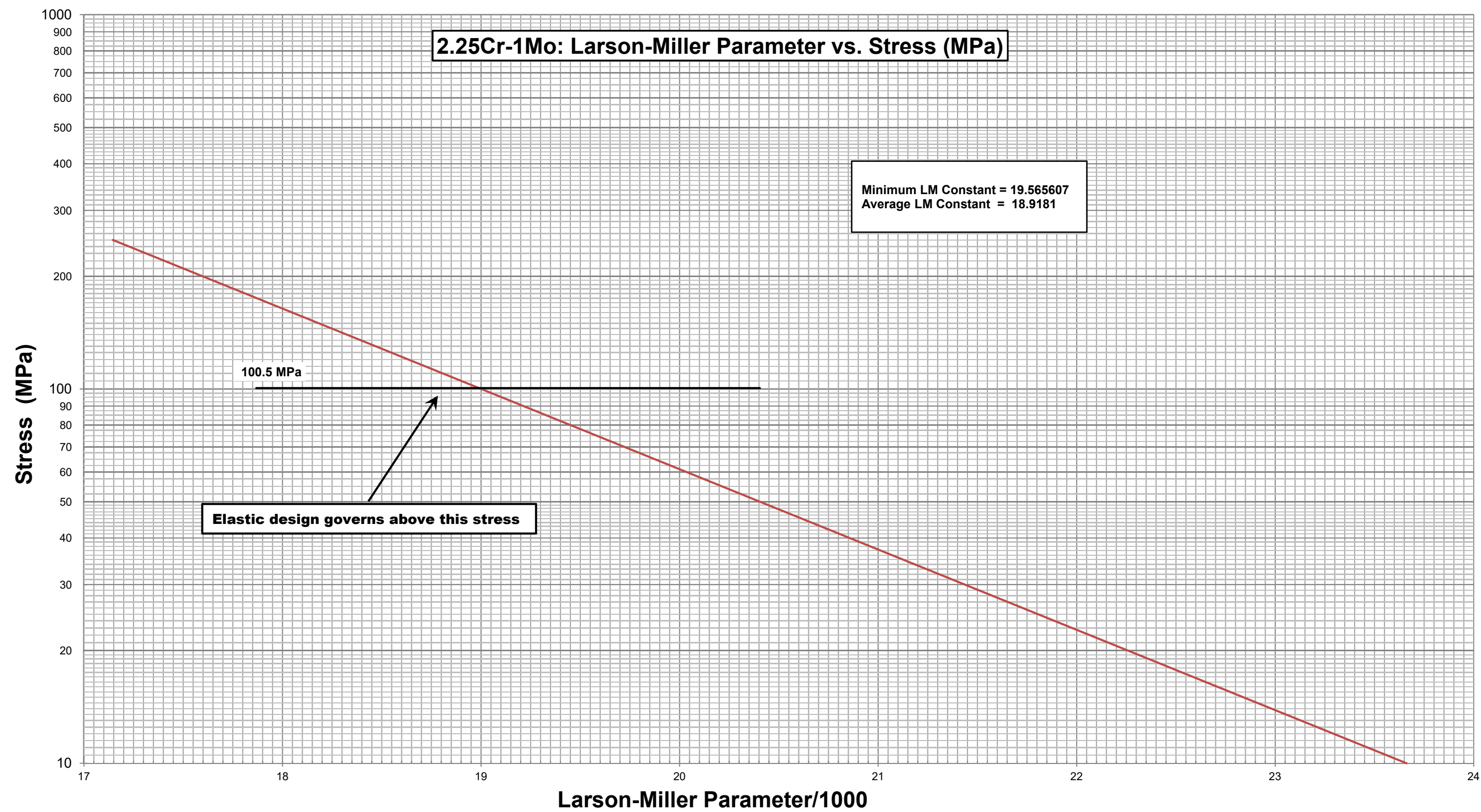


Figure E.15—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

Table E.5—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

2.25Cr-0.5Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	116.2					
310	115.8					
320	115.5					
330	115.1					
340	114.7					
350	114.3					
360	113.8					
370	113.3					
380	112.7					
390	112.1					
400	111.4					
410	110.7					
420	109.9					
430	109.0					
440	108.0					
450	107.0					
460	105.9					
470	104.7					
480	103.4	128.0	139.0	148.4	166.0	6.2
490	102.0	113.3	123.2	131.7	147.5	6.1
500	100.5	100.4	109.3	116.9	131.1	6.0
510	98.9	88.9	96.9	103.7	116.5	6.0
520	97.3	78.8	85.9	92.0	103.6	5.9
530	95.5	69.8	76.2	81.7	92.1	5.8
540	93.6	61.8	67.5	72.5	81.8	5.7
550	91.7	54.7	59.9	64.3	72.7	5.7
560	89.6	48.5	53.1	57.1	64.6	5.6
570	87.5	45.1	49.4	53.2	60.2	5.6
580	85.3	38.0	41.8	45.0	51.1	5.5
590	83.0	33.7	37.0	39.9	45.4	5.4
600	80.7	29.8	32.8	35.4	40.3	5.3
610	78.2	26.4	29.1	31.4	35.8	5.3
620	75.8	23.4	25.8	27.9	31.9	5.2
630	73.2	20.7	22.9	24.8	28.3	5.2
640	70.6	18.4	20.3	22.0	25.2	5.1
649	68.3	16.5	18.2	19.7	22.6	5.1

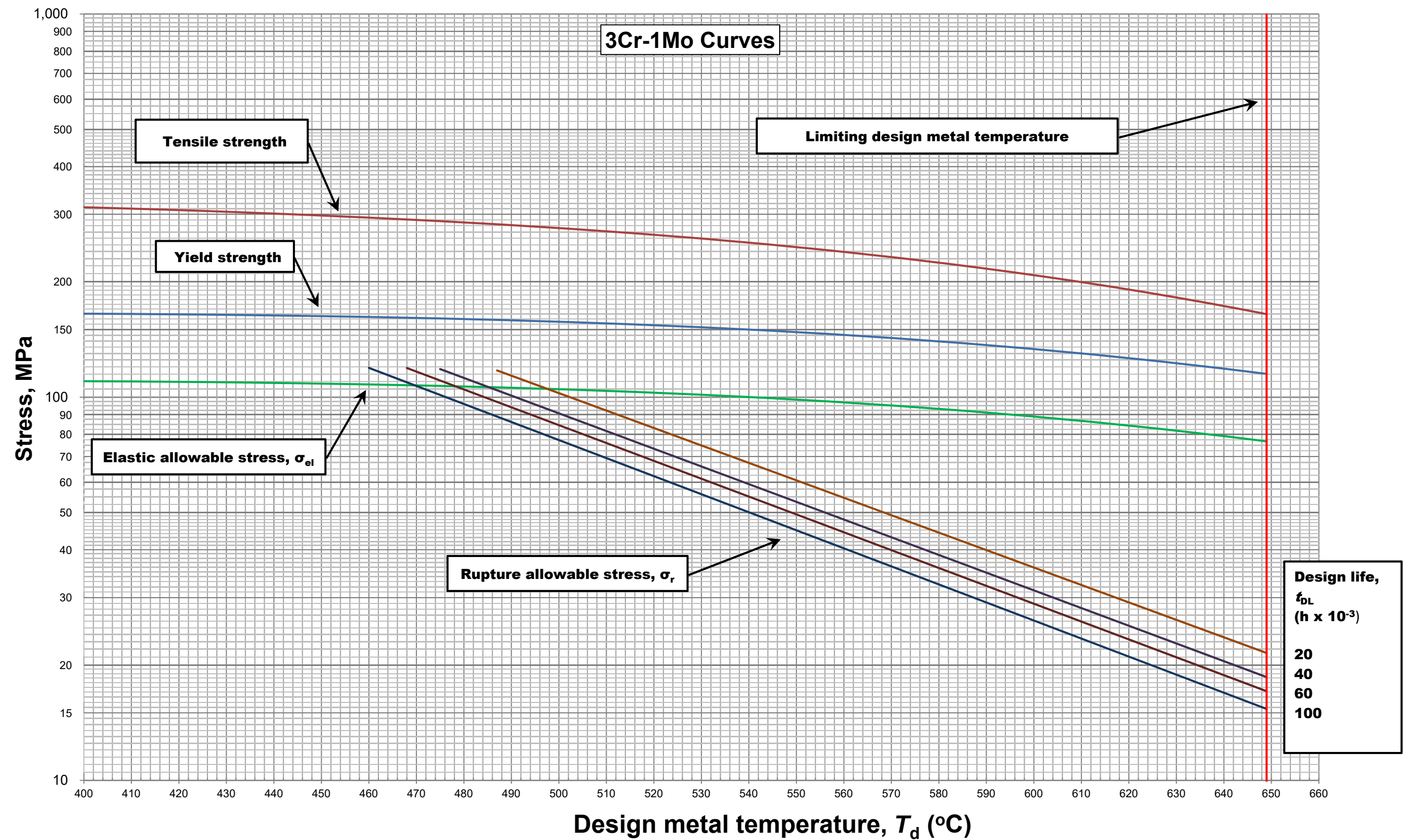


Figure E.16—Stress Curves (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

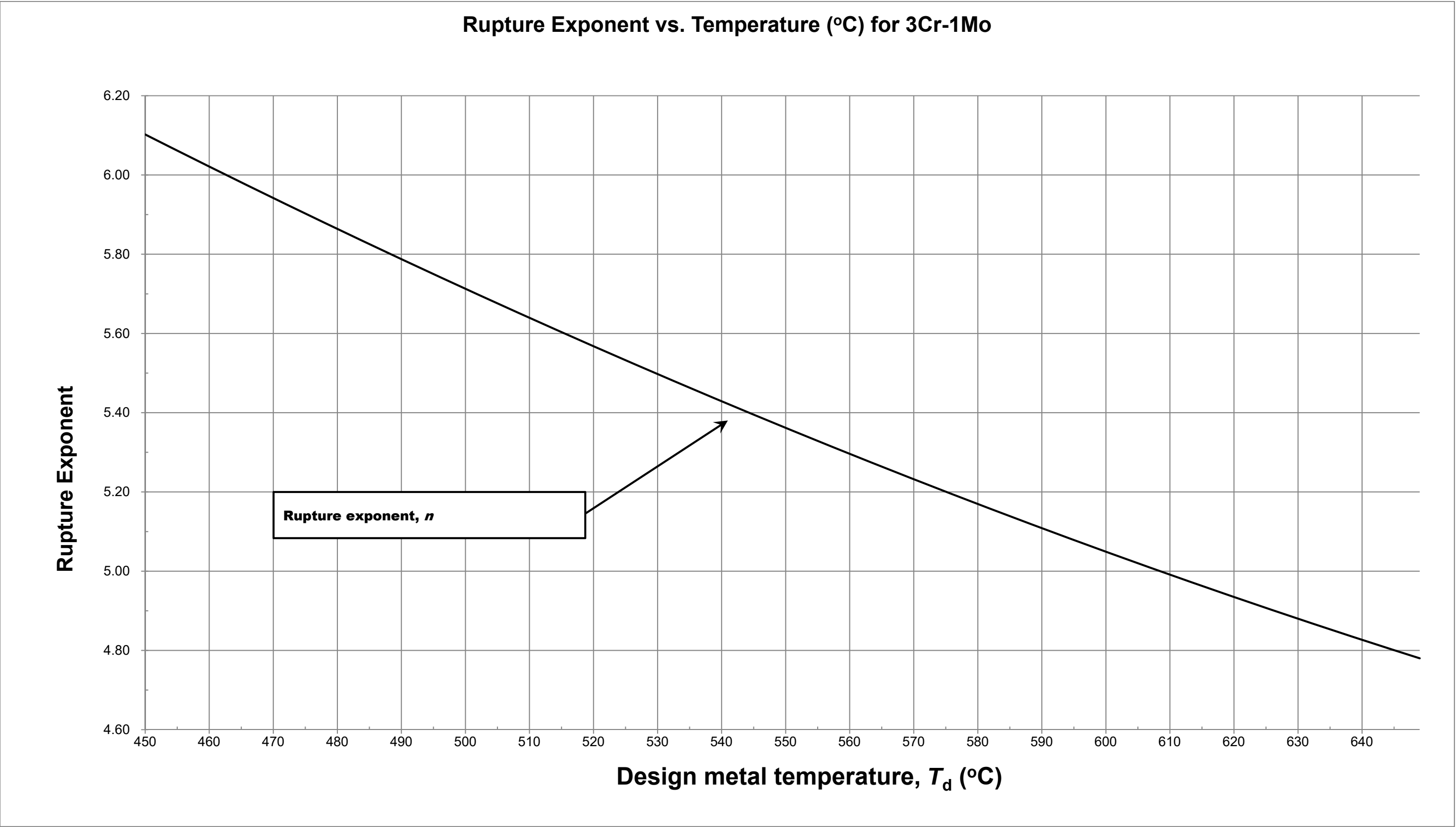


Figure E.17—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

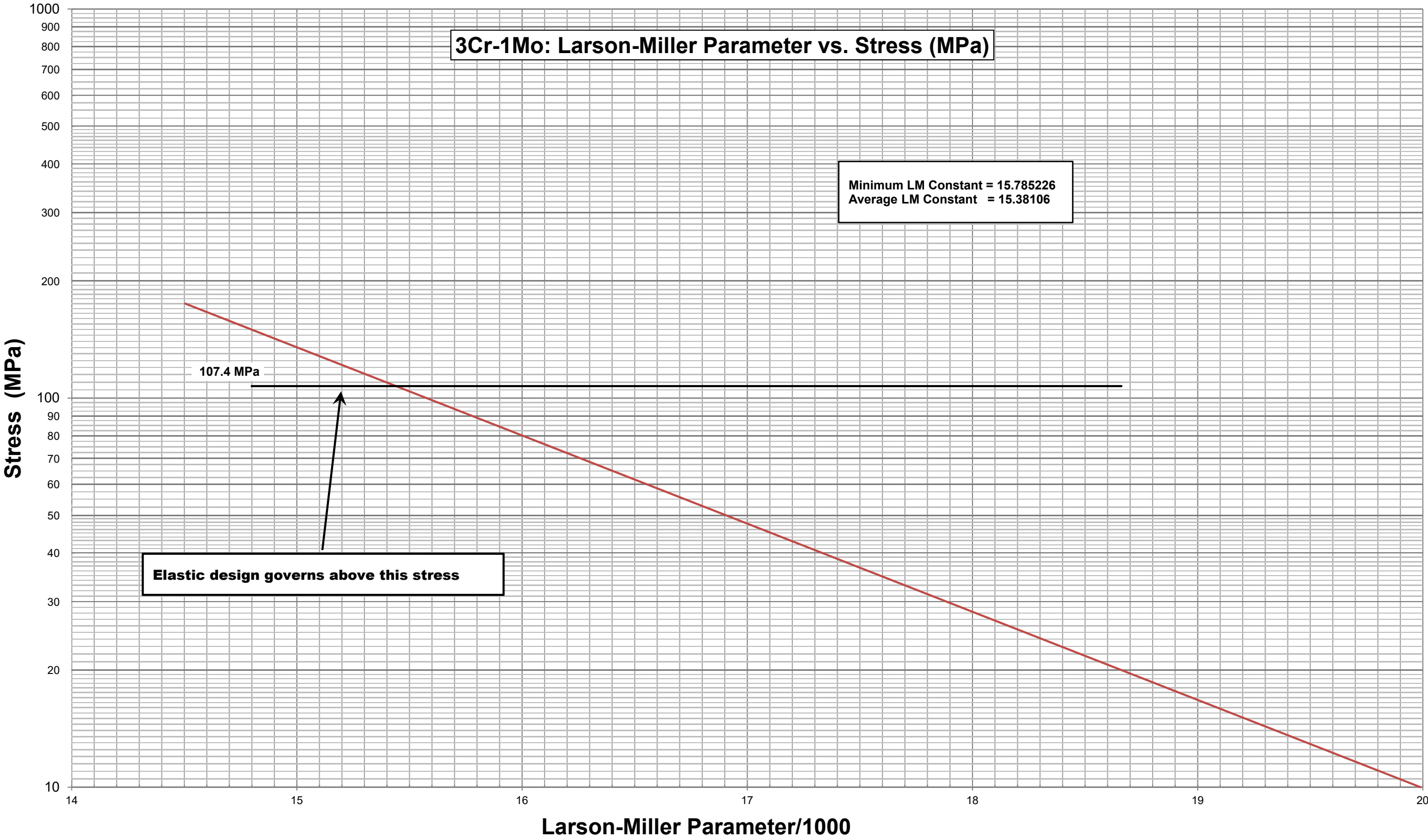


Figure E.18—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Table E.6—Elastic and Rupture Allowable Stresses (SI Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

3Cr-1Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	110.5					
310	110.5					
320	110.5					
330	110.5					
340	110.5					
350	110.5					
360	110.5					
370	110.5					
380	110.4					
390	110.3					
400	110.1					
410	109.9					
420	109.7					
430	109.4					
440	109.0					
450	108.5	132.9	144.5	154.5	173.1	6.1
460	108.0	119.3	129.8	138.9	155.8	6.0
470	107.4	107.0	116.6	124.9	140.3	5.9
480	106.7	96.0	104.8	112.3	126.4	5.9
490	105.8	86.2	94.1	100.9	113.8	5.8
500	104.9	77.3	84.5	90.8	102.5	5.7
510	103.9	69.4	75.9	81.6	92.3	5.6
520	102.7	62.2	68.2	73.4	83.1	5.6
530	101.5	55.8	61.3	66.0	74.8	5.5
540	100.1	50.1	55.0	59.3	67.4	5.4
550	98.6	44.9	49.4	53.3	60.7	5.4
560	96.9	40.3	44.4	47.9	54.6	5.3
570	95.1	37.8	41.6	45.0	51.3	5.3
580	93.2	32.5	35.8	38.8	44.3	5.2
590	91.2	29.1	32.2	34.8	39.9	5.1
600	89.0	26.1	28.9	31.3	35.9	5.0
610	86.7	23.4	26.0	28.2	32.4	5.0
620	84.3	21.0	23.3	25.3	29.1	4.9
630	81.8	18.9	21.0	22.8	26.2	4.9
640	79.2	16.9	18.8	20.5	23.6	4.8
649	76.7	15.4	17.1	18.6	21.5	4.8

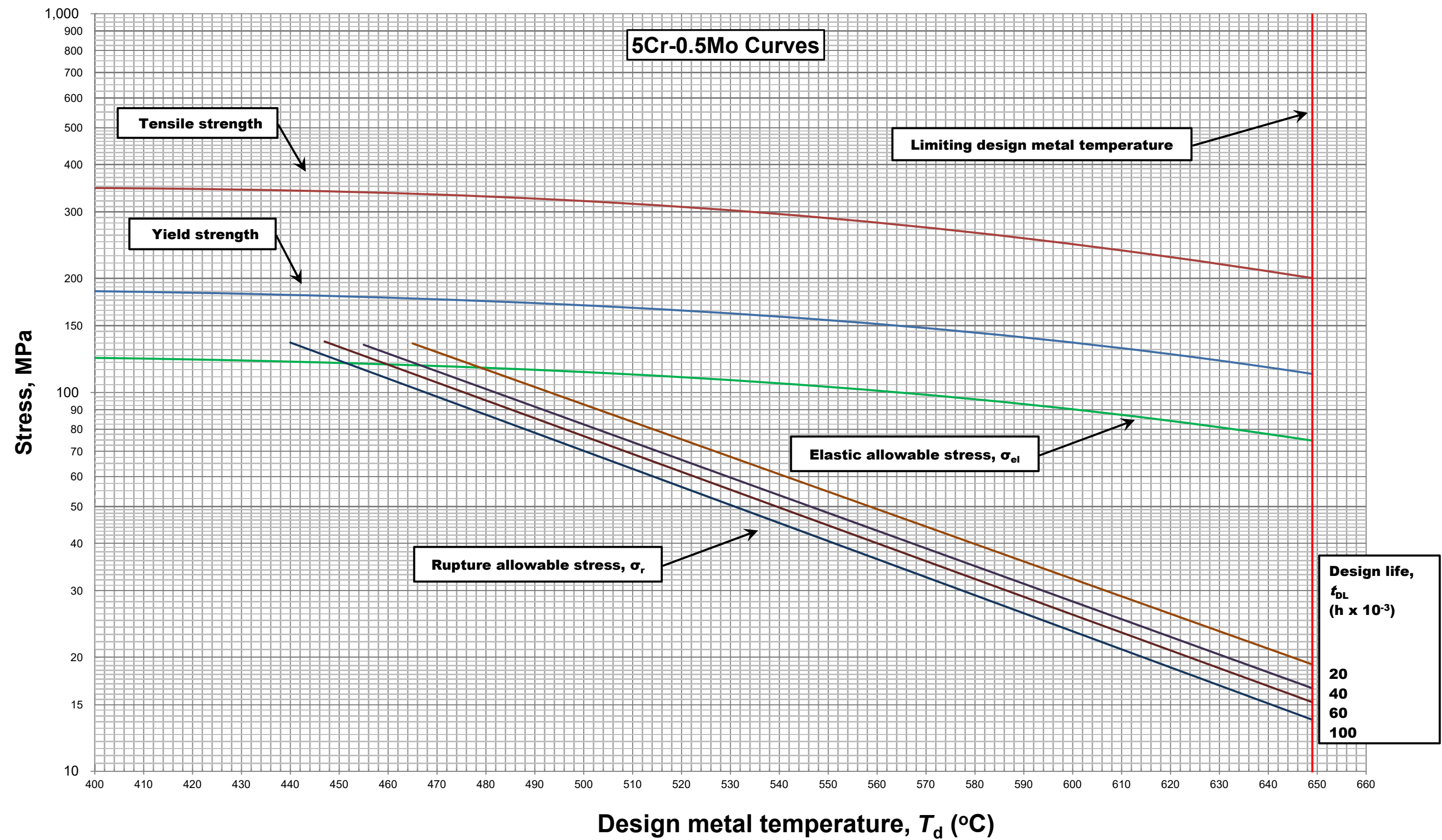


Figure E.19—Stress Curves (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

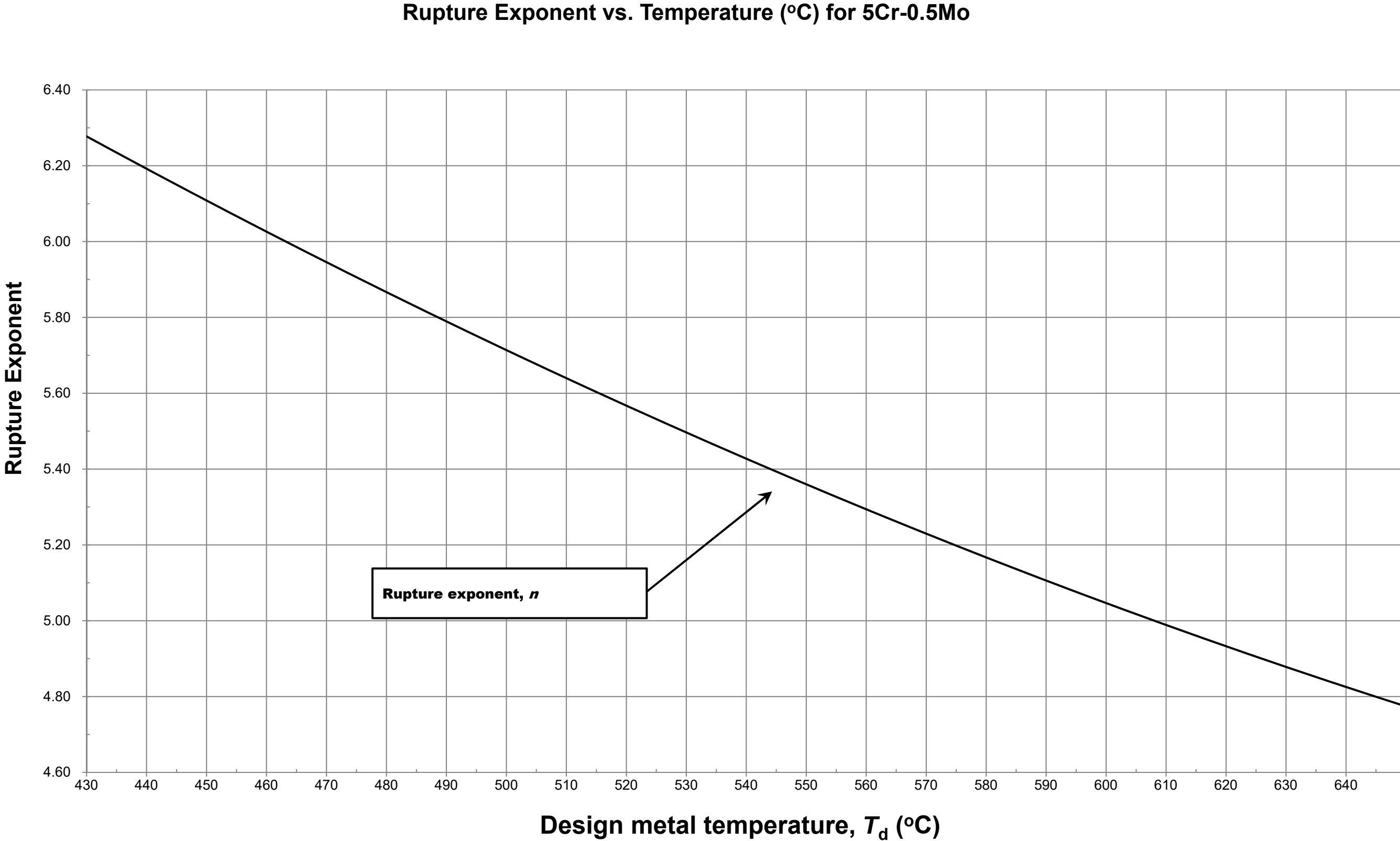


Figure E.20—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

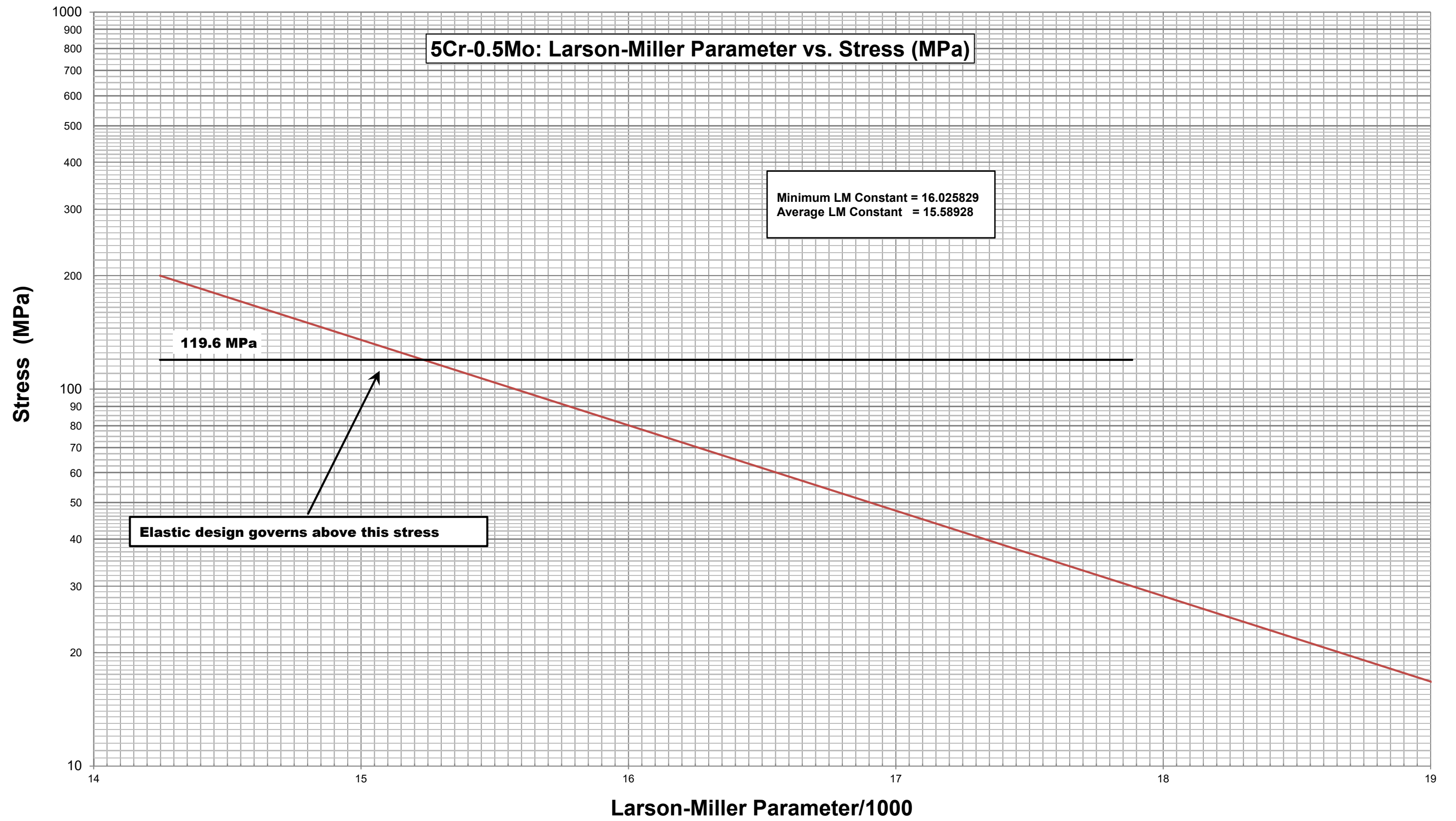


Figure E.21—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Table E.7—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

5Cr-0.5Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	126.2					
310	126.1					
320	126.0					
330	125.8					
340	125.6					
350	125.4					
360	125.1					
370	124.8					
380	124.4					
390	124.0					
400	123.5					
410	122.9					
420	122.3					
430	121.5	151.2	164.0	174.9	195.4	6.3
440	120.7	135.5	147.1	157.1	175.7	6.2
450	119.7	121.4	132.0	141.1	158.0	6.1
460	118.7	108.8	118.4	126.7	142.1	6.0
470	117.5	97.5	106.2	113.8	127.8	5.9
480	116.2	87.4	95.3	102.1	115.0	5.9
490	114.8	78.3	85.5	91.7	103.4	5.8
500	113.3	70.1	76.7	82.4	93.0	5.7
510	111.6	62.9	68.8	74.0	83.6	5.6
520	109.8	56.3	61.7	66.4	75.2	5.6
530	107.8	50.5	55.4	59.6	67.7	5.5
540	105.7	45.2	49.7	53.6	60.8	5.4
550	103.5	40.5	44.6	48.1	54.7	5.4
560	101.1	36.3	40.0	43.2	49.2	5.3
570	98.6	32.5	35.9	38.8	44.3	5.2
580	96.0	29.2	32.2	34.8	39.8	5.2
590	93.2	26.1	28.9	31.3	35.8	5.1
600	90.3	23.4	25.9	28.1	32.2	5.0
610	87.3	21.0	23.2	25.2	29.0	5.0
620	84.2	18.8	20.9	22.6	26.0	4.9
630	81.0	16.9	18.7	20.3	23.4	4.9
640	77.7	15.1	16.8	18.3	21.1	4.8
649	74.6	13.7	15.2	16.6	19.2	4.8

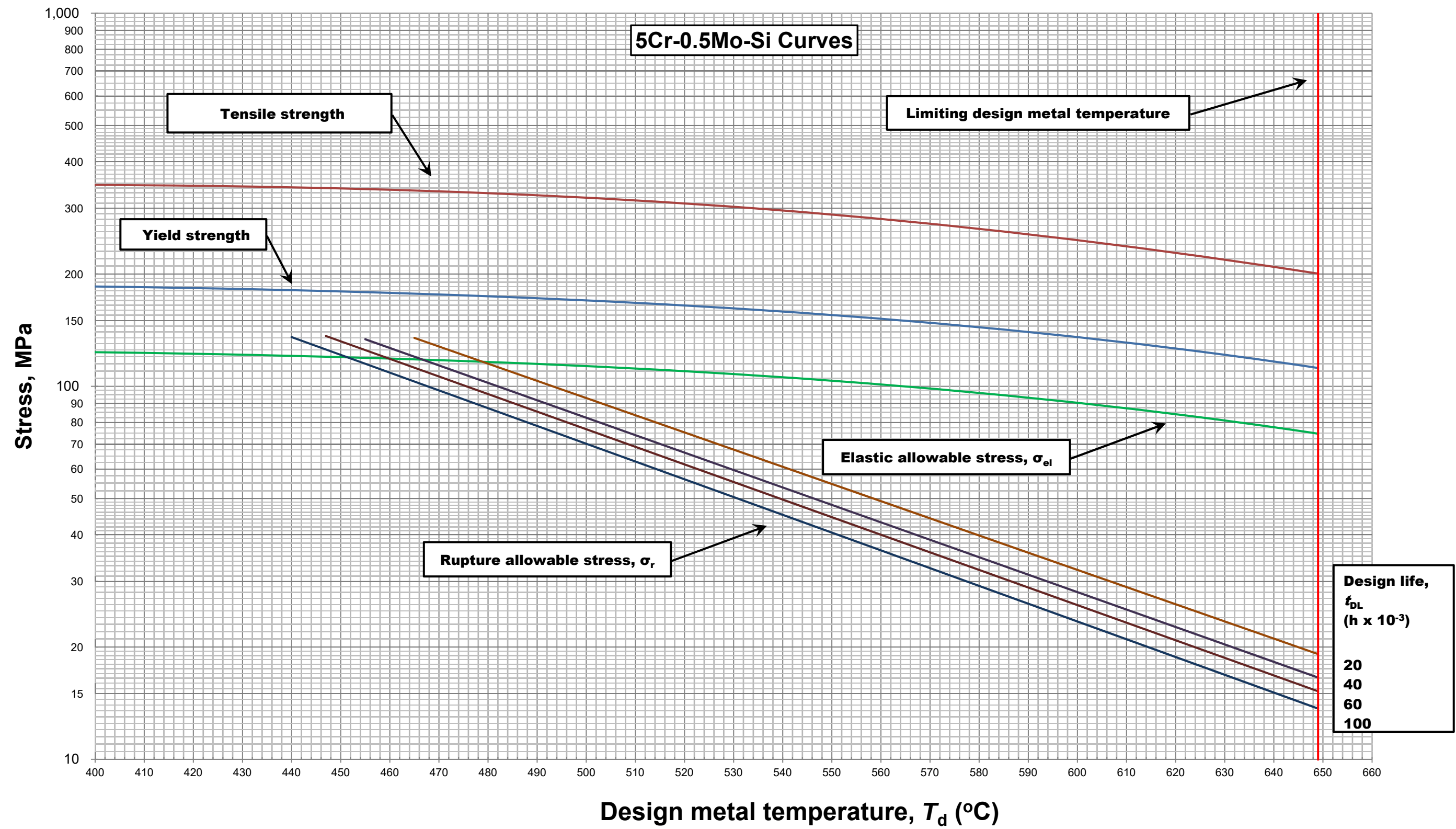


Figure E.22—Stress Curves (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

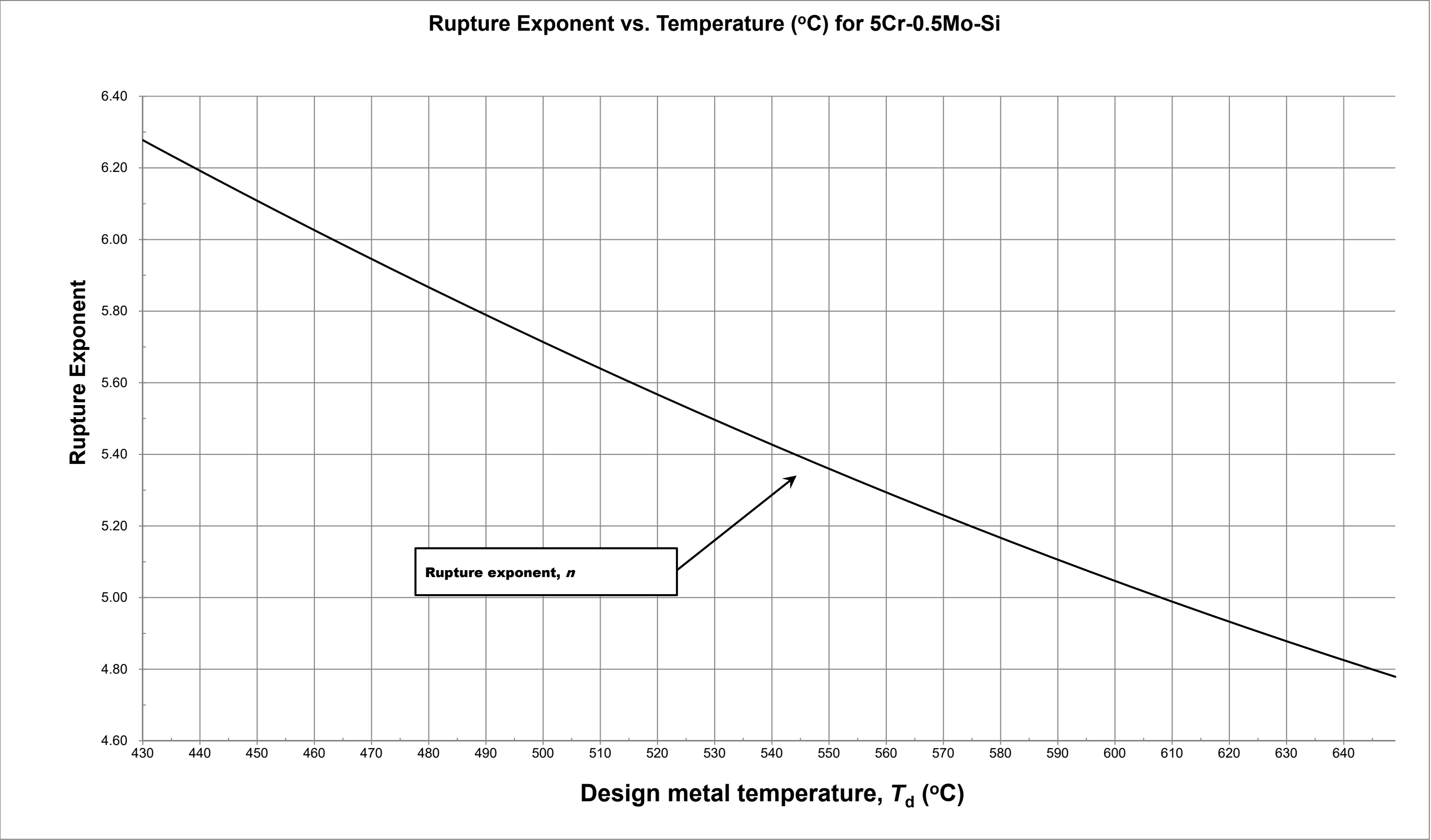


Figure E.23—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

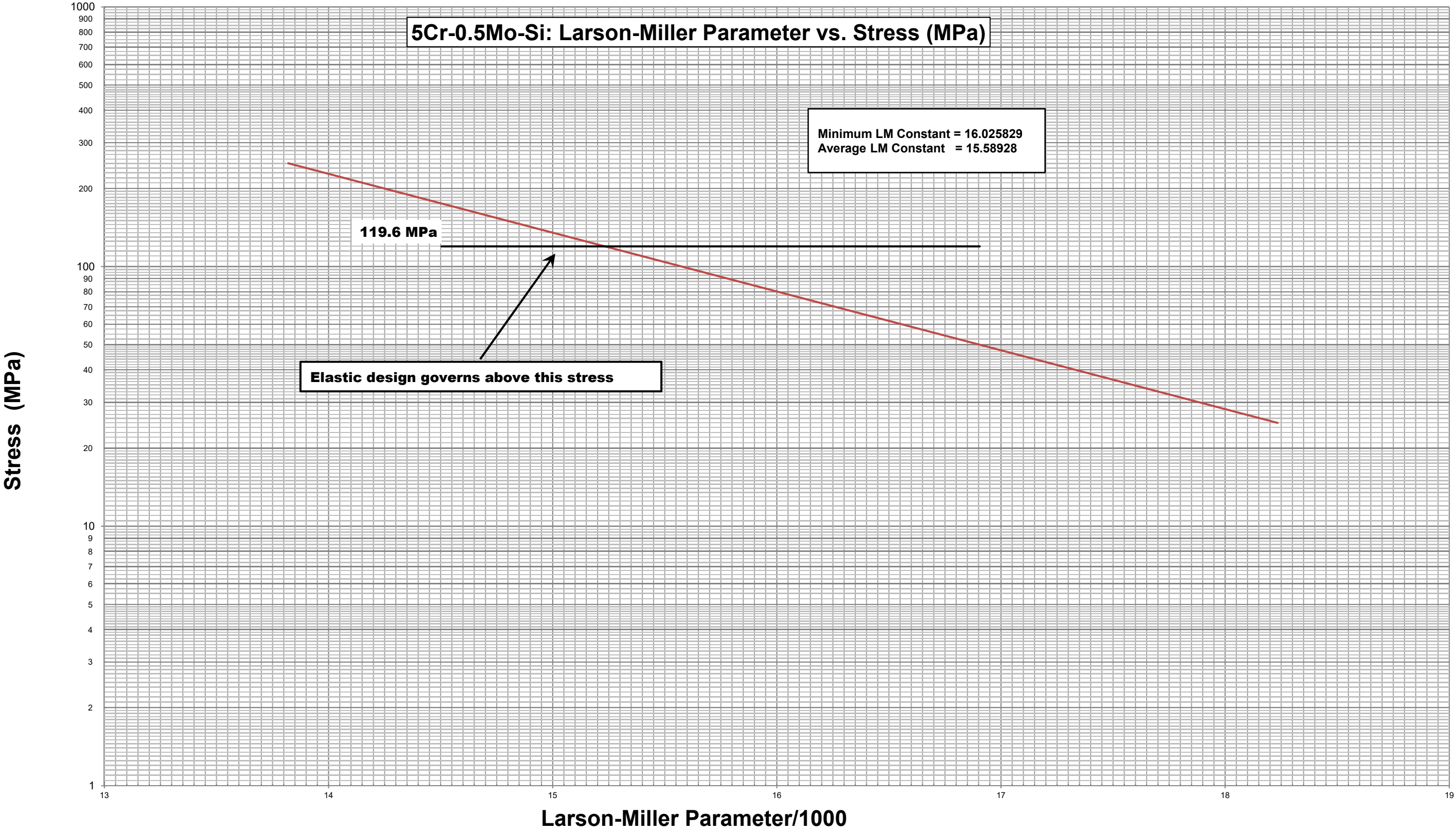


Figure E.24—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Table E.8—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

5Cr-0.5Mo-Si Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	126.2					
310	126.1					
320	126.0					
330	125.8					
340	125.6					
350	125.4					
360	125.1					
370	124.8					
380	124.4					
390	124.0					
400	123.5					
410	122.9					
420	122.3					
430	121.5	151.2	164.0	174.9	195.4	6.3
440	120.7	135.5	147.1	157.1	175.7	6.2
450	119.7	121.4	132.0	141.1	158.0	6.1
460	118.7	108.8	118.4	126.7	142.1	6.0
470	117.5	97.5	106.2	113.8	127.8	5.9
480	116.2	87.4	95.3	102.1	115.0	5.9
490	114.8	78.3	85.5	91.7	103.4	5.8
500	113.3	70.1	76.7	82.4	93.0	5.7
510	111.6	62.9	68.8	74.0	83.6	5.6
520	109.8	56.3	61.7	66.4	75.2	5.6
530	107.8	50.5	55.4	59.6	67.7	5.5
540	105.7	45.2	49.7	53.6	60.8	5.4
550	103.5	40.5	44.6	48.1	54.7	5.4
560	101.1	36.3	40.0	43.2	49.2	5.3
570	98.6	32.5	35.9	38.8	44.3	5.2
580	96.0	29.2	32.2	34.8	39.8	5.2
590	93.2	26.1	28.9	31.3	35.8	5.1
600	90.3	23.4	25.9	28.1	32.2	5.0
610	87.3	21.0	23.2	25.2	29.0	5.0
620	84.2	18.8	20.9	22.6	26.0	4.9
630	81.0	16.9	18.7	20.3	23.4	4.9
640	77.7	15.1	16.8	18.3	21.1	4.8
649	74.6	13.7	15.2	16.6	19.2	4.8

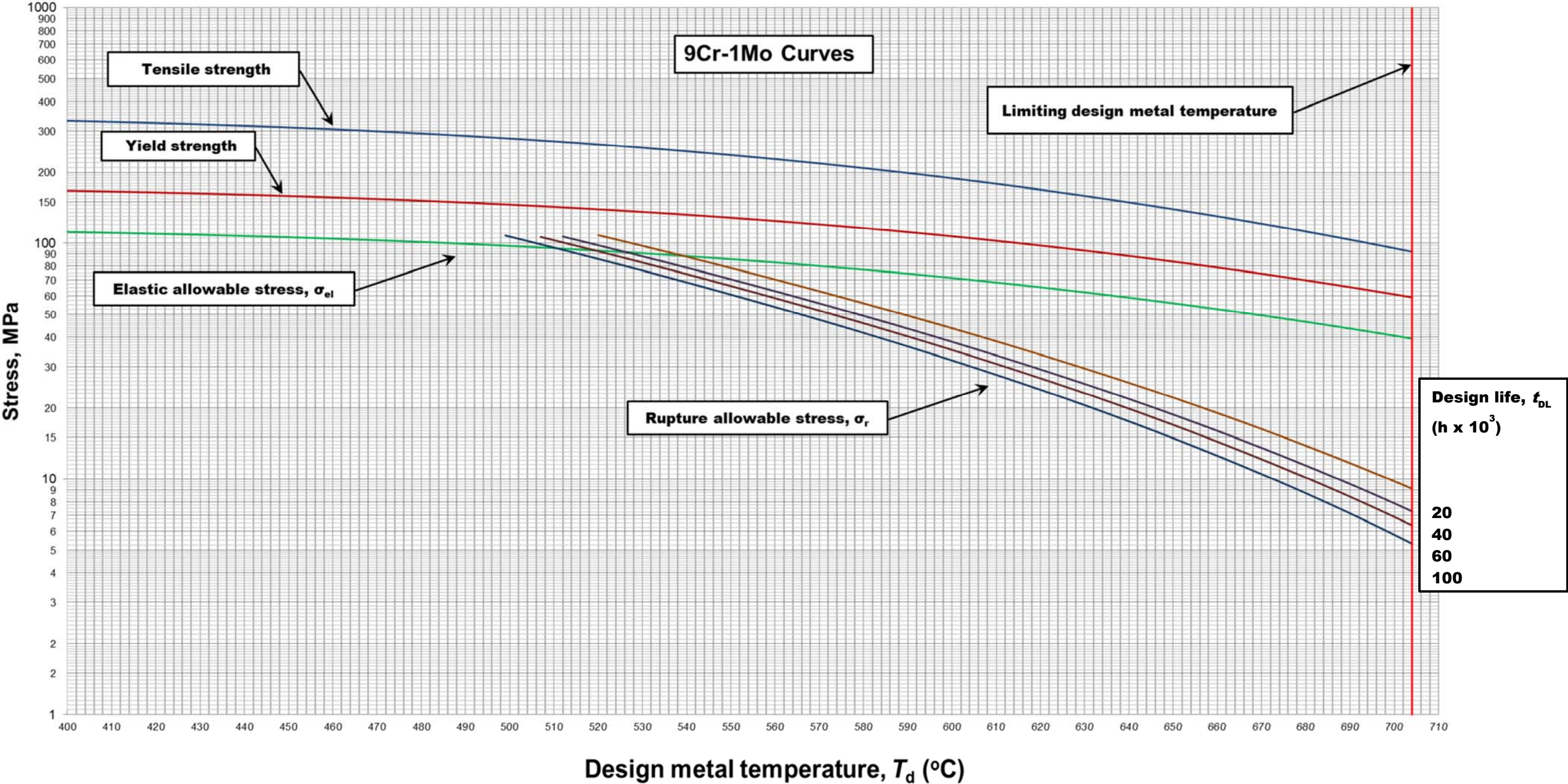


Figure E.25—Stress Curves (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

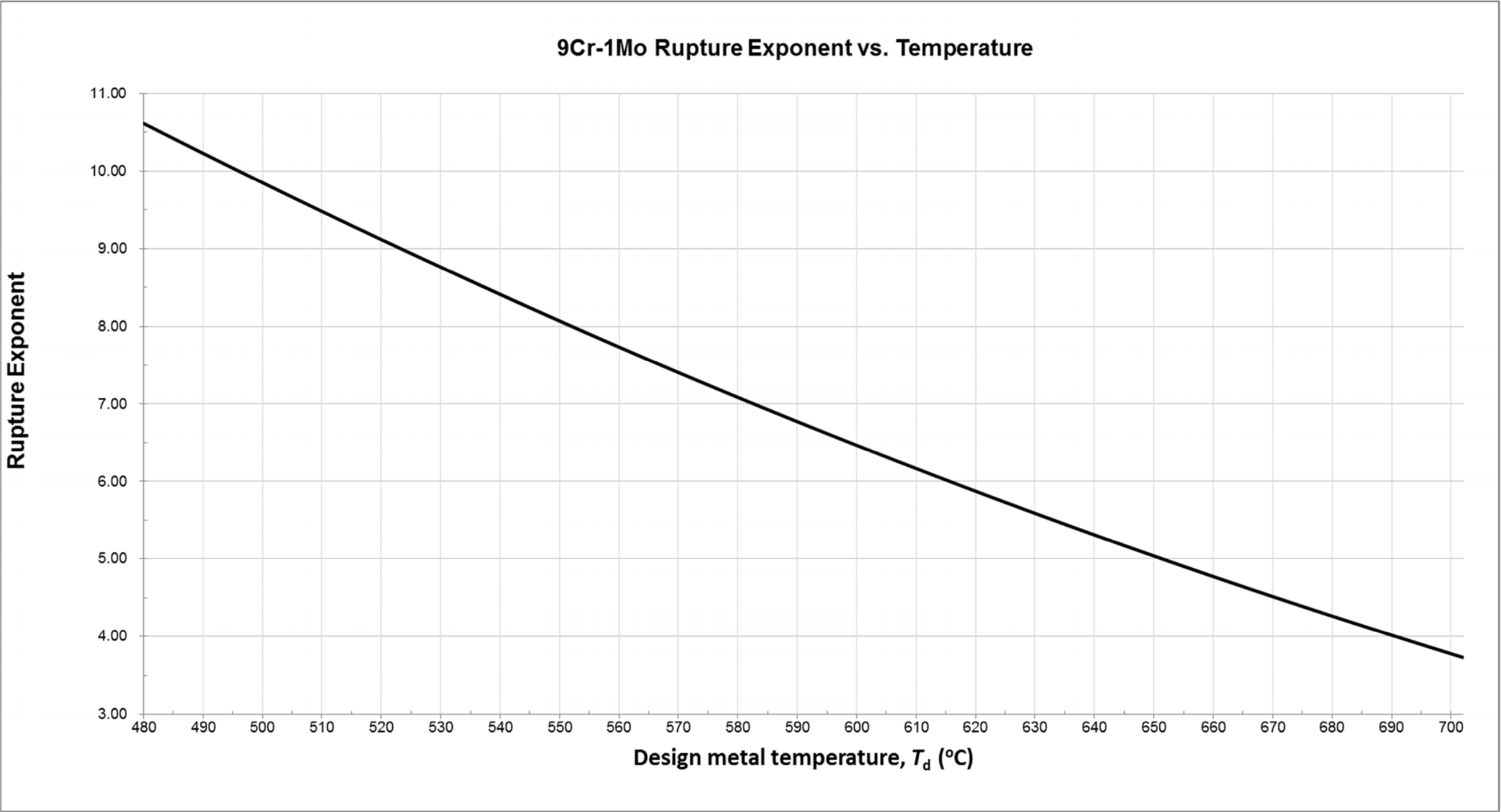


Figure E.26—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

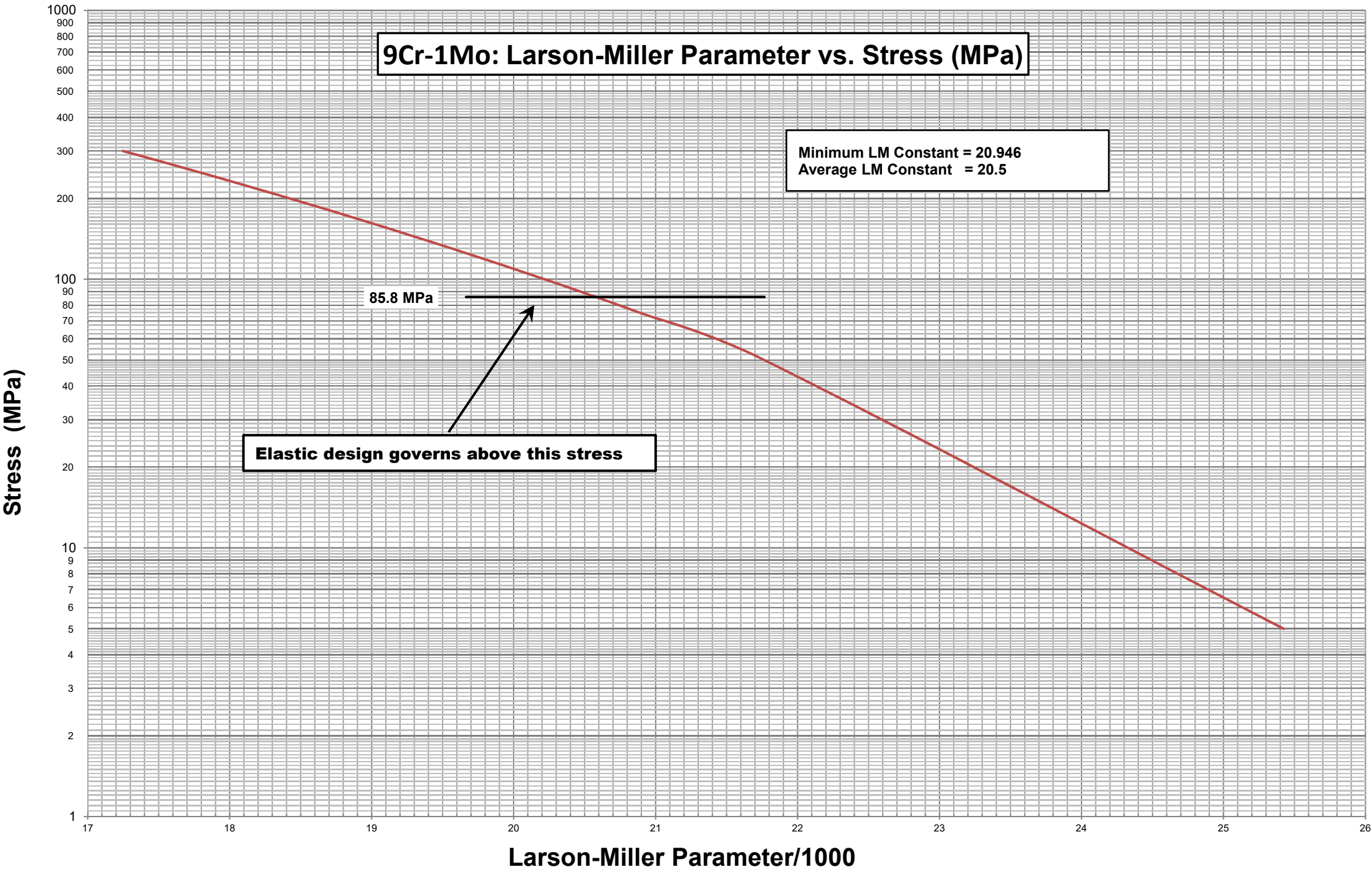


Figure E.27—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Table E.9—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

9Cr-1Mo Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
300	117.0					
310	116.7					
320	116.3					
330	115.9					
340	115.4					
350	115.0					
360	114.4					
370	113.8					
380	113.2					
390	112.4					
400	111.6					
410	110.7					
420	109.7					
430	108.5					
440	107.3					
450	106.0					
460	104.5					
470	102.9					
480	101.2					
490	99.3	118.4	126.7	133.5	145.9	10.3
500	97.4	106.6	114.3	120.7	132.3	9.9
510	95.3	95.7	102.9	108.9	119.8	9.6
520	93.0	85.8	92.4	98.0	108.2	9.2
530	90.7	76.6	82.8	88.0	97.5	8.8
540	88.2	68.3	74.0	78.8	87.6	8.5
550	85.6	60.7	66.0	70.4	78.6	8.1
560	82.9	53.7	58.6	62.7	70.3	7.8
570	80.2	47.4	51.9	55.7	62.7	7.5
580	77.3	41.7	45.8	49.3	55.7	7.1
590	74.3	36.5	40.3	43.5	49.4	6.8
600	71.3	31.9	35.3	38.2	43.6	6.5
610	68.3	27.7	30.8	33.4	38.4	6.2
620	65.2	23.9	26.7	29.2	33.7	5.9
630	62.0	20.5	23.1	25.3	29.4	5.6
640	58.9	17.5	19.8	21.8	25.6	5.4
650	55.7	14.9	17.0	18.7	22.1	5.1
660	52.6	12.6	14.4	16.0	19.0	4.8
670	49.5	10.5	12.1	13.6	16.3	4.6
680	46.5	8.7	10.1	11.4	13.8	4.3
690	43.5	7.1	8.4	9.5	11.7	4.1
700	40.6	5.8	6.9	7.9	9.8	3.8
704	39.4	5.3	6.4	7.3	9.1	3.7

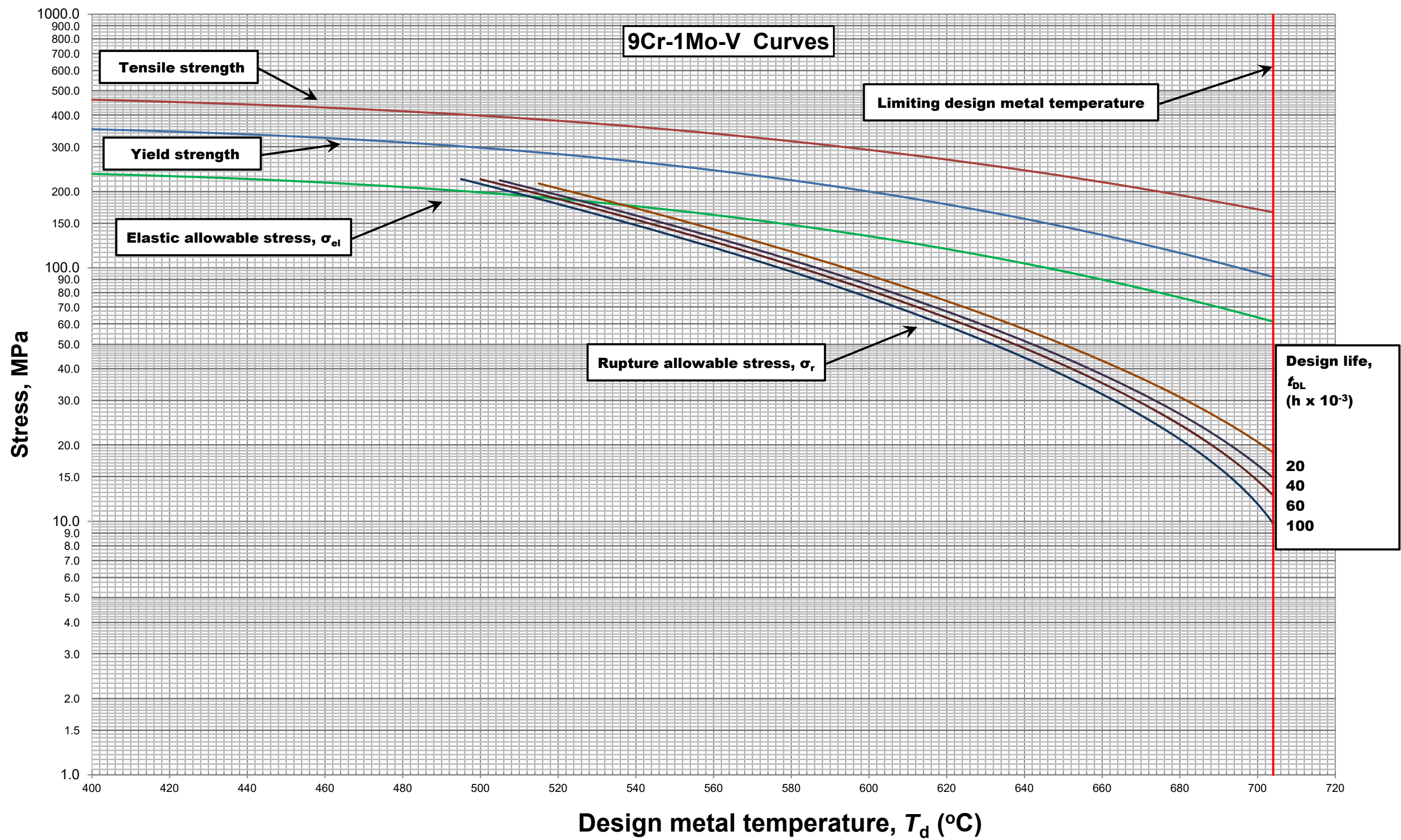


Figure E.28—Stress Curves (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

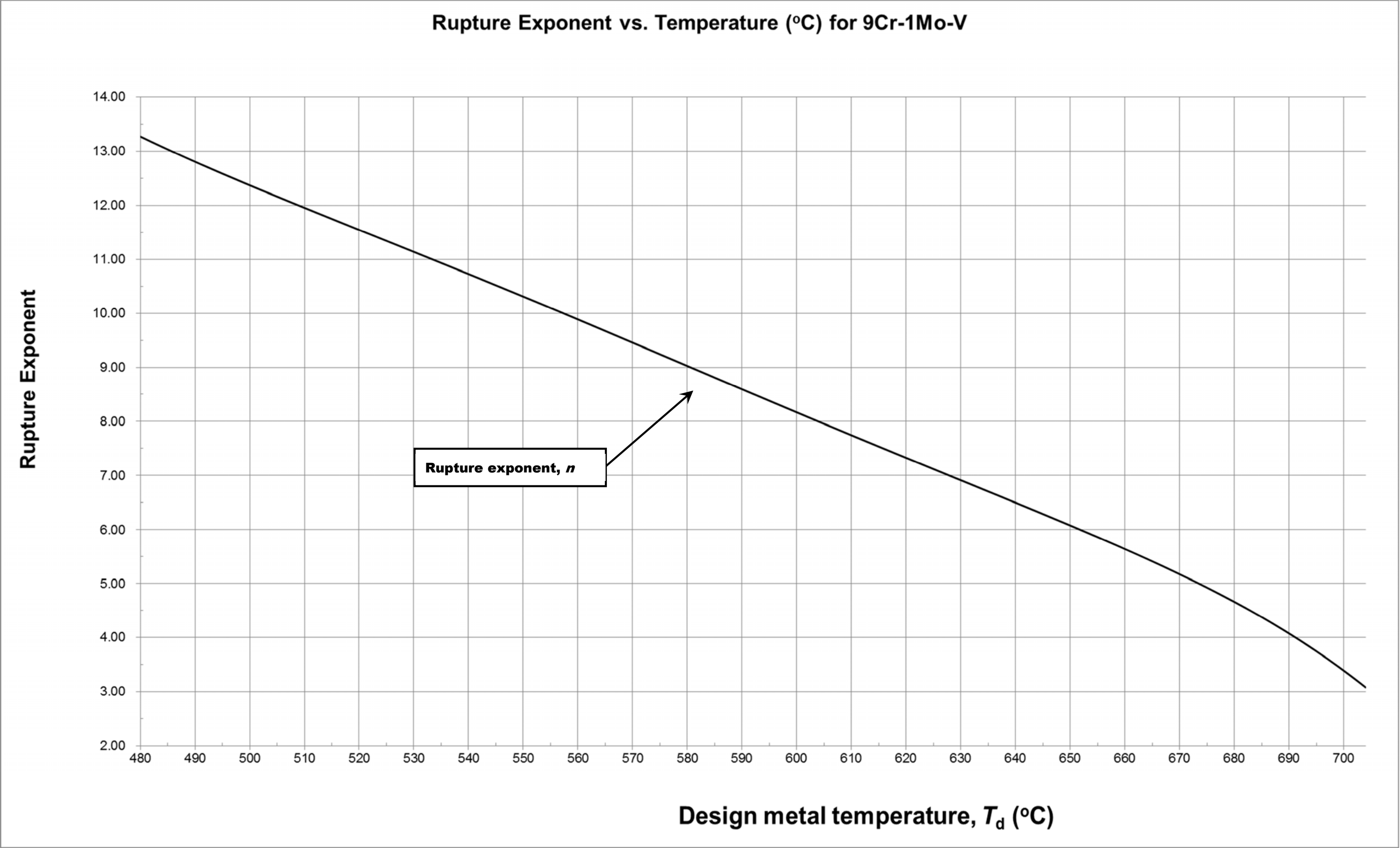


Figure E.29—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

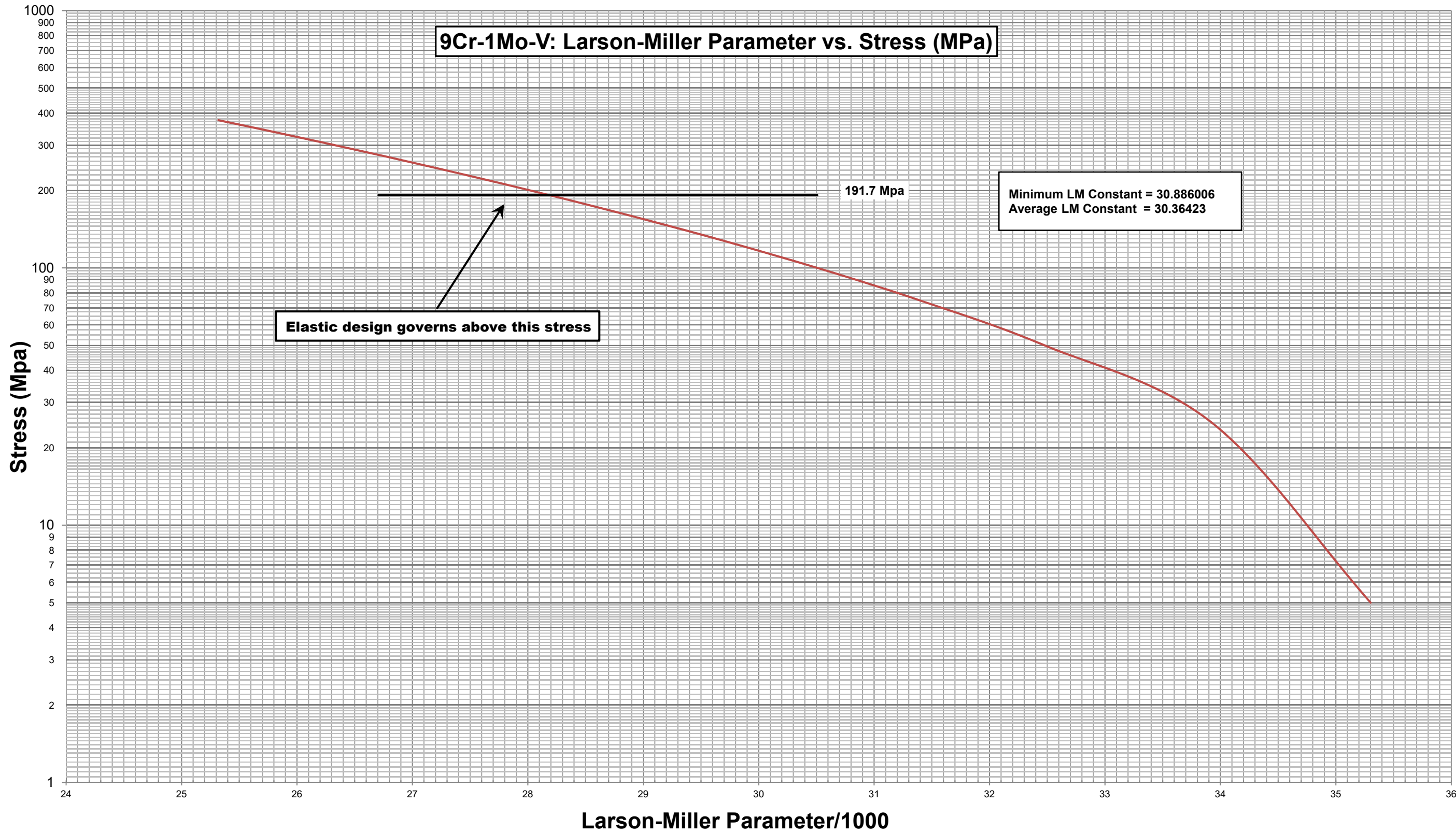


Figure E.30—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Table E.10—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

9Cr-1Mo-V Steel						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	234.8					
410	232.6					
420	230.1					
430	227.3					
440	224.2					
450	220.7					
460	216.9					
470	212.8					
480	208.3					
490	203.6	234.0	243.7	251.7	265.7	12.8
500	198.4	214.3	223.6	231.1	244.5	12.4
510	193.0	195.9	204.6	211.8	224.5	12.0
520	187.3	178.6	186.9	193.7	205.8	11.5
530	181.3	162.4	170.3	176.8	188.2	11.1
540	175.0	147.4	154.8	160.9	171.7	10.7
550	168.5	133.3	140.3	146.1	156.3	10.3
560	161.8	120.2	126.8	132.3	141.9	9.9
570	154.9	108.0	114.2	119.4	128.5	9.5
580	147.8	96.7	102.5	107.4	116.0	9.0
590	140.6	86.1	91.7	96.2	104.3	8.6
600	133.3	76.4	81.6	85.8	93.4	8.2
610	126.0	67.4	72.2	76.2	83.3	7.7
620	118.7	59.0	63.6	67.3	74.0	7.3
630	111.3	51.3	55.6	59.0	65.3	6.9
640	104.1	44.3	48.2	51.4	57.3	6.5
650	96.9	37.7	41.4	44.4	49.9	6.1
660	89.9	31.7	35.1	37.9	43.0	5.6
670	83.0	26.2	29.4	32.0	36.7	5.2
676	79.0	23.1	26.1	28.6	33.2	4.9
680	76.4	21.1	24.1	26.5	30.9	4.7
690	69.9	16.3	19.1	21.4	25.5	4.1
700	63.7	11.7	14.5	16.7	20.6	3.4
702	62.5	10.8	13.6	15.8	19.6	3.2
704	61.3	9.8	12.7	14.9	18.7	3.1

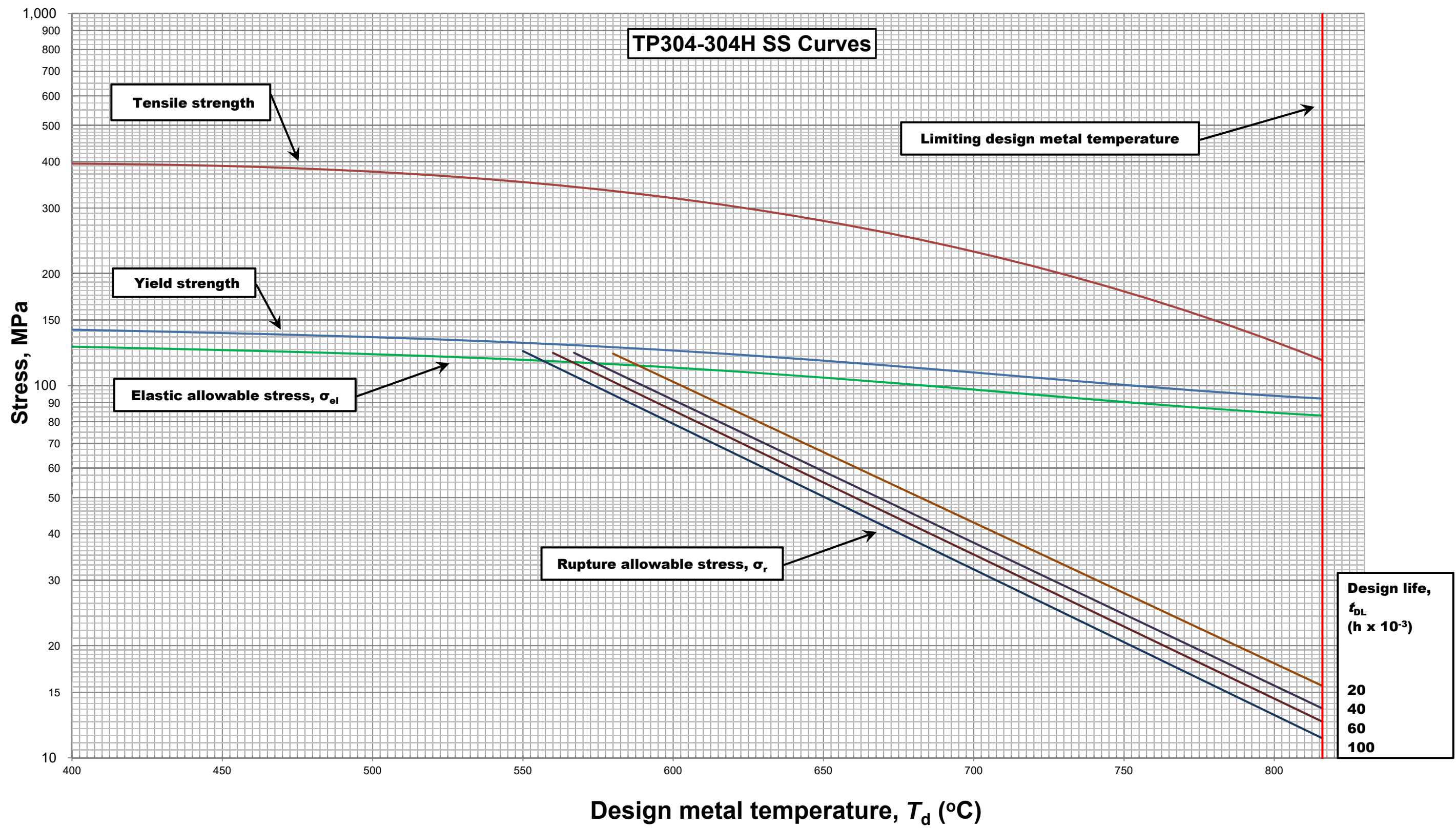


Figure E.31—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

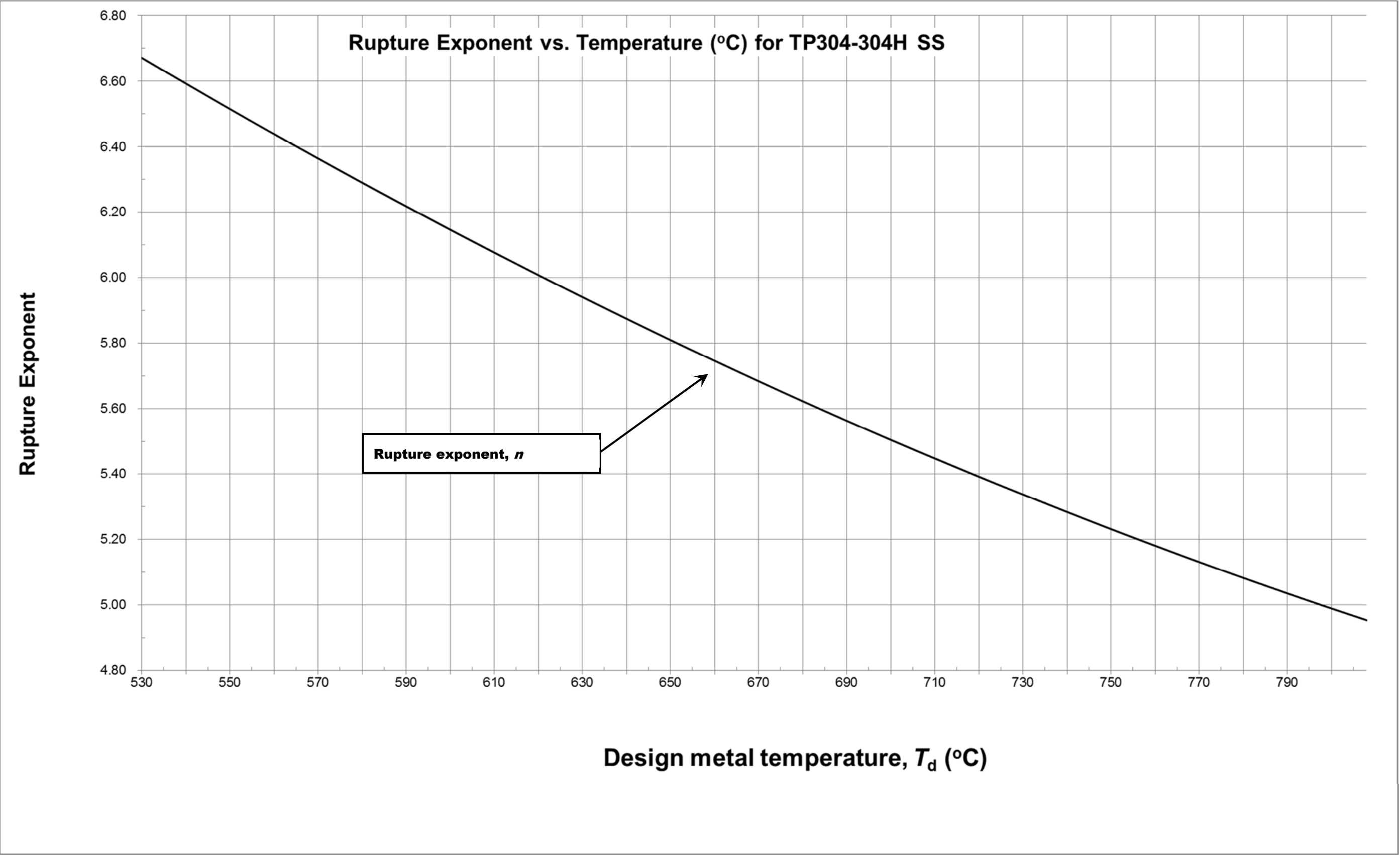


Figure E.32—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

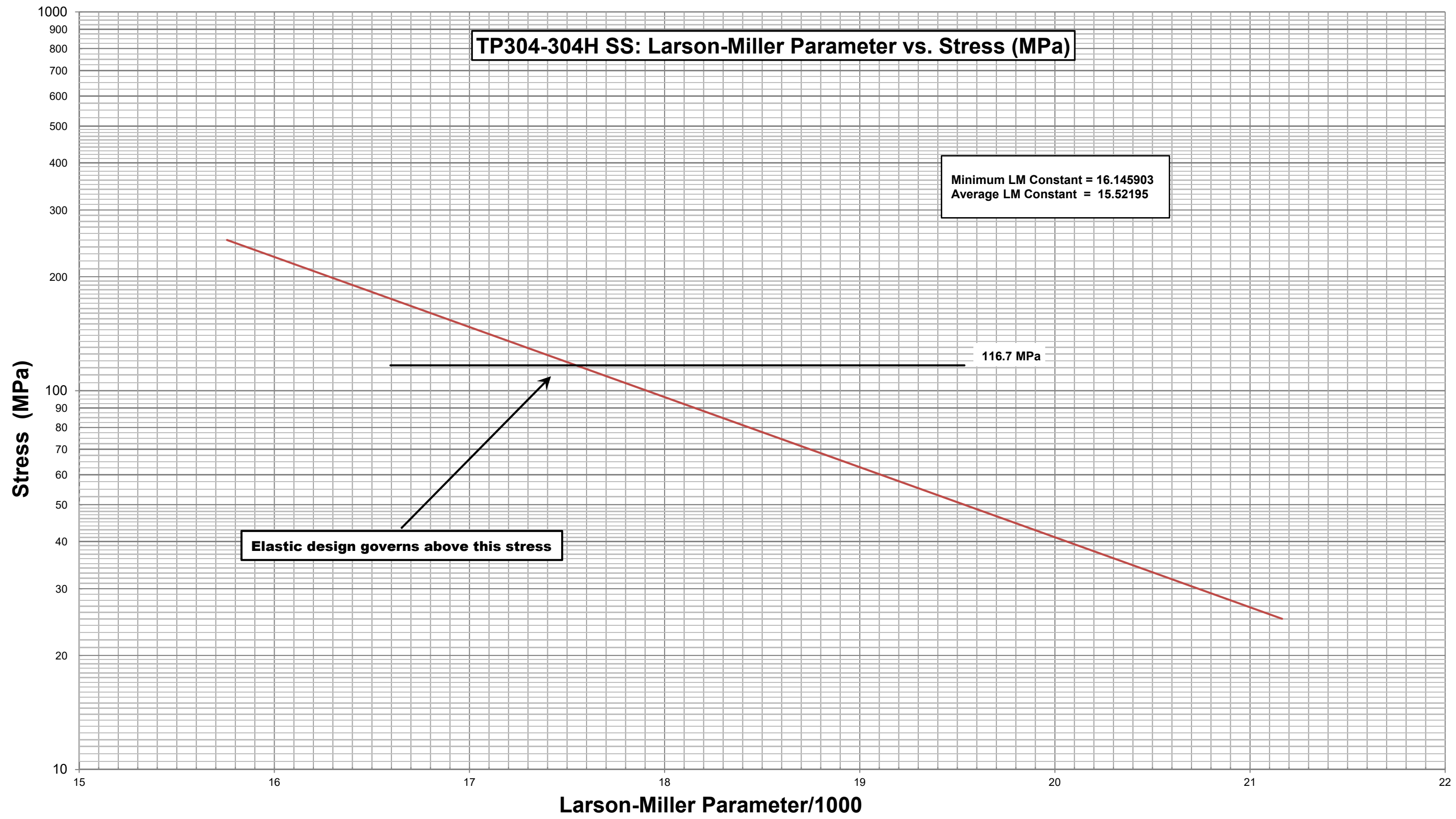


Figure E.33—Larson-Miller Parameter vs. Stress Curve (SI Units) for A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Table E.11—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for A213, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

TP304-304H SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	127.2					
410	126.7					
420	126.2					
430	125.7					
440	125.2					
450	124.6					
460	124.1					
470	123.5					
480	122.9					
490	122.2					
500	121.5					
510	120.8					
520	120.0					
530	119.2					
540	118.3	135.5	146.4	155.6	172.7	6.7
550	117.3	123.9	133.9	142.4	158.3	6.6
560	116.3	113.2	122.5	130.4	145.1	6.5
570	115.3	103.5	112.0	119.3	133.0	6.4
580	114.2	94.5	102.5	109.3	121.9	6.3
590	113.0	86.4	93.7	100.0	111.7	6.3
600	111.8	79.0	85.8	91.6	102.4	6.2
610	110.5	72.2	78.4	83.8	93.9	6.1
620	109.2	65.9	71.8	76.7	86.0	6.1
630	107.9	60.3	65.6	70.2	78.9	6.0
640	106.5	55.1	60.0	64.3	72.3	5.9
650	105.1	50.3	54.9	58.9	66.3	5.9
660	103.6	46.0	50.2	53.9	60.7	5.8
670	102.1	42.0	46.0	49.3	55.7	5.7
680	100.6	38.4	42.0	45.2	51.0	5.7
690	99.1	35.1	38.5	41.3	46.8	5.6
700	97.6	32.1	35.2	37.8	42.9	5.6
710	96.1	29.3	32.2	34.6	39.3	5.5
720	94.6	26.8	29.4	31.7	36.0	5.4
730	93.2	24.5	26.9	29.0	33.0	5.4
740	91.8	22.4	24.6	26.6	30.3	5.3
750	90.4	20.5	22.5	24.3	27.7	5.3
760	89.1	18.7	20.6	22.3	25.4	5.2
770	87.8	17.1	18.9	20.4	23.3	5.2
780	86.6	15.6	17.2	18.7	21.4	5.1
790	85.5	14.3	15.8	17.1	19.6	5.1
800	84.5	13.0	14.4	15.6	17.9	5.0
810	83.6	11.9	13.2	14.3	16.4	5.0
816	83.1	11.3	12.5	13.6	15.6	5.0

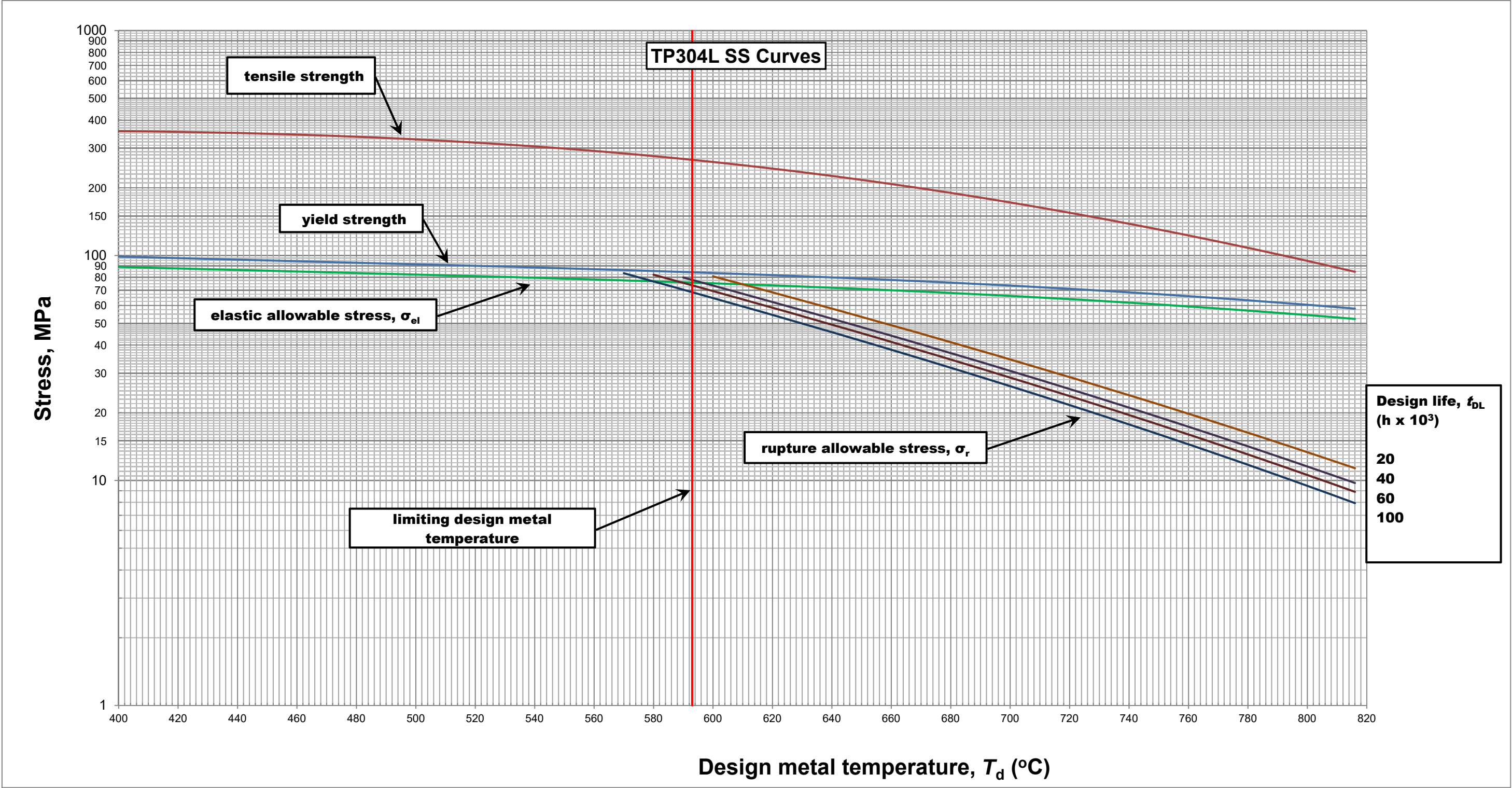


Figure E.34—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

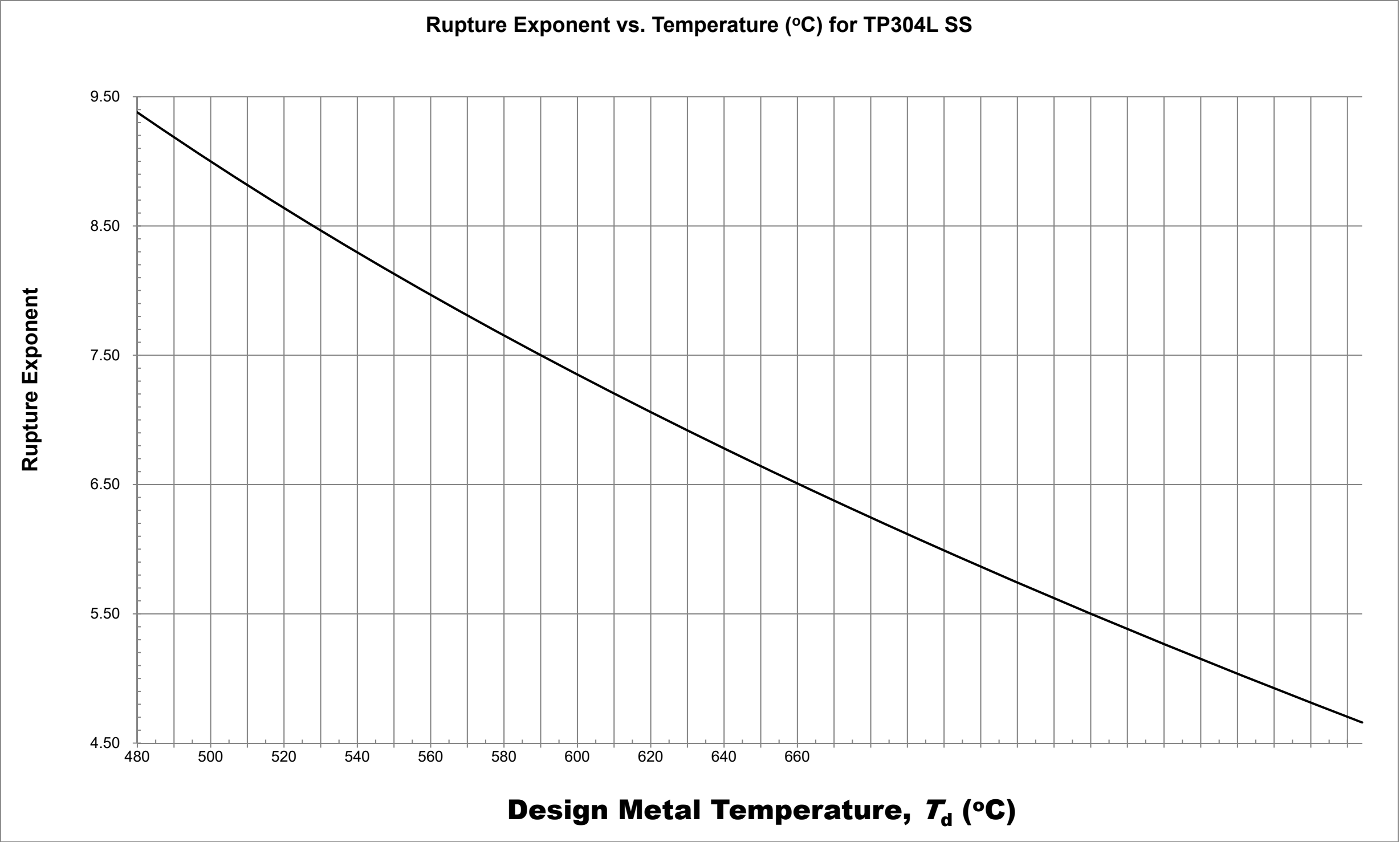


Figure E.35—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

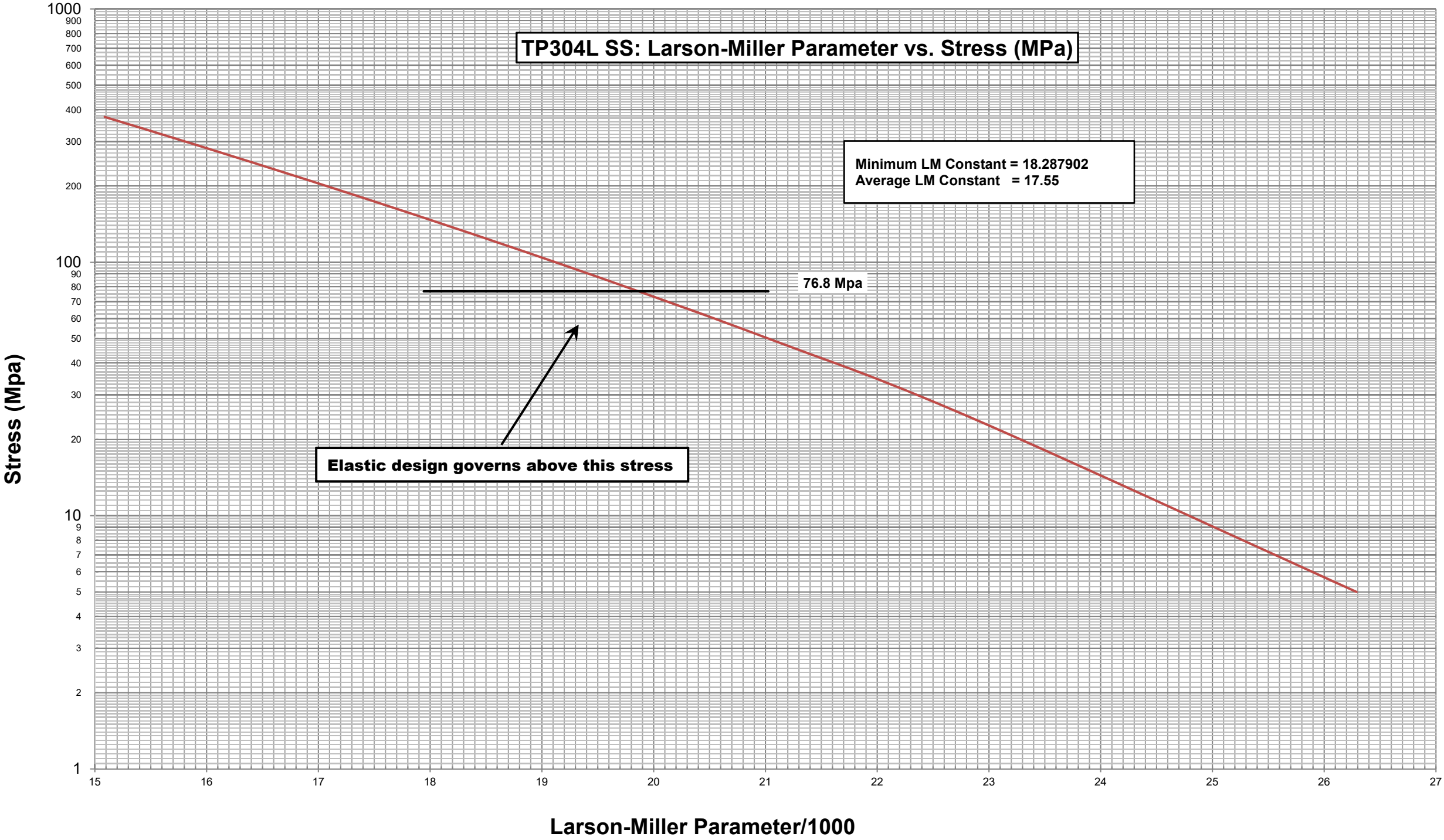


Figure E.36—Larson-Miller Parameter vs. Stress Curve (SI Units) for A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

Table E.12—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for A213, ASTM A312, and ASTM 376 TP 304L (18Cr-8Ni) Stainless Steels

TP304L SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	89.1					
410	88.4					
420	87.7					
430	87.0					
440	86.3					
450	85.7					
460	85.0					
470	84.3					
480	83.7					
490	83.0					
500	82.4					9.2
510	81.7					9.0
520	81.0					8.9
530	80.4					8.7
540	79.7					8.5
550	79.0					8.3
560	78.3	90.6	96.8	101.9	111.2	8.2
570	77.5	83.4	89.2	94.0	102.8	8.0
580	76.8	76.7	82.1	86.7	94.9	7.8
590	76.0	70.5	75.6	79.8	87.6	7.7
600	75.2	64.7	69.5	73.5	80.8	7.5
610	74.4	59.4	63.9	67.6	74.5	7.4
620	73.6	54.5	58.6	62.2	68.6	7.2
630	72.8	49.9	53.8	57.1	63.2	7.1
640	71.9	45.6	49.3	52.4	58.1	6.9
650	71.0	41.7	45.2	48.0	53.4	6.8
660	70.1	38.1	41.3	44.0	49.0	6.7
670	69.2	34.8	37.8	40.3	45.0	6.5
680	68.2	31.7	34.5	36.8	41.2	6.4
690	67.2	28.9	31.5	33.7	37.7	6.3
700	66.2	26.2	28.7	30.7	34.5	6.1
710	65.1	23.8	26.1	28.0	31.5	6.0
720	64.0	21.6	23.7	25.5	28.8	5.9
730	62.9	19.6	21.5	23.2	26.3	5.8
740	61.8	17.7	19.5	21.1	23.9	5.6
750	60.6	16.0	17.7	19.1	21.8	5.5
760	59.4	14.5	16.0	17.3	19.8	5.4
770	58.2	13.1	14.5	15.7	18.0	5.3
780	57.0	11.7	13.1	14.2	16.3	5.2
790	55.7	10.6	11.8	12.8	14.8	5.1
800	54.4	9.5	10.6	11.5	13.4	4.9
810	53.1	8.5	9.5	10.4	12.1	4.8
816	52.3	7.9	8.9	9.7	11.3	4.7

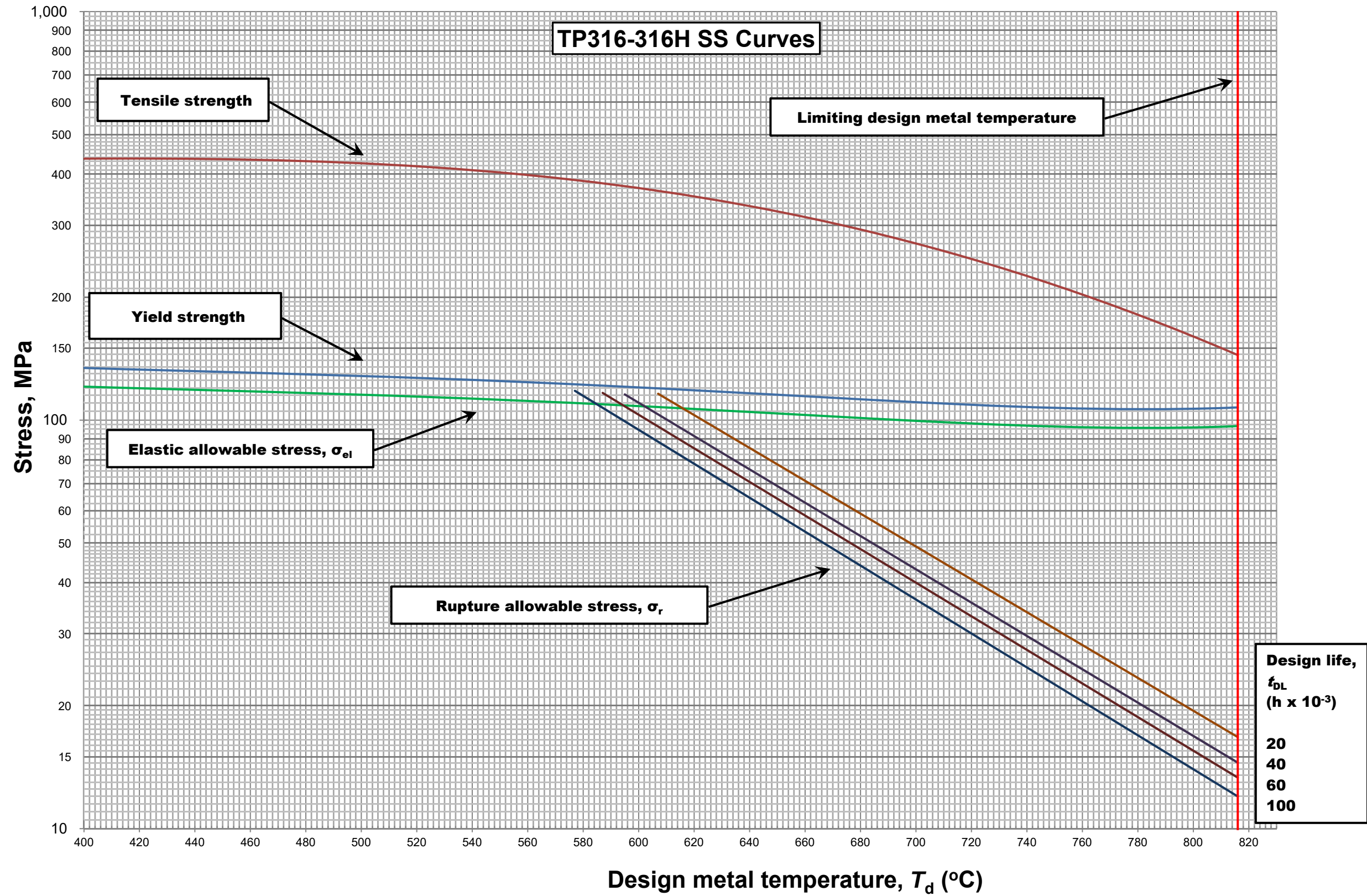


Figure E.37—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

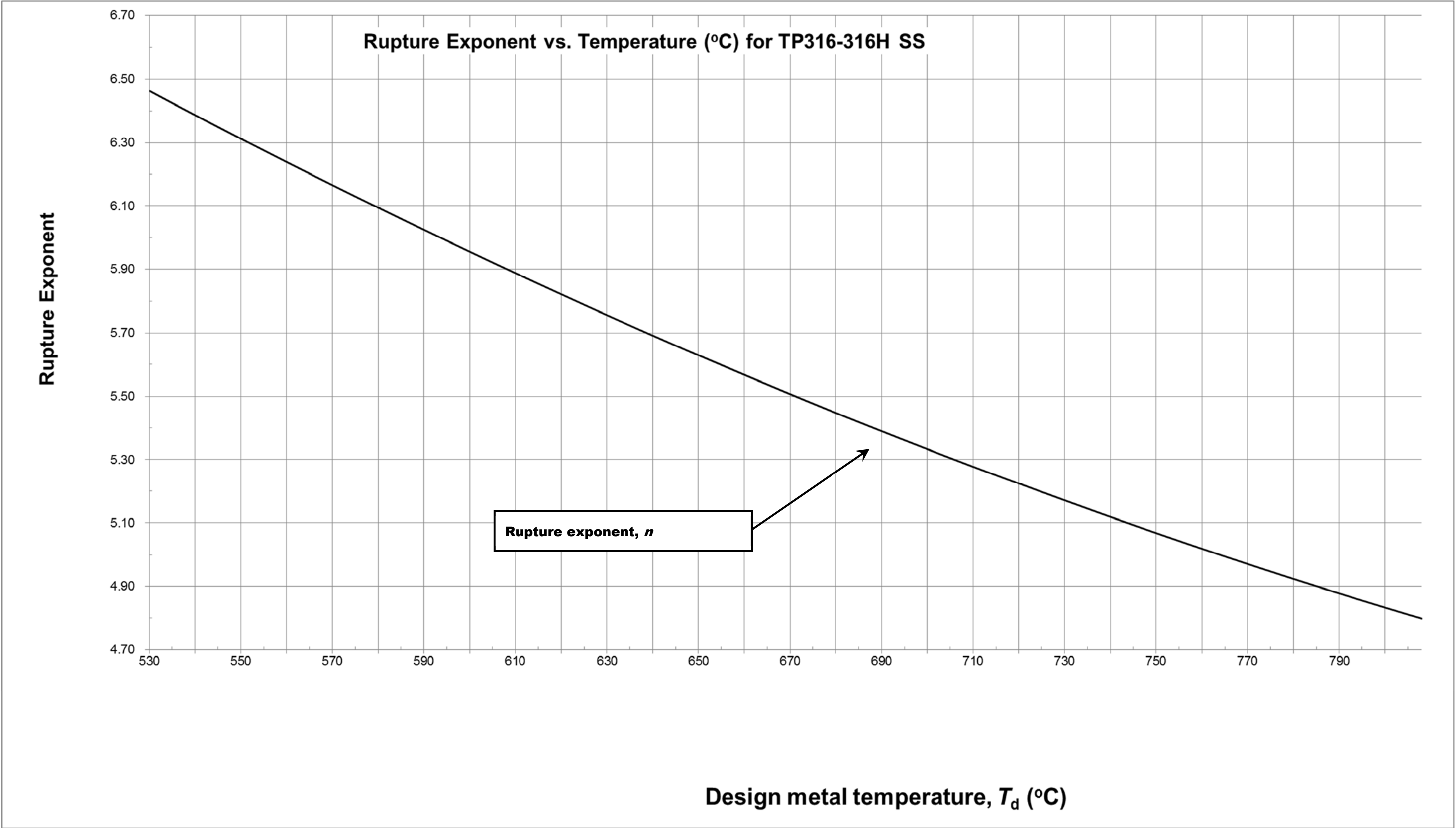


Figure E.38—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

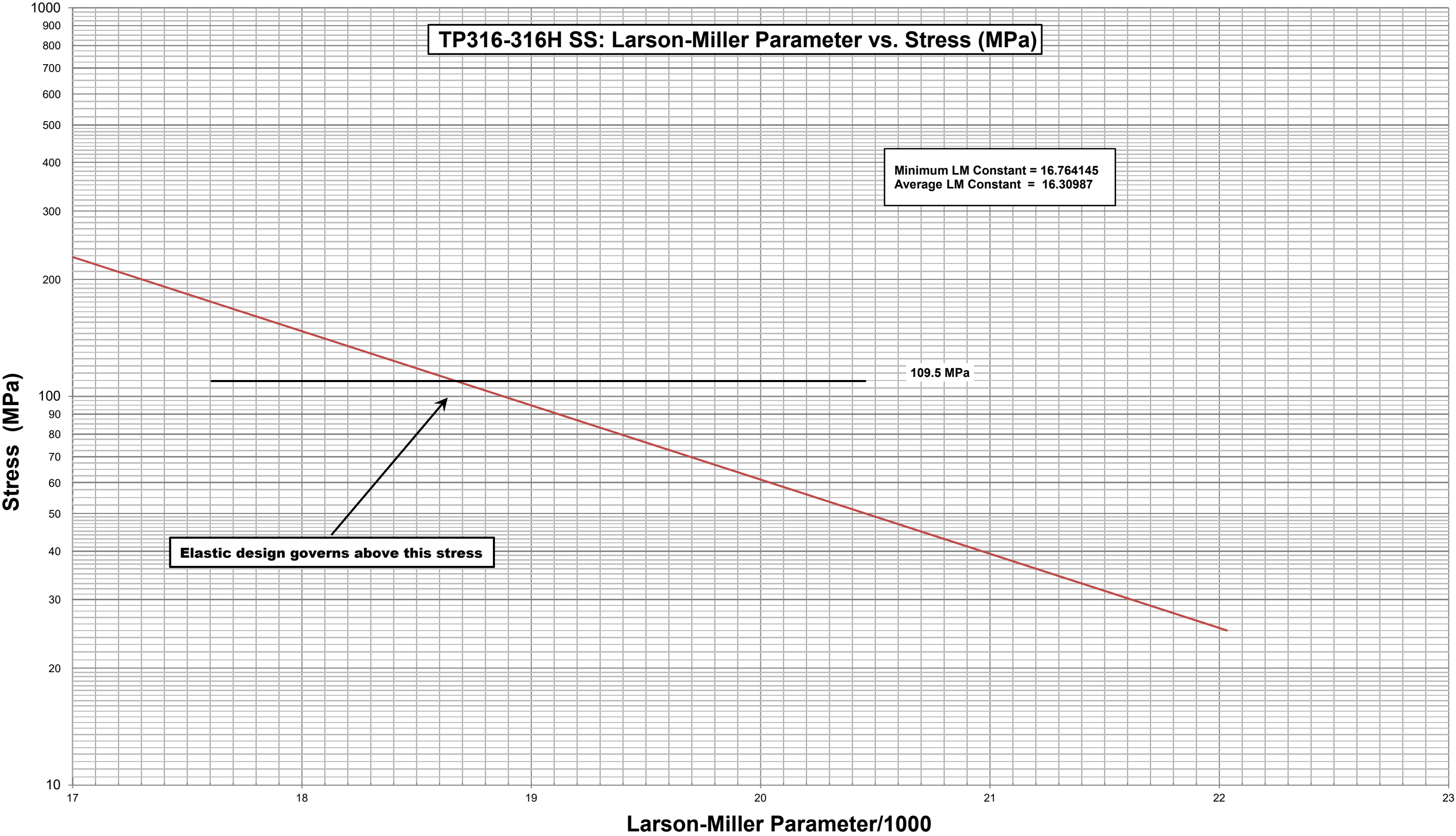


Figure E.39—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Table E.13—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

TP316-316H SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	120.8					
410	120.2					
420	119.7					
430	119.2					
440	118.7					
450	118.2					
460	117.6					
470	117.1					
480	116.6					
490	116.0					
500	115.4					
510	114.8					
520	114.2					
530	113.6					
540	112.9					
550	112.2					6.4
560	111.5					6.4
570	110.7	126.2	137.0	146.2	163.5	6.3
580	109.9	114.7	124.6	133.1	149.0	6.2
590	109.1	104.2	113.3	121.2	135.8	6.2
600	108.3	94.7	103.1	110.3	123.8	6.1
610	107.4	86.1	93.8	100.4	112.9	6.0
620	106.5	78.2	85.3	91.4	102.9	5.9
630	105.7	71.1	77.6	83.2	93.8	5.9
640	104.8	64.6	70.6	75.8	85.5	5.8
650	103.9	58.7	64.2	69.0	77.9	5.7
660	103.0	53.3	58.4	62.8	71.0	5.7
670	102.1	48.5	53.1	57.2	64.8	5.6
680	101.2	44.0	48.3	52.0	59.0	5.6
690	100.4	40.0	44.0	47.4	53.8	5.5
700	99.6	36.4	40.0	43.1	49.1	5.4
710	98.8	33.1	36.4	39.3	44.7	5.4
720	98.1	30.0	33.1	35.7	40.8	5.3
730	97.5	27.3	30.1	32.5	37.2	5.3
740	96.9	24.8	27.4	29.6	33.9	5.2
750	96.5	22.5	24.9	27.0	30.9	5.2
760	96.1	20.5	22.7	24.5	28.1	5.1
770	95.8	18.6	20.6	22.3	25.7	5.1
780	95.7	16.9	18.8	20.3	23.4	5.0
790	95.8	15.4	17.1	18.5	21.3	5.0
800	96.0	14.0	15.5	16.9	19.4	4.9
810	96.4	12.7	14.1	15.3	17.7	4.9
816	96.7	12.0	13.3	14.5	16.8	4.8

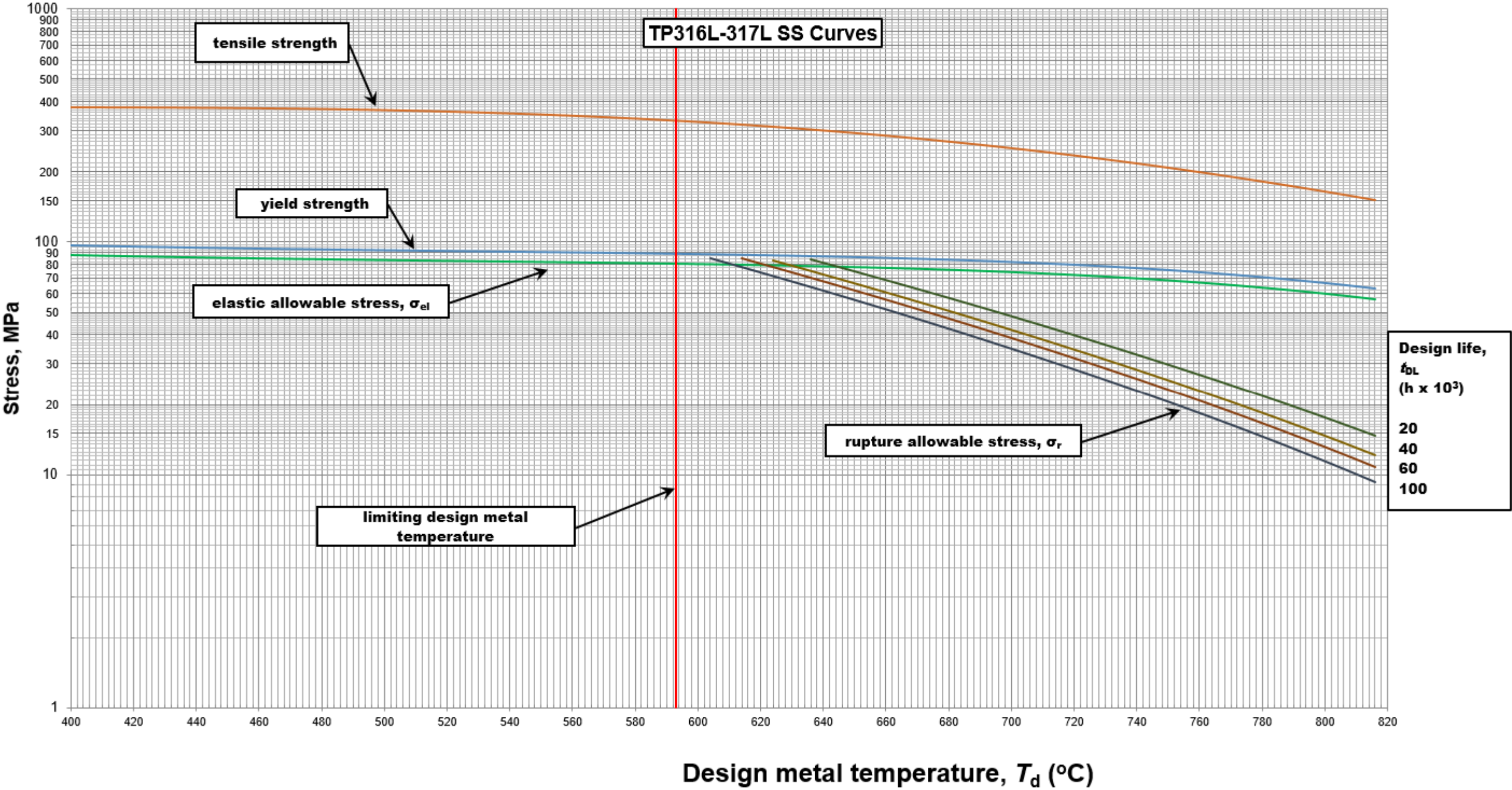


Figure E.40—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

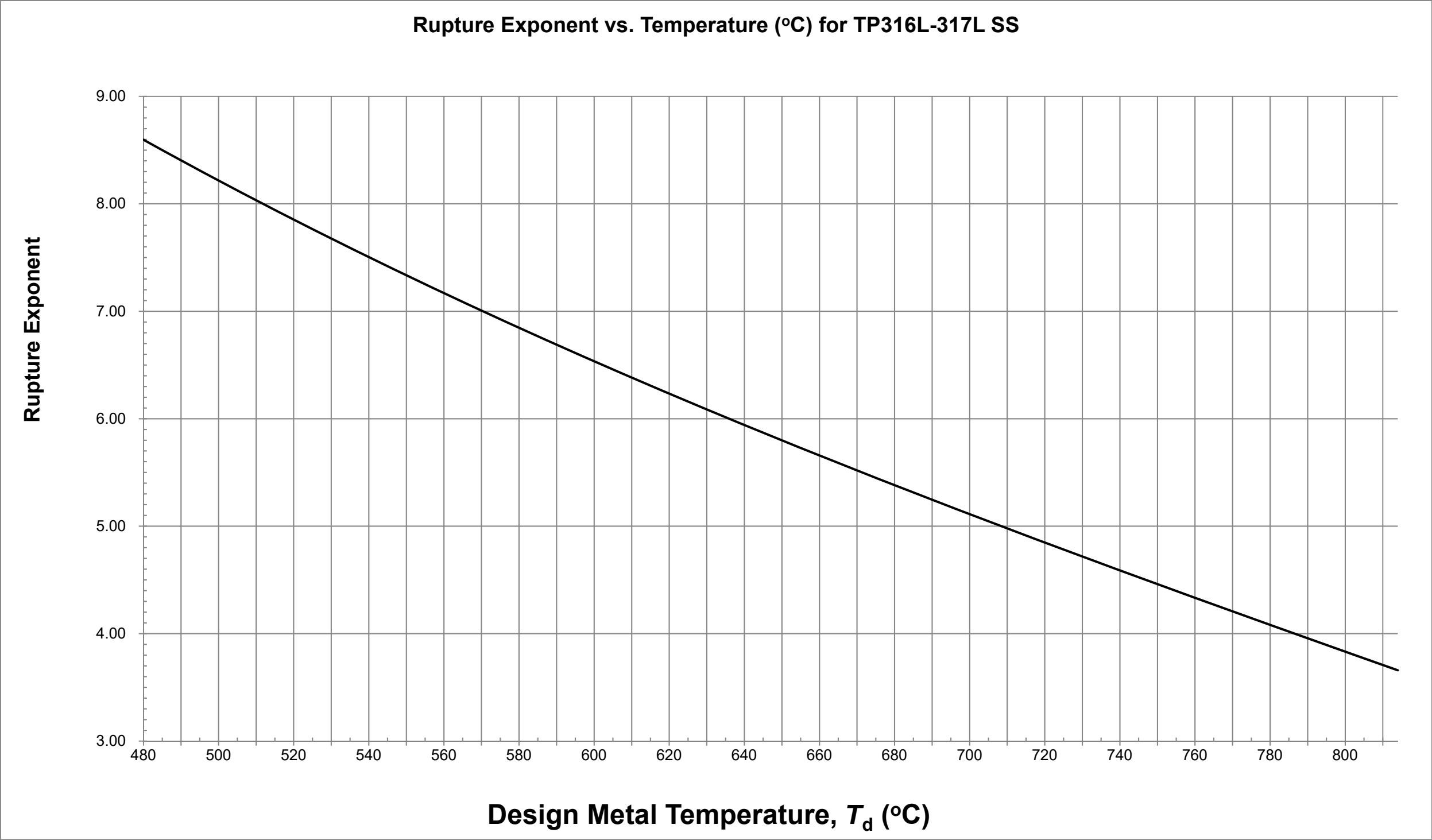


Figure E.41—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steel

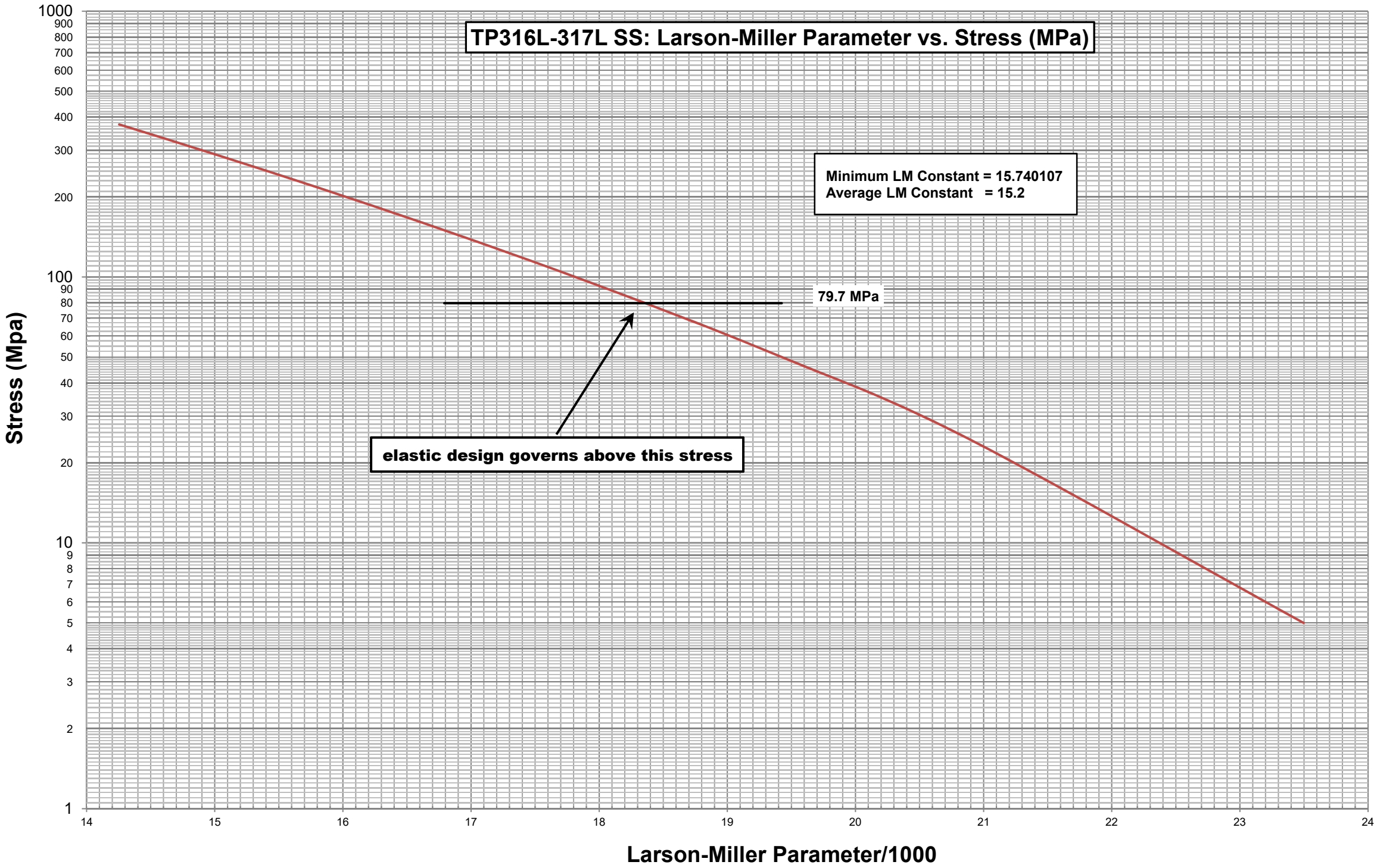


Figure E.42—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table E.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

TP316L-317L SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	87.6					
410	87.0					
420	86.5					
430	86.0					
440	85.6					
450	85.2					
460	84.8					
470	84.4					
480	84.0					
490	83.7					8.4
500	83.4					8.3
510	83.1					8.1
520	82.8					7.9
530	82.5					7.7
540	82.2					7.5
550	81.9					7.4
560	81.6					7.2
570	81.2					7.0
580	80.9					6.9
590	80.6					6.7
600	80.2	88.6	96.0	102.2	113.6	6.6
610	79.8	81.2	88.2	94.0	104.8	6.4
620	79.4	74.4	80.9	86.4	96.6	6.3
630	78.9	68.0	74.2	79.3	88.9	6.1
640	78.4	62.1	67.9	72.8	81.8	6.0
650	77.8	56.7	62.1	66.6	75.1	5.8
660	77.2	51.6	56.7	61.0	68.9	5.7
670	76.6	47.0	51.7	55.7	63.2	5.5
680	75.8	42.7	47.1	50.8	57.8	5.4
690	75.0	38.7	42.8	46.3	52.8	5.3
700	74.1	35.0	38.8	42.1	48.2	5.1
710	73.1	31.6	35.2	38.2	44.0	5.0
720	72.1	28.5	31.8	34.7	40.0	4.9
730	70.9	25.7	28.7	31.4	36.4	4.7
740	69.7	23.0	25.9	28.4	33.0	4.6
750	68.3	20.6	23.3	25.6	29.9	4.5
760	66.9	18.5	20.9	23.0	27.0	4.4
770	65.3	16.5	18.7	20.7	24.4	4.2
780	63.6	14.6	16.7	18.5	21.9	4.1
790	61.9	13.0	14.9	16.5	19.7	4.0
800	60.0	11.4	13.2	14.7	17.7	3.9
810	58.0	10.1	11.7	13.1	15.8	3.7
816	56.8	9.3	10.8	12.2	14.7	3.7

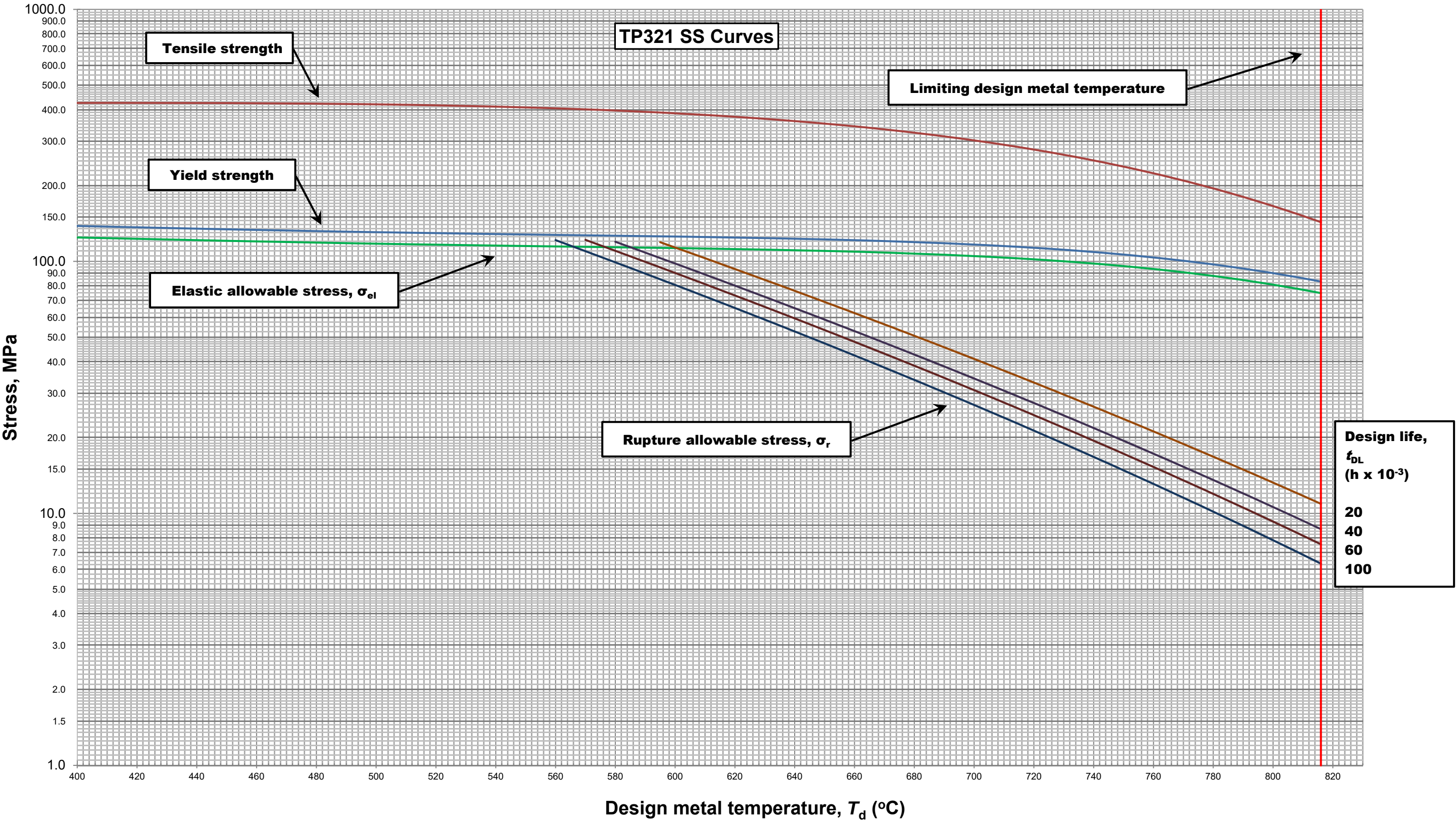


Figure E.43—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

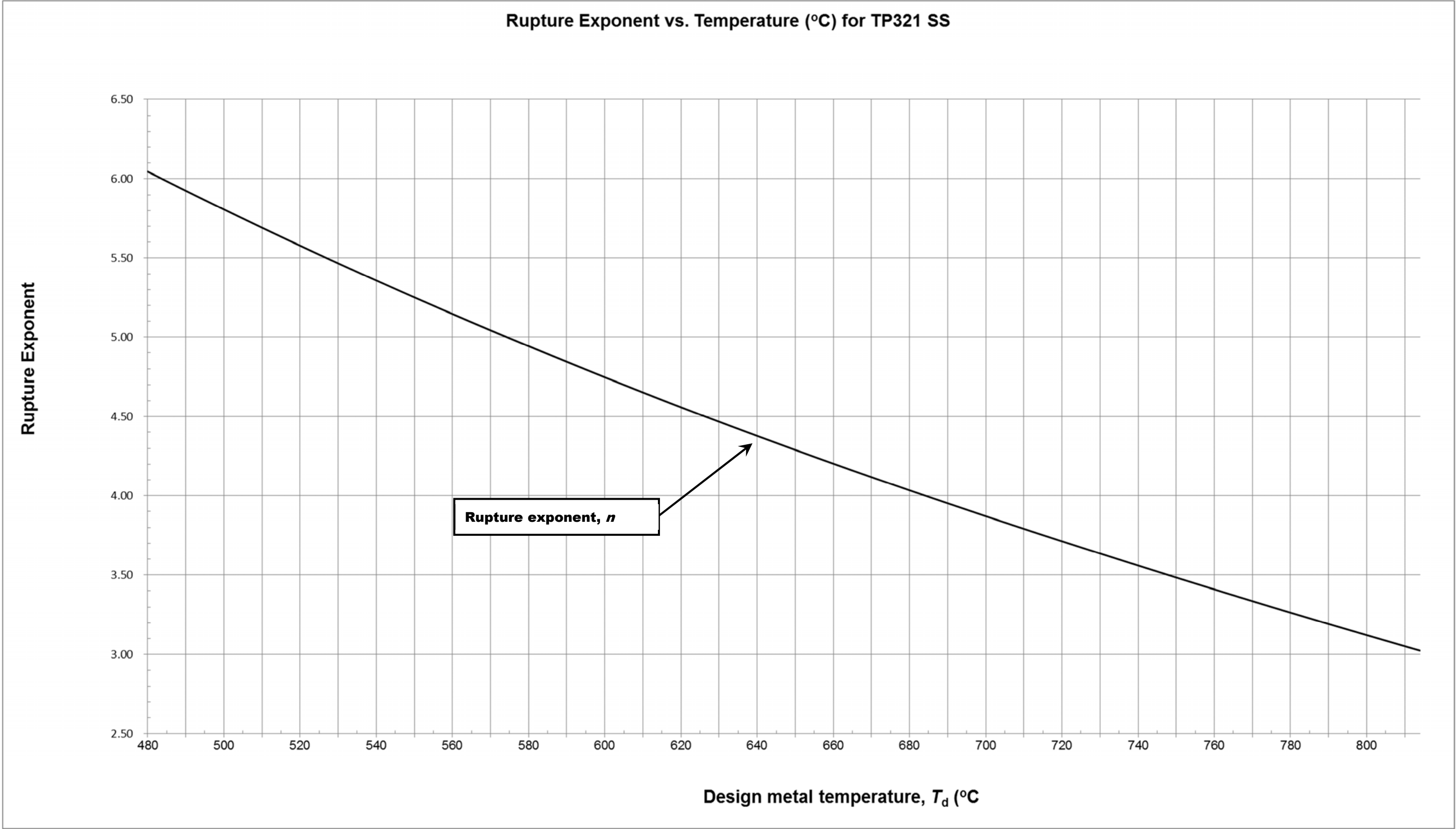


Figure E.44—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

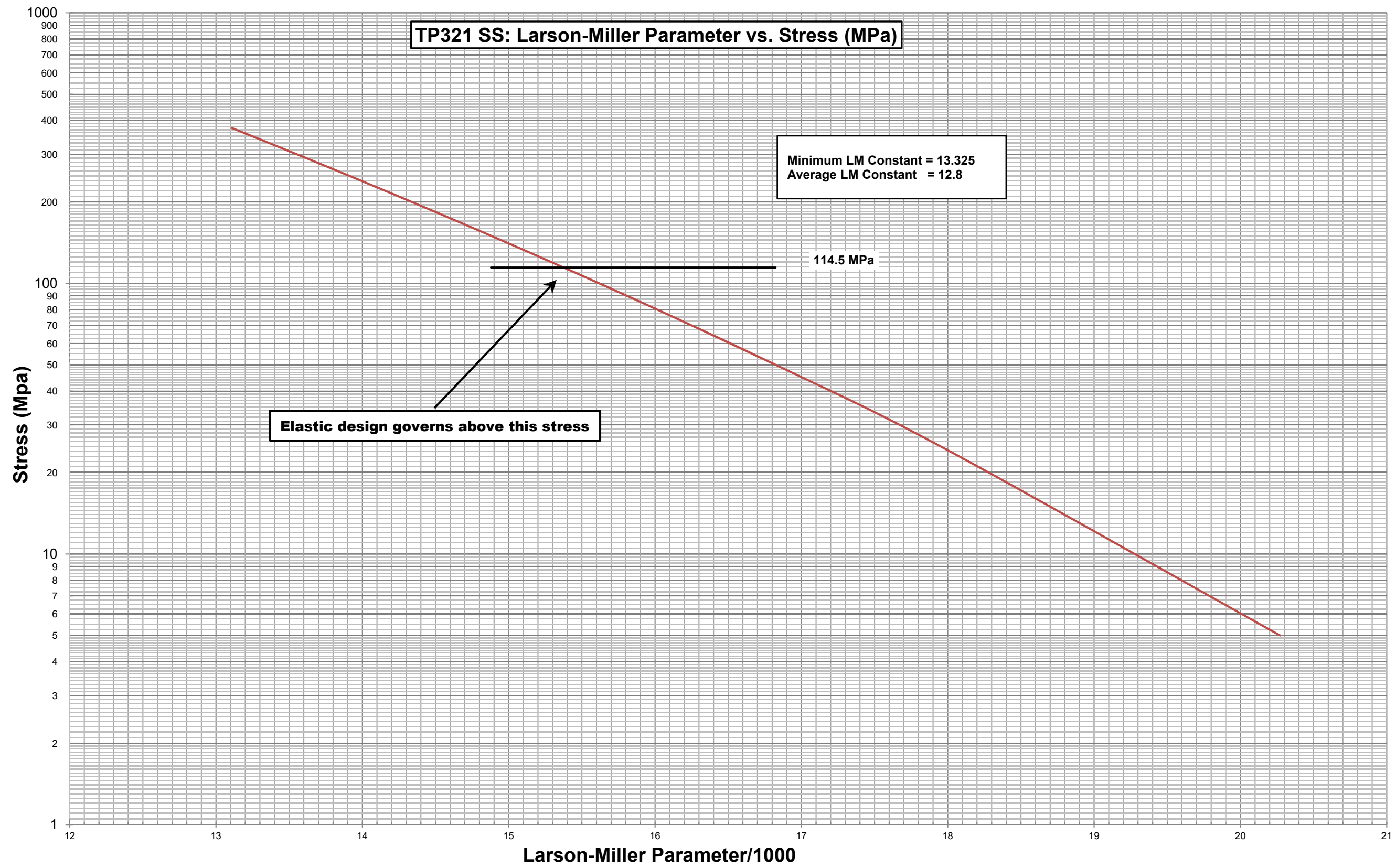


Figure E.45—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Table E.15—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

TP321 SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	124.5					
410	123.7					
420	122.9					
430	122.1					
440	121.4					
450	120.7					
460	120.0					
470	119.4					
480	118.8					
490	118.2					
500	117.6					5.9
510	117.1					5.8
520	116.6					5.7
530	116.1					5.6
540	115.6					5.5
550	115.2					5.4
560	114.7	134.3	148.2	160.2	182.8	5.3
570	114.3	121.5	134.4	145.5	166.5	5.2
580	113.9	109.8	121.7	132.0	151.5	5.1
590	113.4	99.2	110.2	119.7	137.7	5.0
600	113.0	89.5	99.6	108.4	125.1	4.9
610	112.5	80.7	90.0	98.1	113.6	4.8
620	112.0	72.7	81.3	88.7	103.0	4.7
630	111.4	65.4	73.3	80.2	93.3	4.6
640	110.8	58.7	66.0	72.4	84.5	4.5
650	110.1	52.7	59.4	65.2	76.4	4.4
660	109.3	47.3	53.4	58.8	69.1	4.3
670	108.4	42.4	48.0	52.9	62.4	4.2
680	107.4	37.9	43.0	47.5	56.3	4.1
690	106.3	33.9	38.6	42.7	50.7	4.1
700	105.0	30.2	34.5	38.3	45.6	4.0
710	103.6	26.9	30.8	34.3	41.0	3.9
720	102.0	24.0	27.5	30.7	36.9	3.8
730	100.1	21.3	24.5	27.4	33.1	3.7
740	98.1	18.9	21.9	24.5	29.6	3.7
750	95.8	16.8	19.4	21.8	26.5	3.6
760	93.3	14.8	17.3	19.4	23.7	3.5
770	90.6	13.1	15.3	17.3	21.2	3.4
780	87.6	11.5	13.5	15.3	18.9	3.4
790	84.4	10.2	12.0	13.6	16.8	3.3
800	80.9	8.9	10.5	12.0	14.9	3.2
810	77.2	7.8	9.3	10.6	13.3	3.1
816	74.9	6.9	8.2	9.4	11.7	3.1
		6.3	7.5	8.7	10.9	3.0

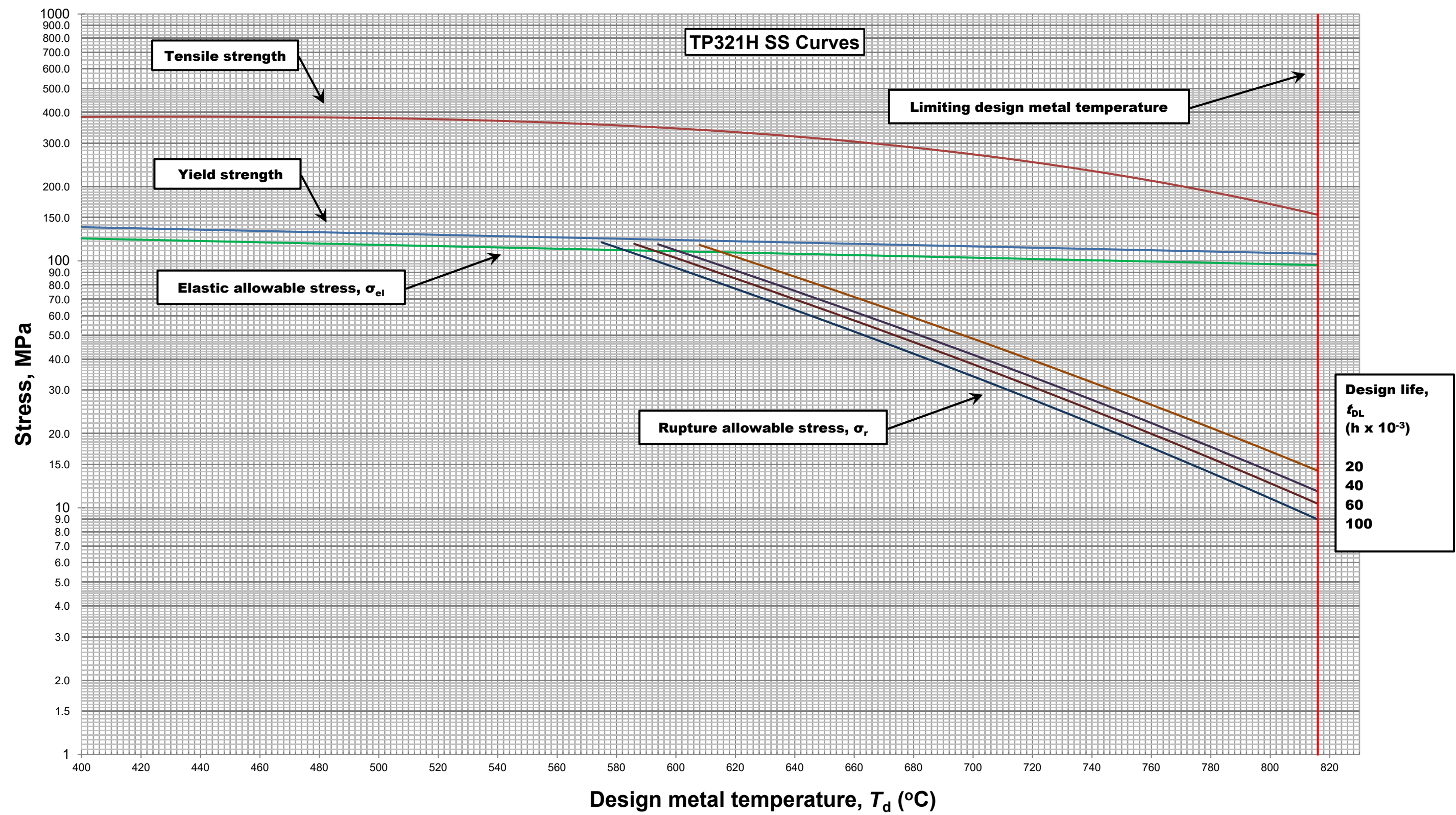


Figure E.46—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

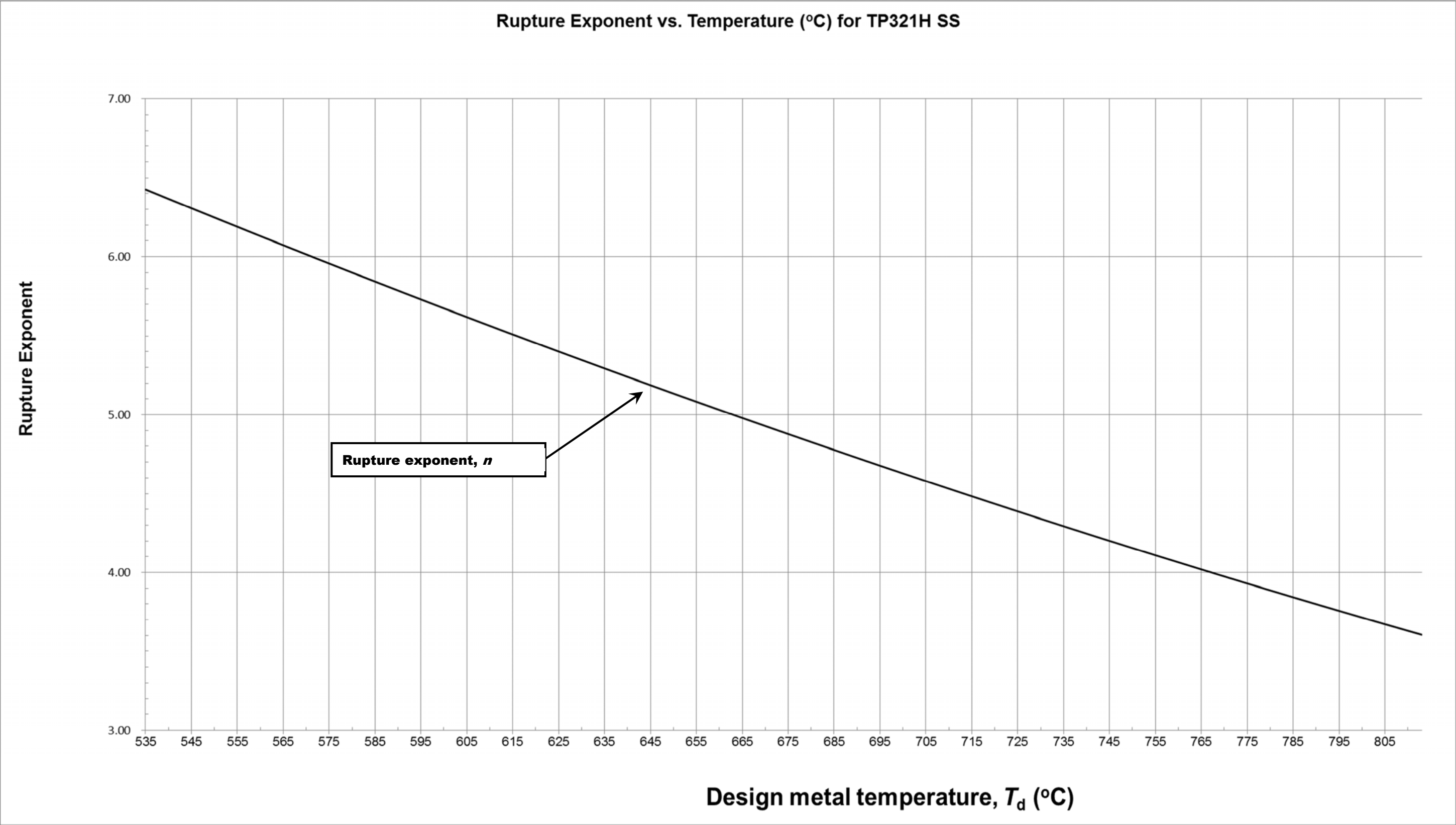


Figure E.47—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

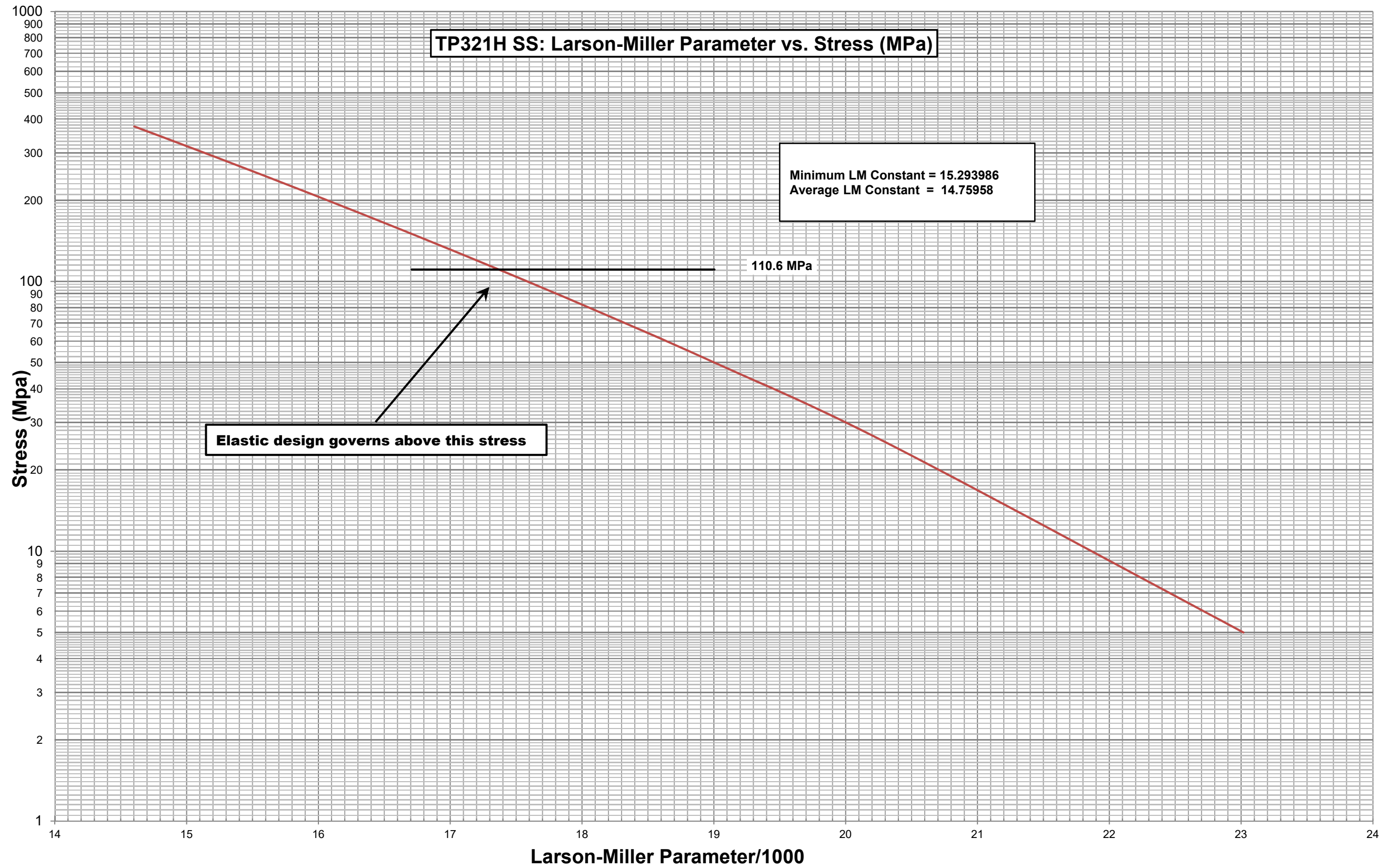


Figure E.48—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Table E.16—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

TP321H SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	123.4					
410	122.6					
420	121.9					
430	121.2					
440	120.5					
450	119.7					
460	119.0					
470	118.3					
480	117.6					
490	116.9					
500	116.2					
510	115.5					
520	114.8					
530	114.1					
540	113.5					6.4
550	112.8					6.3
560	112.1					6.2
570	111.4	124.7	135.9	145.5	163.2	6.0
580	110.8	113.5	123.9	132.8	149.3	5.9
590	110.1	103.2	112.9	121.2	136.6	5.8
600	109.5	93.8	102.8	110.5	124.8	5.7
610	108.8	85.1	93.5	100.6	114.0	5.6
620	108.2	77.2	84.9	91.6	104.0	5.5
630	107.5	70.0	77.1	83.3	94.8	5.4
640	106.9	63.3	69.9	75.6	86.3	5.3
650	106.2	57.3	63.4	68.7	78.6	5.2
660	105.6	51.7	57.4	62.3	71.5	5.1
670	105.0	46.7	51.9	56.4	64.9	5.0
680	104.3	42.1	46.9	51.0	58.9	4.9
690	103.7	37.9	42.3	46.1	53.4	4.8
700	103.1	34.1	38.1	41.7	48.4	4.7
710	102.5	30.6	34.3	37.6	43.8	4.6
720	101.9	27.4	30.9	33.9	39.6	4.5
730	101.3	24.6	27.7	30.5	35.7	4.4
740	100.7	22.0	24.9	27.4	32.2	4.3
750	100.1	19.6	22.3	24.6	29.1	4.2
760	99.5	17.5	19.9	22.1	26.1	4.1
770	98.9	15.6	17.8	19.7	23.5	4.0
780	98.3	13.9	15.9	17.7	21.1	3.9
790	97.7	12.3	14.1	15.8	18.9	3.8
800	97.1	10.9	12.6	14.0	16.9	3.7
810	96.5	9.7	11.2	12.5	15.1	3.7
816	96.2	9.0	10.4	11.6	14.1	3.6

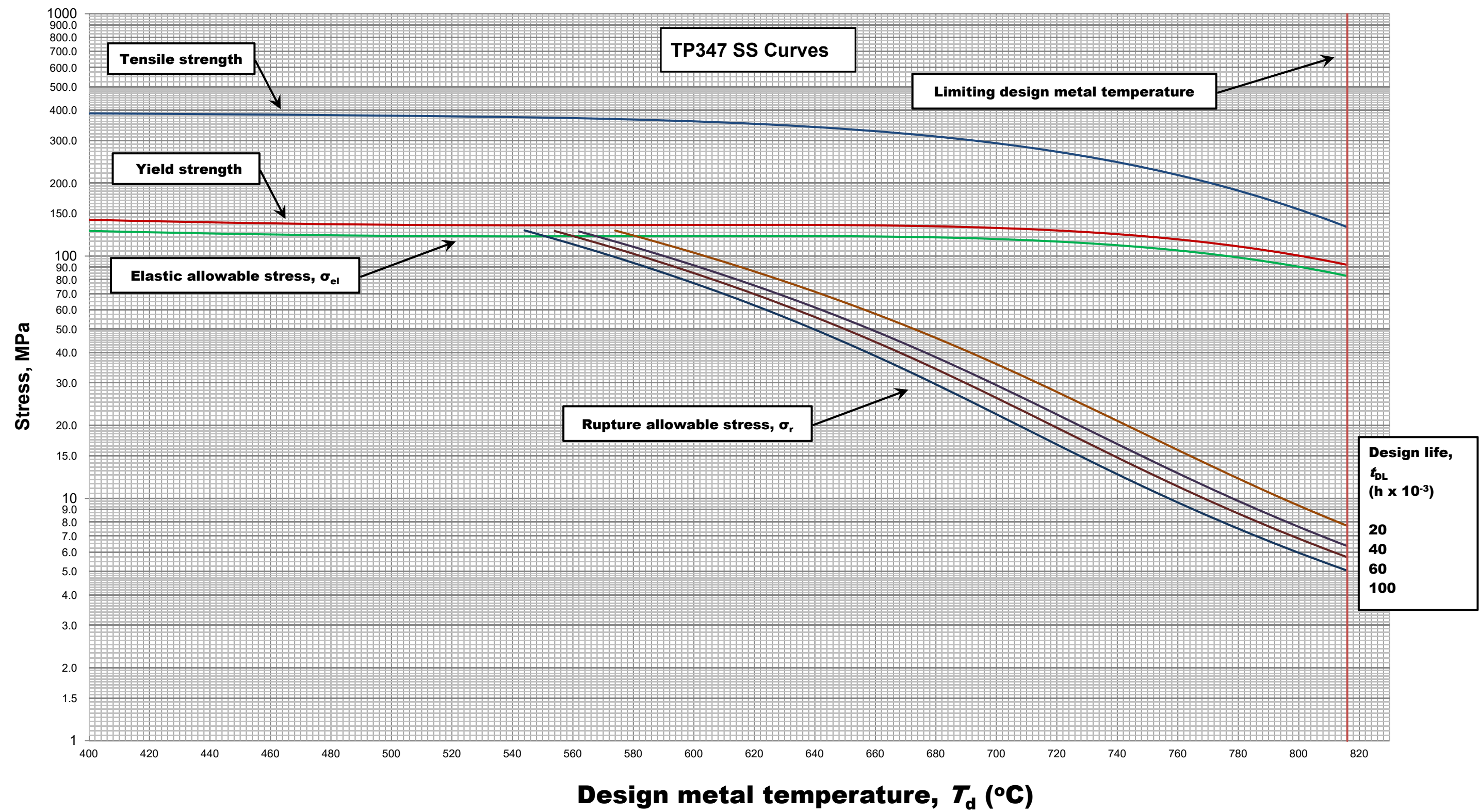


Figure E.49—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

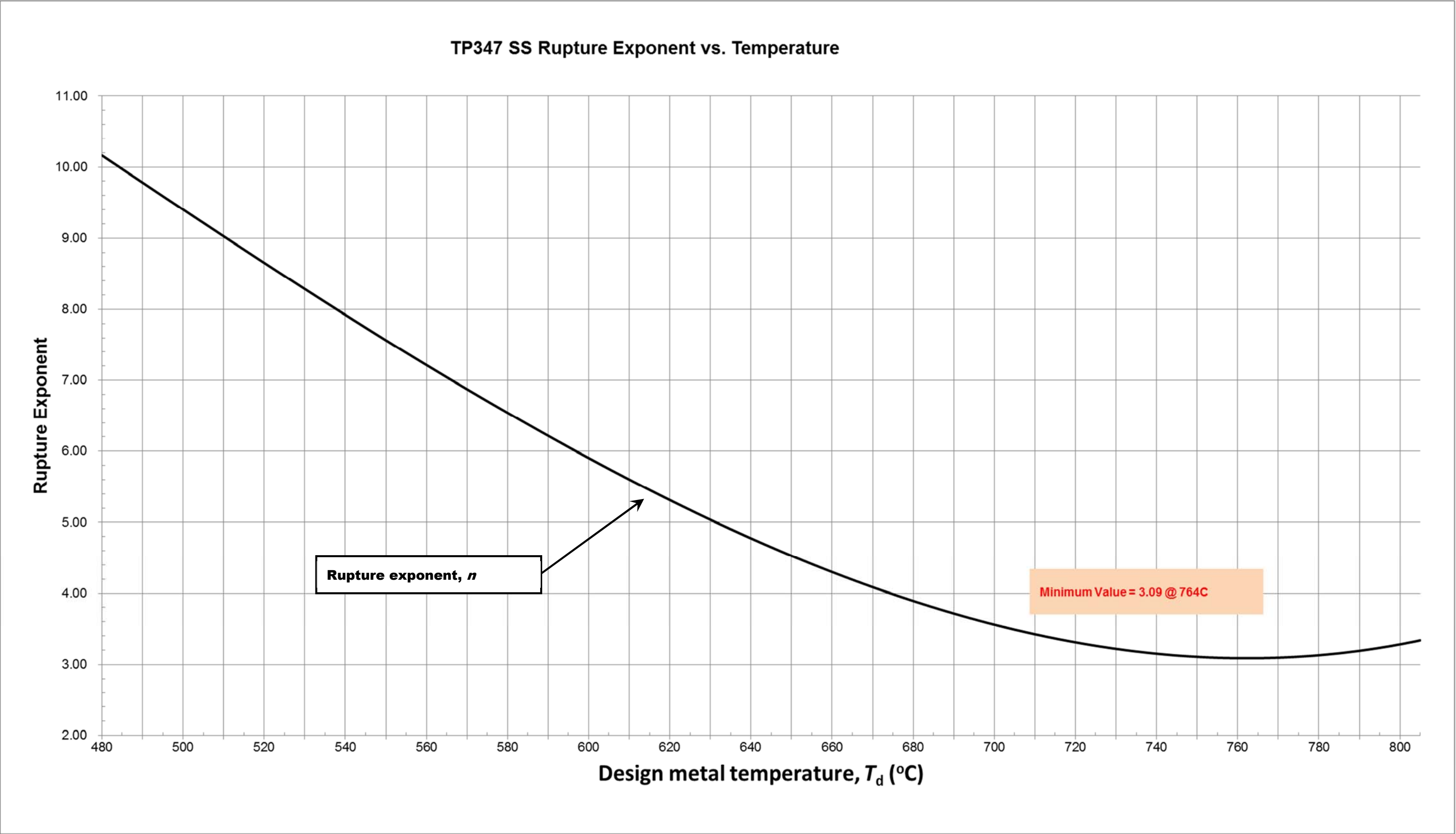


Figure E.50—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

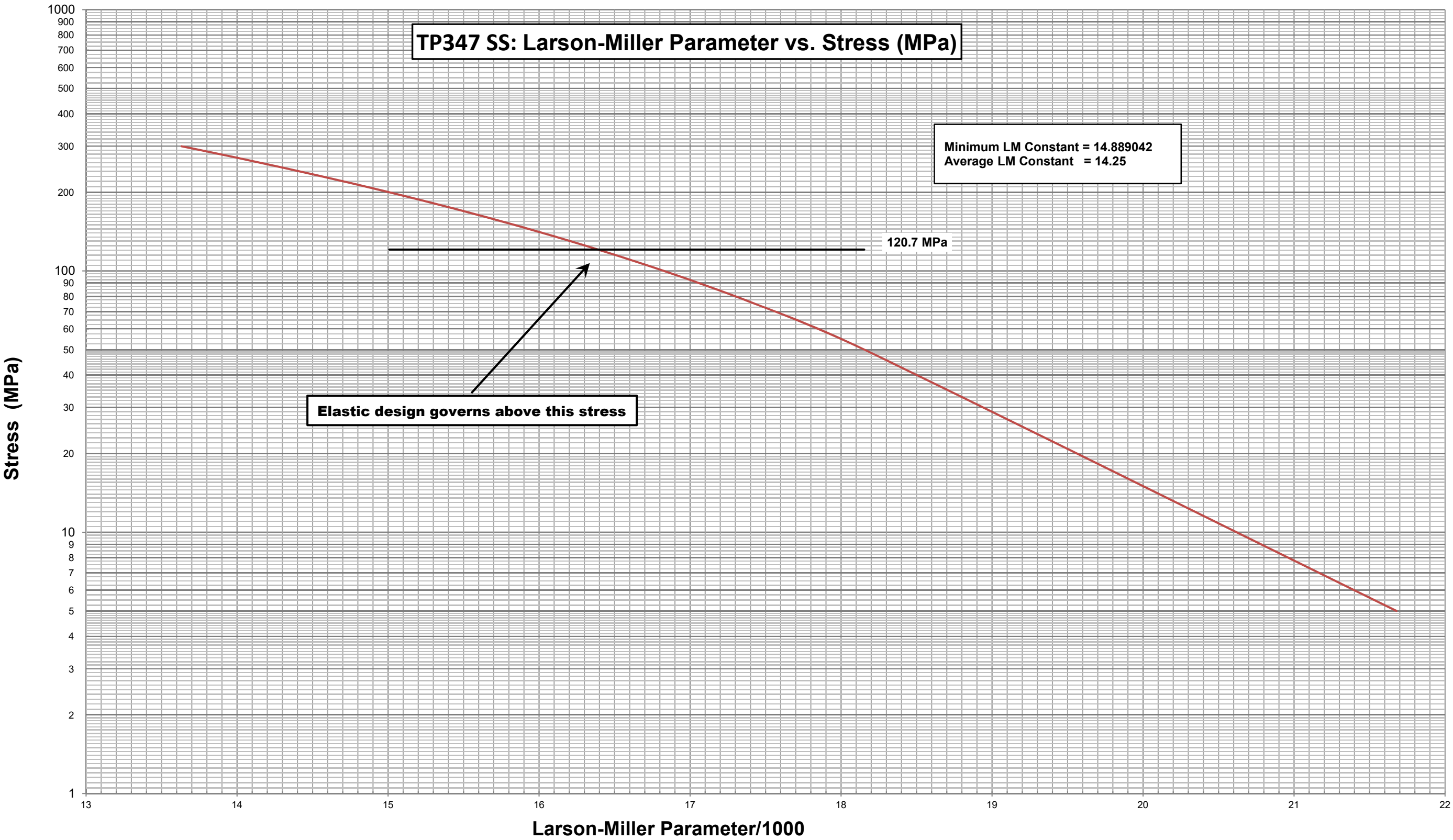


Figure E.51—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Table E.17—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

TP347 SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	127.1					
410	126.2					
420	125.4					
430	124.7					
440	124.0					
450	123.4					
460	122.8					
470	122.3					
480	121.9					
490	121.6					
500	121.3					9.9
510	121.0					9.5
520	120.9					9.1
530	120.8					8.7
540	120.7					8.4
550	120.7					8.0
560	120.7					7.6
570	120.8					7.3
580	120.9					6.9
590	121.0					6.6
600	121.1	131.9	141.4	149.3	163.3	6.3
610	121.1	121.7	131.0	138.7	152.3	6.0
620	121.2	111.9	121.0	128.4	141.7	5.7
630	121.1	102.6	111.4	118.6	131.5	5.4
640	121.0	93.8	102.2	109.2	121.7	5.1
650	120.9	85.3	93.4	100.2	112.3	4.8
660	120.6	77.3	85.1	91.6	103.3	4.6
670	120.1	69.7	77.2	83.4	94.7	4.3
680	119.5	62.6	69.7	75.7	86.5	4.1
690	118.7	56.0	62.7	68.3	78.7	3.9
700	117.7	49.7	56.1	61.4	71.3	3.7
710	116.4	44.0	49.9	55.0	64.3	3.6
720	114.9	38.7	44.2	49.0	57.8	3.4
730	113.1	33.9	39.0	43.4	51.6	3.3
740	110.9	29.6	34.2	38.2	46.0	3.2
750	108.4	25.7	29.9	33.6	40.7	3.1
760	105.5	22.3	26.0	29.4	35.9	3.1
770	102.3	19.3	22.6	25.6	31.5	3.1
780	98.7	16.7	19.6	22.2	27.5	3.1
790	94.8	14.5	17.0	19.3	24.0	3.2
800	90.4	12.6	14.7	16.8	20.9	3.3
810	85.8	11.0	12.8	14.6	18.2	3.4
816	82.9	9.6	11.2	12.7	15.8	3.5
		8.5	9.8	11.1	13.8	
		7.5	8.7	9.8	12.1	
		6.7	7.7	8.6	10.6	
		6.0	6.8	7.6	9.3	
		5.4	6.1	6.8	8.3	
		5.0	5.7	6.4	7.7	

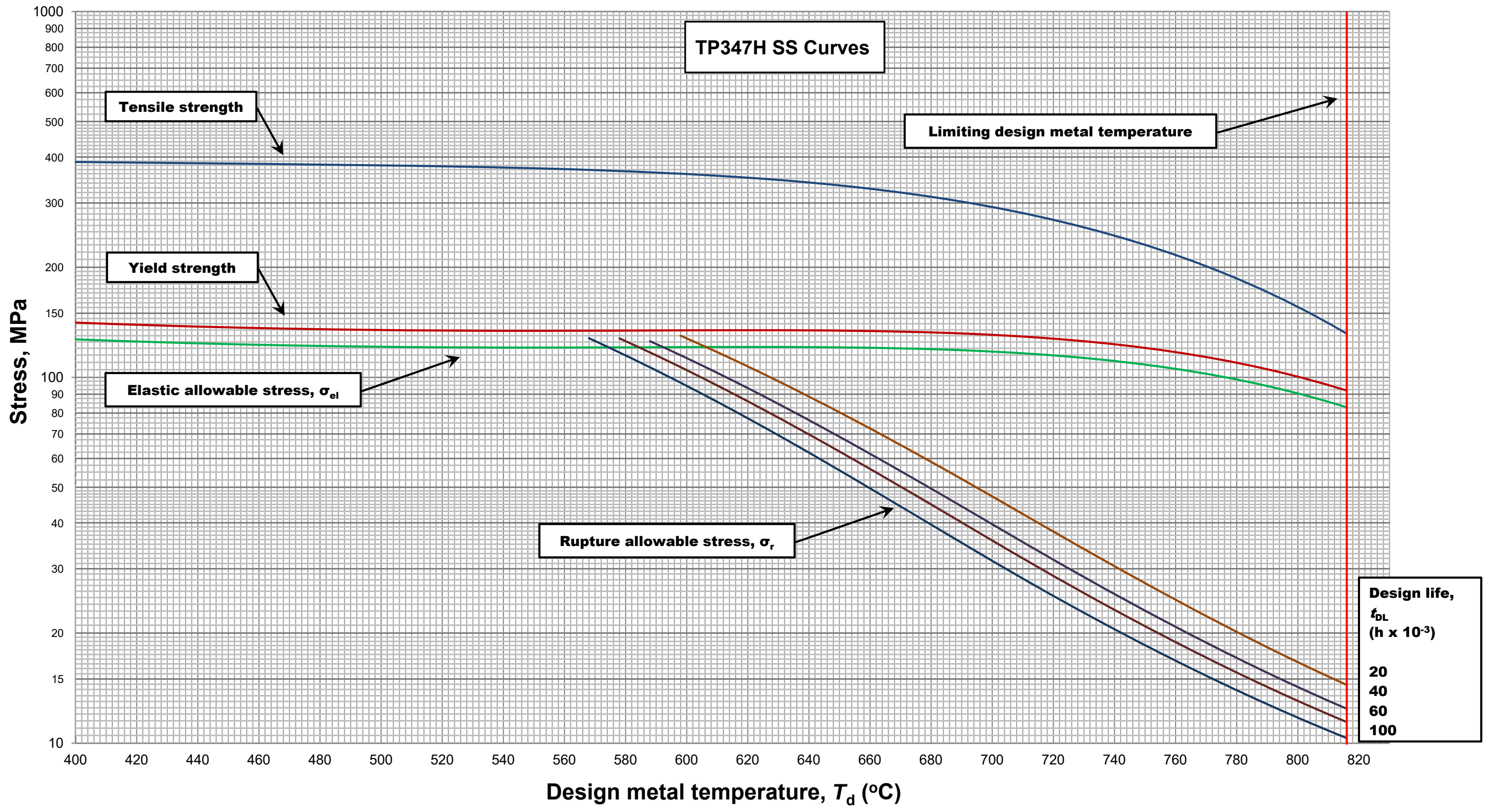


Figure E.52—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

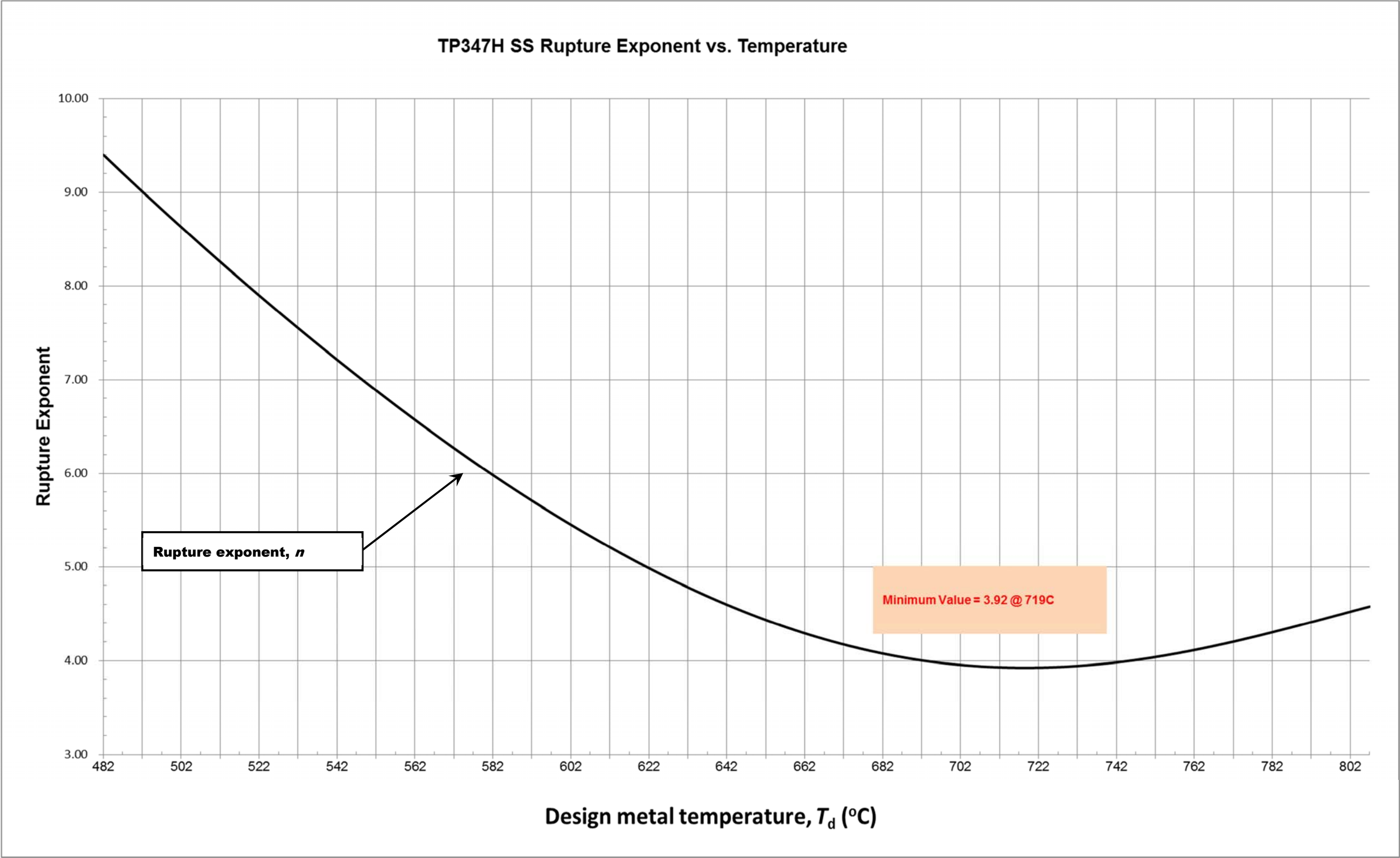


Figure E.53—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

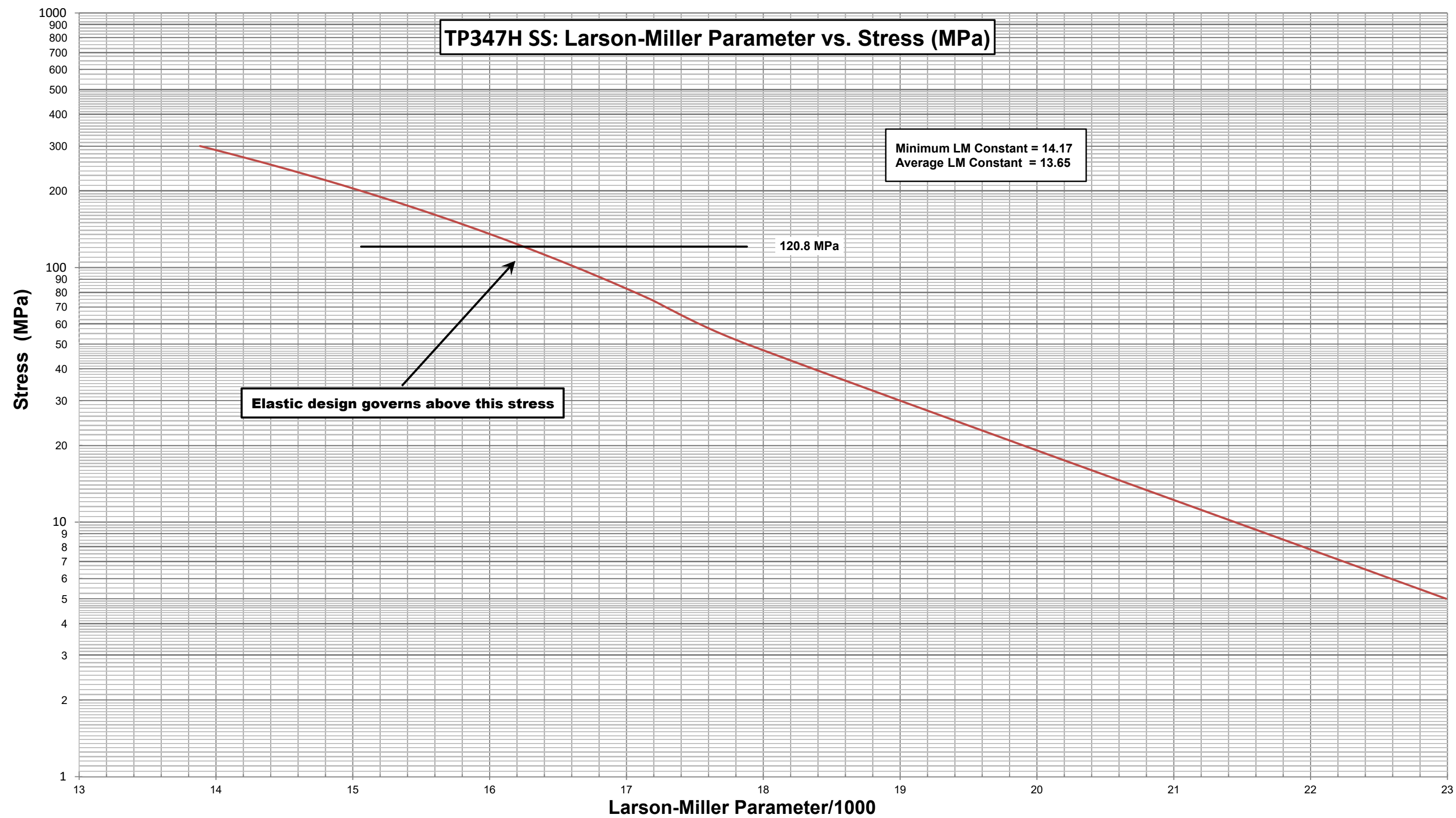


Figure E.54—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Table E.18—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

TP347H SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	127.1					
410	126.2					
420	125.4					
430	124.7					
440	124.0					
450	123.4					
460	122.8					
470	122.3					
480	121.9					
490	121.6					
500	121.3					9.1
510	121.0					8.7
520	120.9					8.3
530	120.8					8.0
540	120.7					7.6
550	120.7					7.3
560	120.7					6.9
570	120.8					6.6
580	120.9					6.3
590	121.0					6.0
600	121.1	137.3	149.0	158.6	175.9	5.8
610	121.1	125.8	137.0	146.3	163.1	5.5
620	121.2	114.8	125.6	134.6	150.8	5.3
630	121.1	104.5	114.8	123.4	139.0	5.0
640	121.0	94.8	104.6	112.9	127.8	4.8
650	120.9	85.8	95.0	102.9	117.2	4.6
660	120.6	77.3	86.0	93.5	107.1	4.5
670	120.1	69.5	77.7	84.7	97.6	4.3
680	119.5	62.3	69.9	76.5	88.7	4.2
690	118.7	55.7	62.8	68.9	80.3	4.1
700	117.7	49.8	56.2	61.9	72.6	4.0
710	116.4	44.4	50.3	55.5	65.4	4.0
720	114.9	39.6	44.9	49.6	58.8	3.9
730	113.1	35.3	40.1	44.4	52.7	3.9
740	110.9	31.5	35.8	39.7	47.3	4.0
750	108.4	28.2	32.0	35.5	42.3	4.1
760	105.5	25.3	28.7	31.8	37.9	4.2
770	102.3	22.7	25.7	28.5	34.0	4.3
780	98.7	20.5	23.1	25.6	30.5	4.4
790	94.8	18.5	20.9	23.0	27.4	4.5
800	90.4	16.8	18.9	20.8	24.7	4.6
810	85.8	15.3	17.1	18.8	22.3	4.7
816	82.9	14.0	15.6	17.1	20.2	
		12.8	14.3	15.6	18.3	
		11.8	13.1	14.3	16.7	
		10.8	12.0	13.1	15.2	
		10.3	11.4	12.4	14.4	

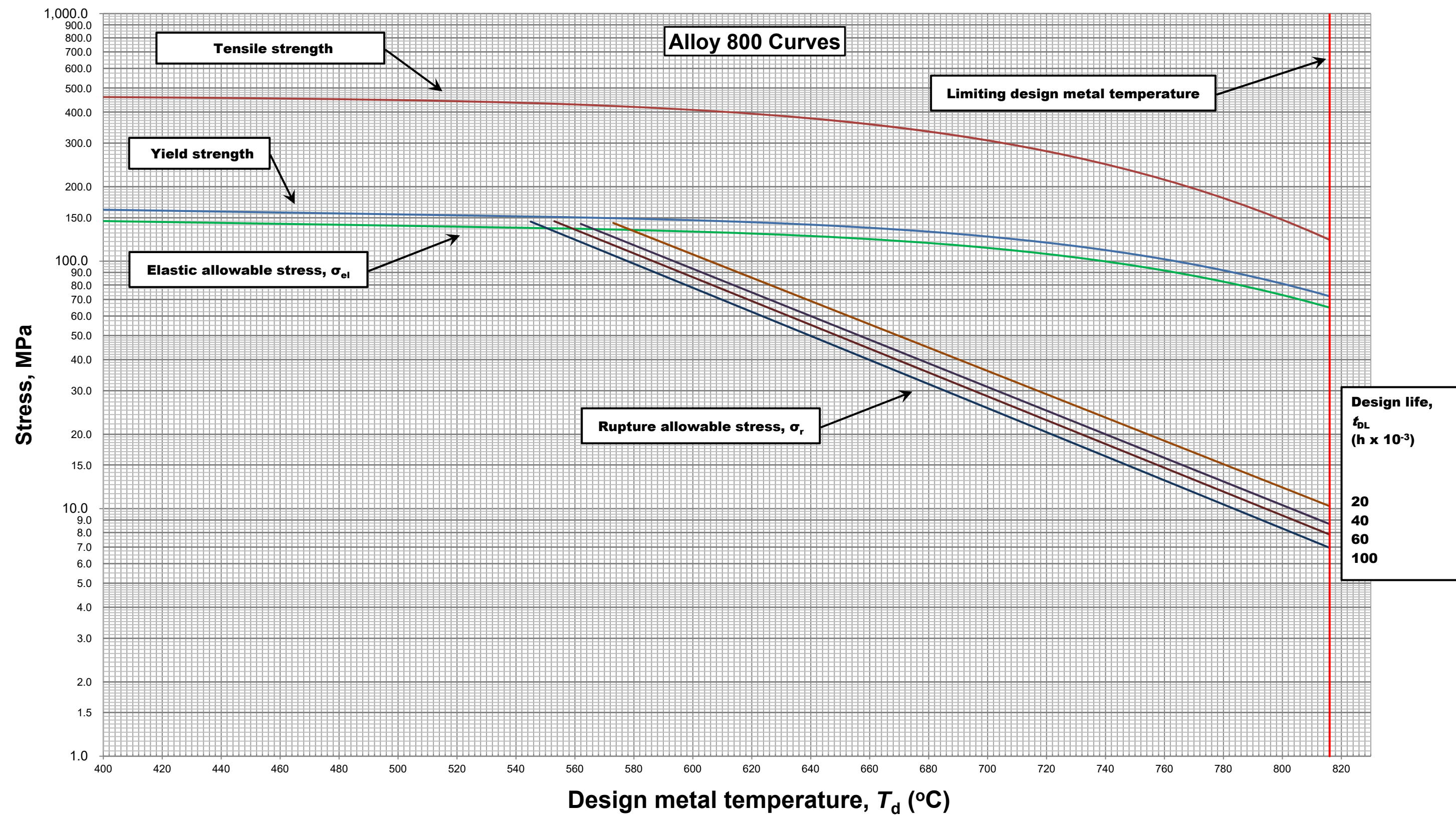


Figure E.55—Stress Curves (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

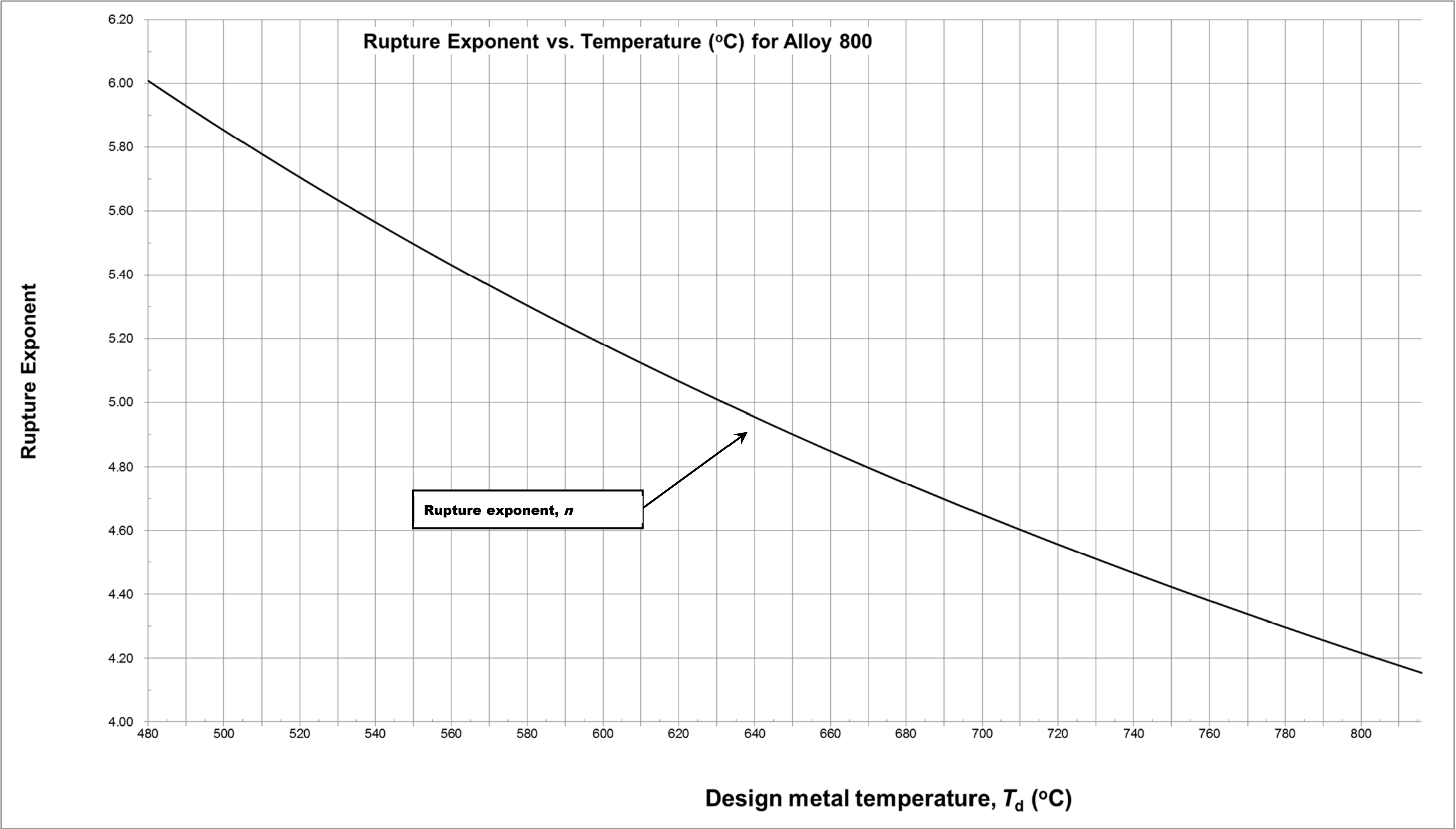


Figure E.56—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

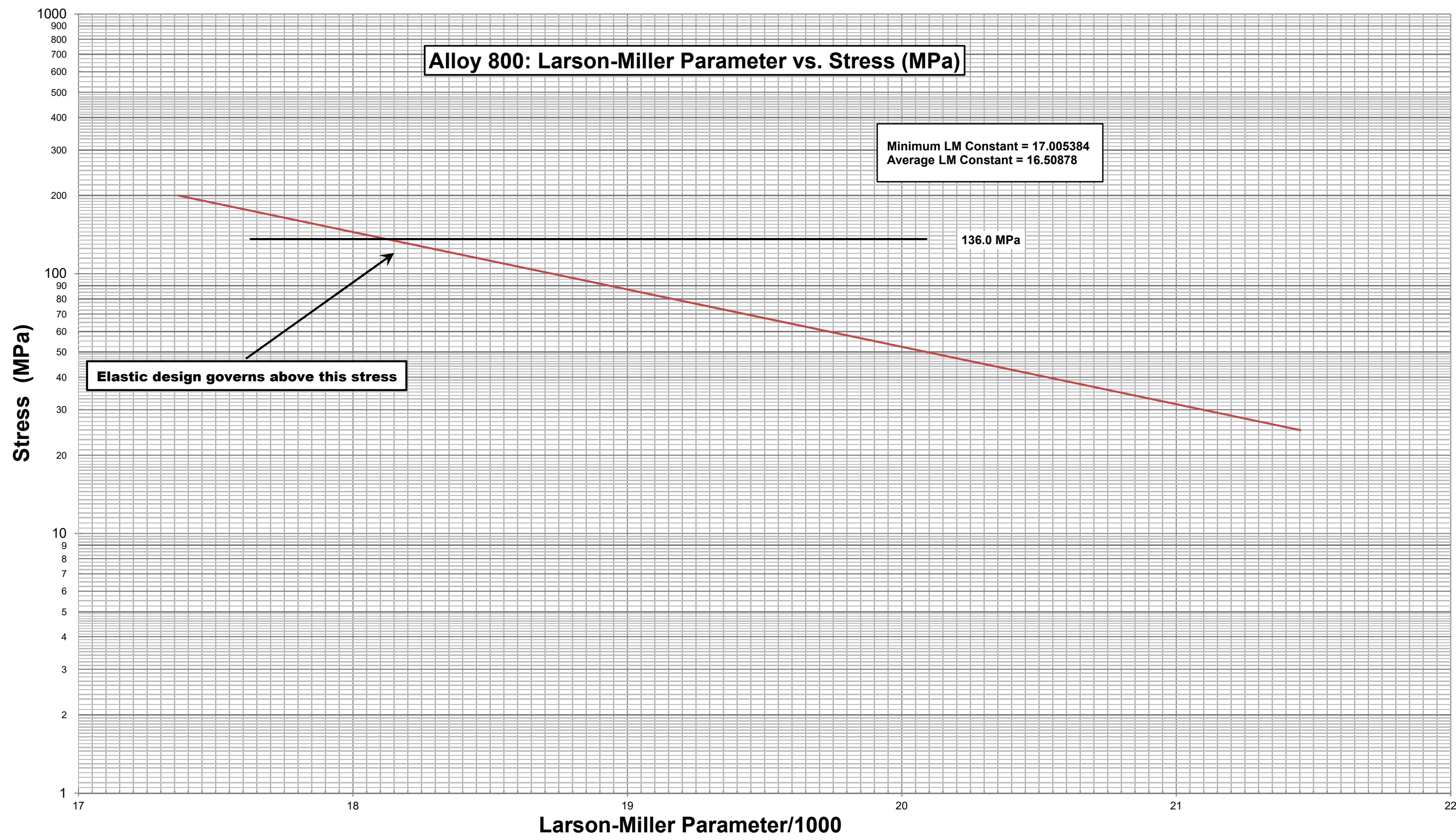


Figure E.57—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Table E.19—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Alloy 800						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	145.2					
410	144.6					
420	143.9					
430	143.3					
440	142.7					
450	142.1					
460	141.5					
470	140.9					
480	140.3					
490	139.7					
500	139.2					5.9
510	138.6					5.9
520	138.0					5.8
530	137.4					5.7
540	136.7					5.6
550	136.0					5.6
560	135.3	152.8	167.5	180.1	204.0	5.5
570	134.5	136.6	149.9	161.4	183.1	5.4
580	133.7	122.1	134.2	144.6	164.3	5.4
590	132.8	109.2	120.1	129.5	147.4	5.3
600	131.7	97.6	107.5	116.0	132.2	5.2
610	130.6	87.3	96.2	104.0	118.7	5.2
620	129.3	78.1	86.1	93.1	106.5	5.1
630	127.9	69.8	77.1	83.4	95.5	5.1
640	126.4	62.4	69.0	74.8	85.7	5.0
650	124.7	55.8	61.8	67.0	76.9	5.0
660	122.8	49.9	55.3	60.0	69.0	4.9
670	120.7	44.6	49.5	53.8	61.9	4.8
680	118.4	39.9	44.3	48.2	55.6	4.8
690	115.9	35.6	39.7	43.1	49.9	4.8
700	113.2	31.9	35.5	38.7	44.7	4.7
710	110.2	28.5	31.8	34.6	40.1	4.7
720	107.0	25.5	28.4	31.0	36.0	4.7
730	103.5	22.8	25.5	27.8	32.3	4.6
740	99.8	20.4	22.8	24.9	29.0	4.6
750	95.8	18.2	20.4	22.3	26.0	4.5
760	91.6	16.3	18.3	20.0	23.3	4.5
770	87.2	14.6	16.3	17.9	20.9	4.4
780	82.6	13.0	14.6	16.0	18.8	4.4
790	77.9	11.6	13.1	14.4	16.9	4.3
800	73.0	10.4	11.7	12.9	15.1	4.3
810	68.0	9.3	10.5	11.5	13.6	4.3
816	64.9	8.3	9.4	10.3	12.2	4.2
		7.4	8.4	9.3	10.9	4.2
		7.0	7.9	8.7	10.2	4.2

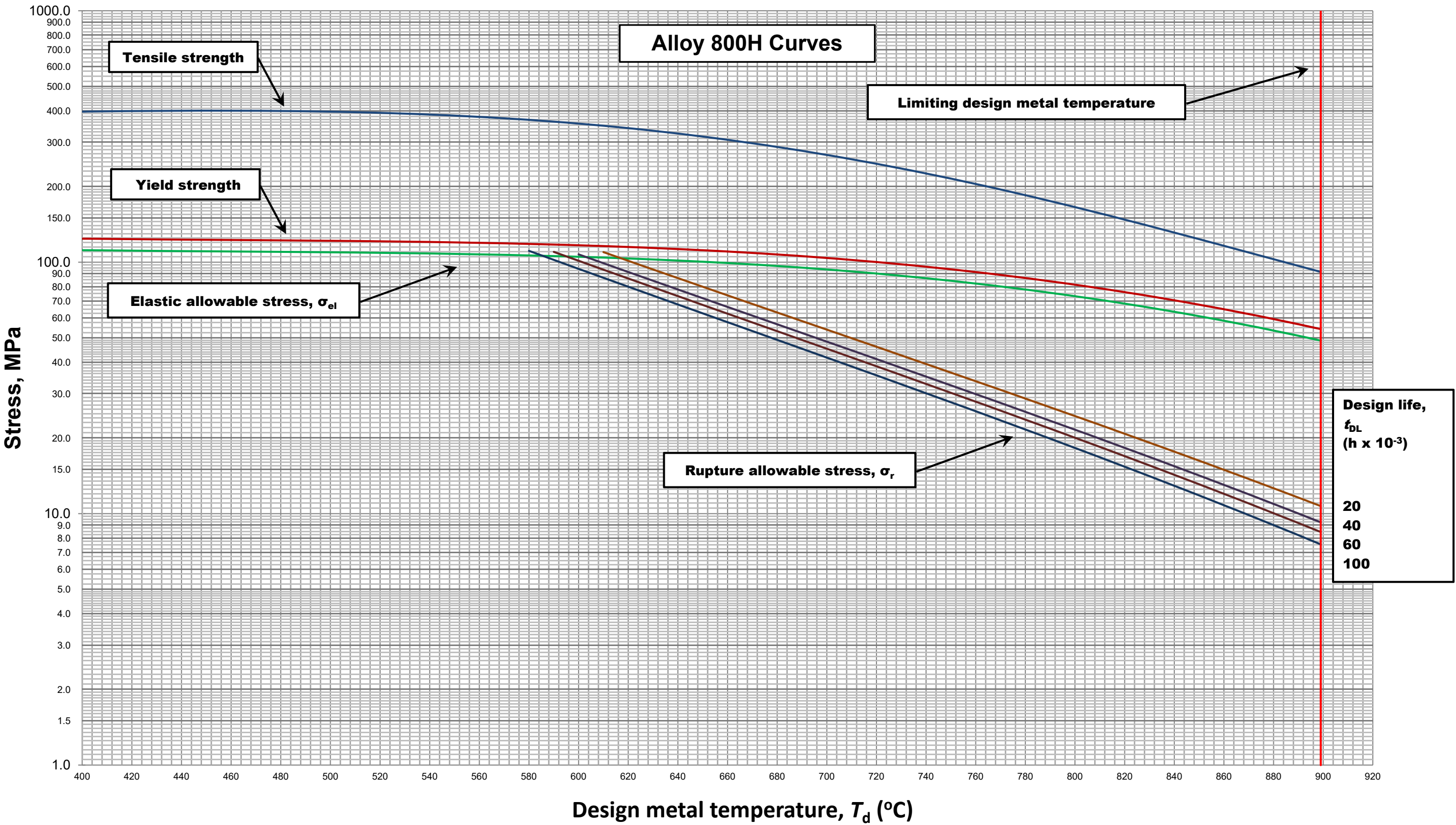


Figure E.58—Stress Curves (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

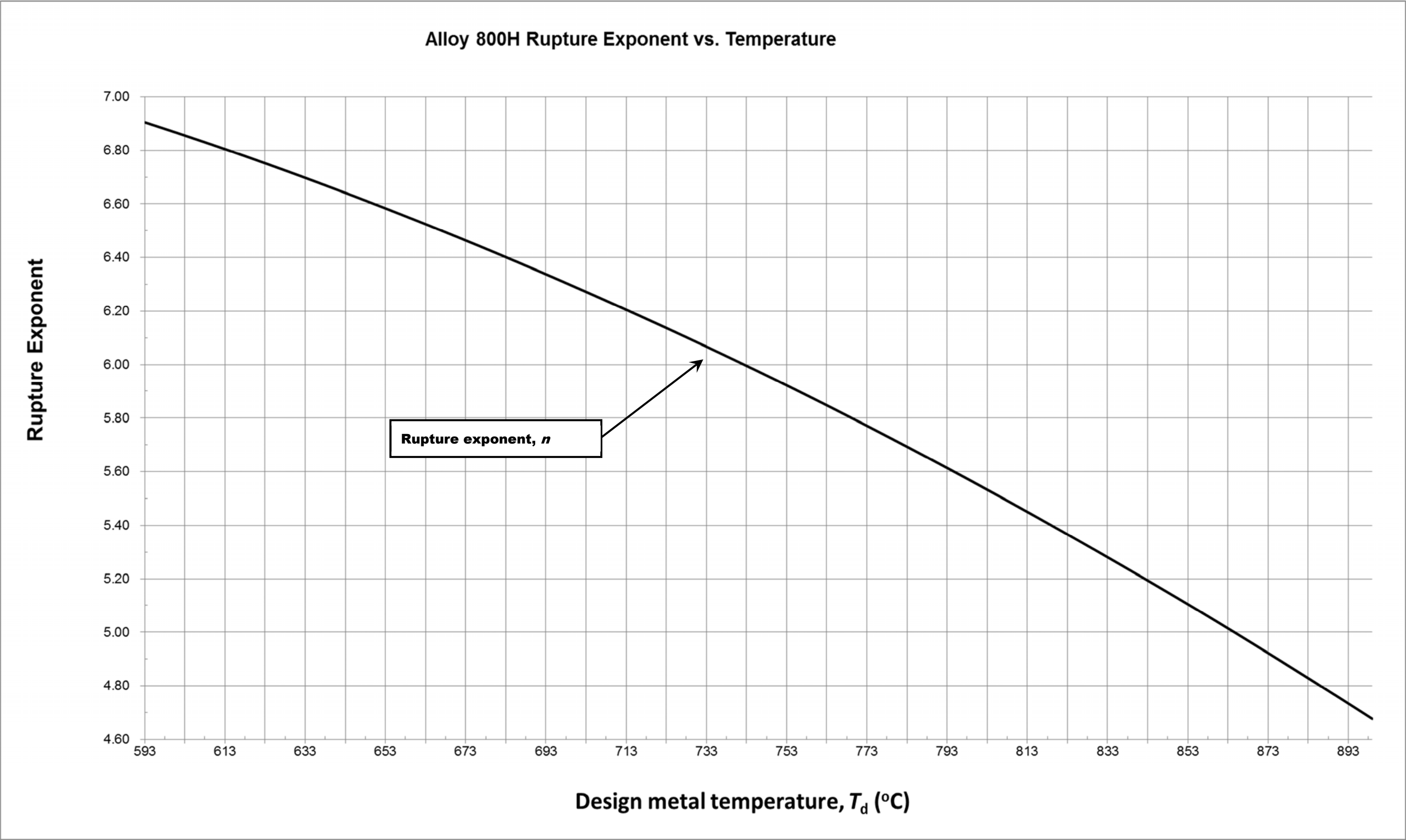


Figure E.59—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

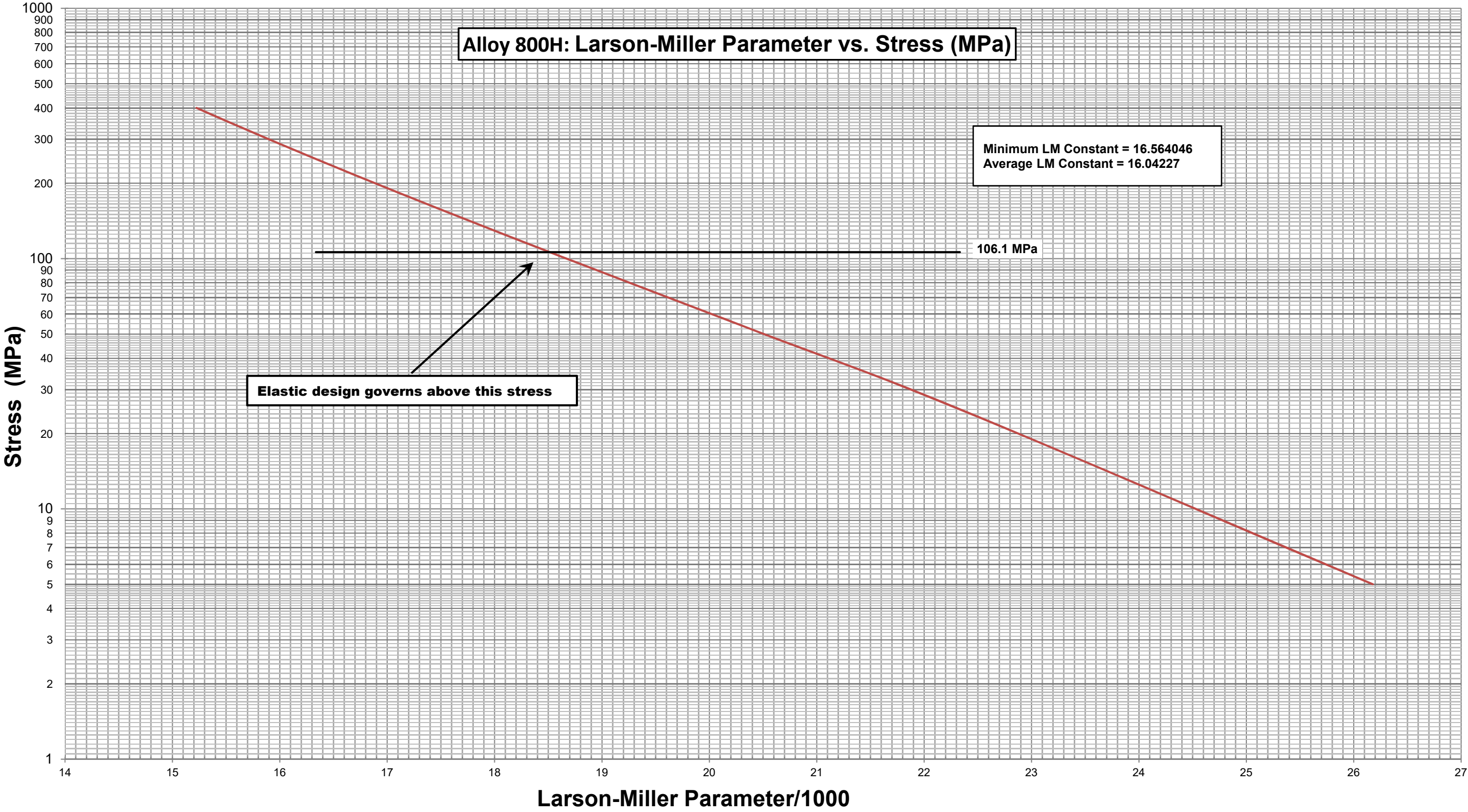


Figure E.60—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Table E.20—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Alloy 800H						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
500	109.5					
510	109.3					
520	109.0					
530	108.7					
540	108.3					
550	107.9					
560	107.5					
570	107.0					
580	106.4	120.5	129.5	137.2	151.4	
590	105.8	111.0	119.3	126.4	139.6	
600	105.1	102.2	109.9	116.5	128.8	
610	104.4	94.1	101.3	107.5	118.8	6.9
620	103.5	86.7	93.4	99.1	109.7	6.8
630	102.6	79.9	86.2	91.5	101.3	6.8
640	101.6	73.7	79.5	84.4	93.6	6.7
650	100.5	67.9	73.3	77.9	86.5	6.7
660	99.3	62.6	67.7	71.9	79.9	6.6
670	98.0	57.8	62.4	66.4	73.8	6.5
680	96.6	53.3	57.6	61.3	68.3	6.5
690	95.1	49.1	53.2	56.6	63.1	6.4
700	93.6	45.3	49.1	52.3	58.3	6.4
710	91.9	41.7	45.3	48.3	53.9	6.3
720	90.2	38.5	41.8	44.6	49.9	6.2
730	88.3	35.5	38.6	41.2	46.1	6.2
740	86.4	32.7	35.6	38.0	42.6	6.1
750	84.4	30.1	32.8	35.1	39.4	6.0
760	82.3	27.7	30.2	32.4	36.4	5.9
770	80.1	25.5	27.9	29.9	33.6	5.9
780	77.9	23.5	25.7	27.6	31.1	5.8
790	75.6	21.6	23.7	25.4	28.7	5.7
800	73.3	19.9	21.8	23.4	26.5	5.6
810	70.9	18.2	20.0	21.6	24.4	5.6
820	68.5	16.8	18.4	19.9	22.5	5.5
830	66.0	15.4	16.9	18.3	20.8	5.4
840	63.5	14.1	15.6	16.8	19.2	5.3
850	61.0	12.9	14.3	15.5	17.7	5.2
860	58.5	11.8	13.1	14.2	16.2	5.1
870	56.0	10.8	12.0	13.0	14.9	5.0
880	53.5	9.9	11.0	11.9	13.7	5.0
890	51.0	9.0	10.0	10.9	12.6	4.9
899	48.8	8.2	9.2	10.0	11.6	4.8
		7.5	8.5	9.2	10.7	4.7

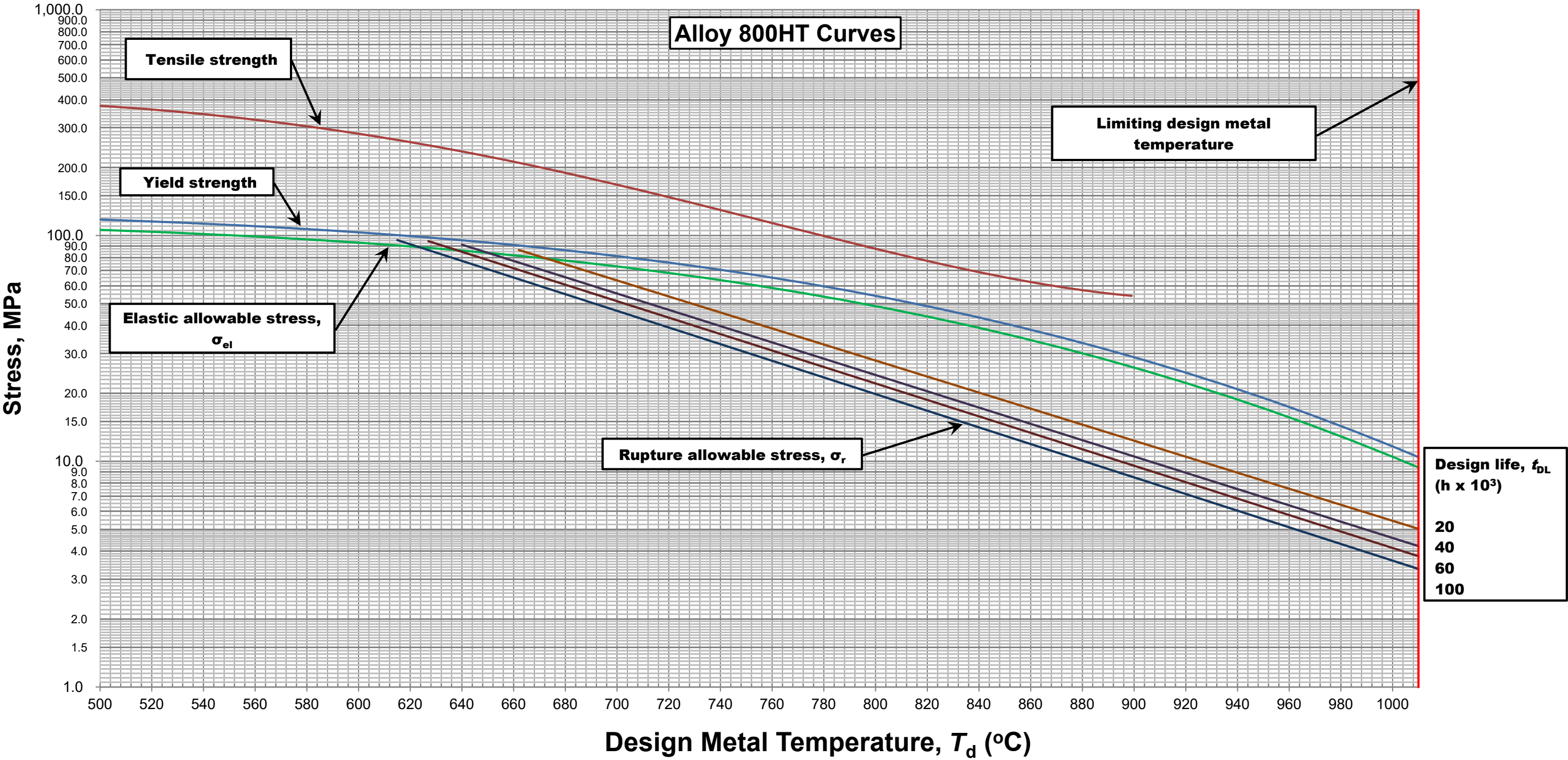


Figure E.61—Stress Curves (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

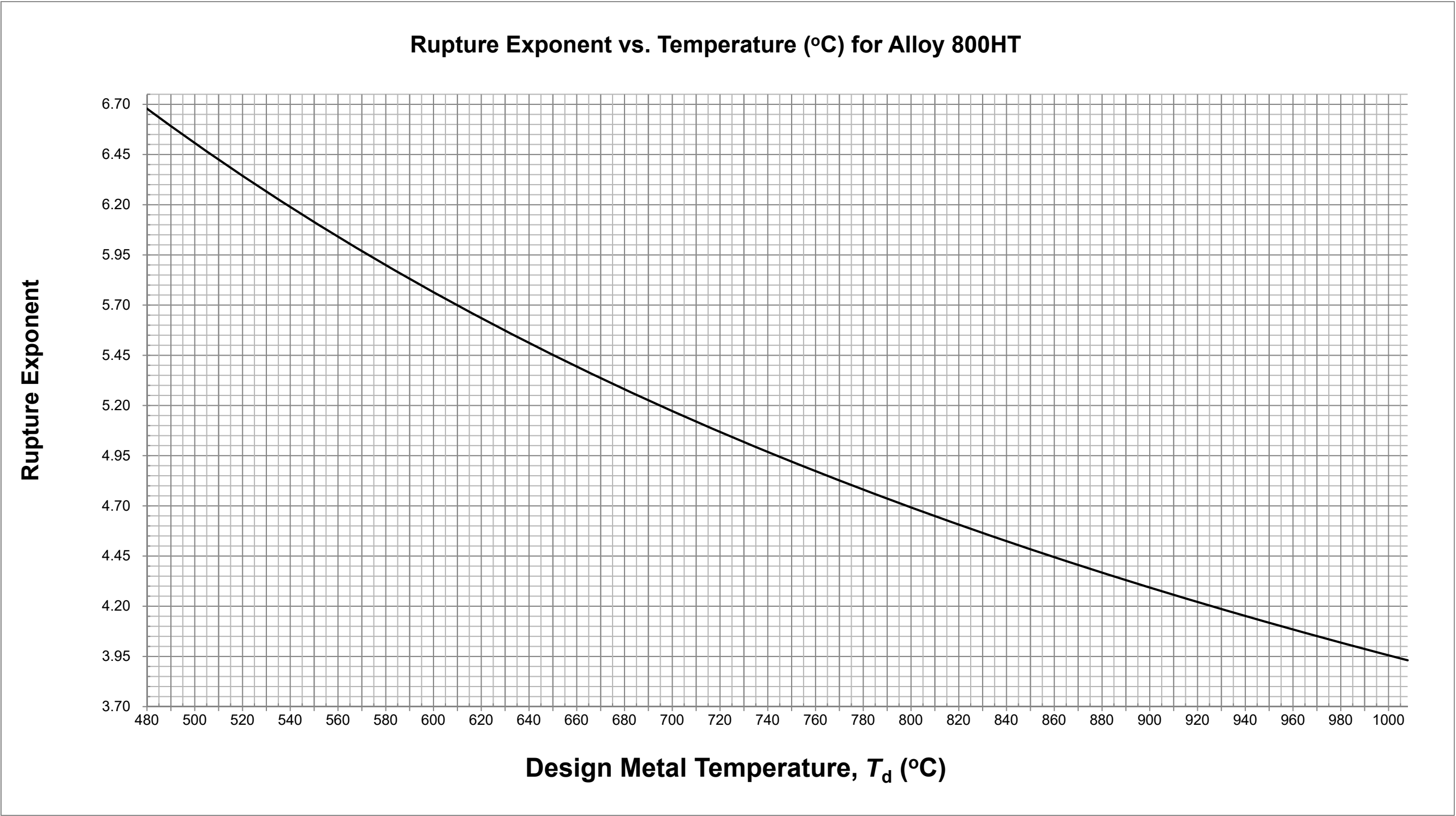


Figure E.62—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

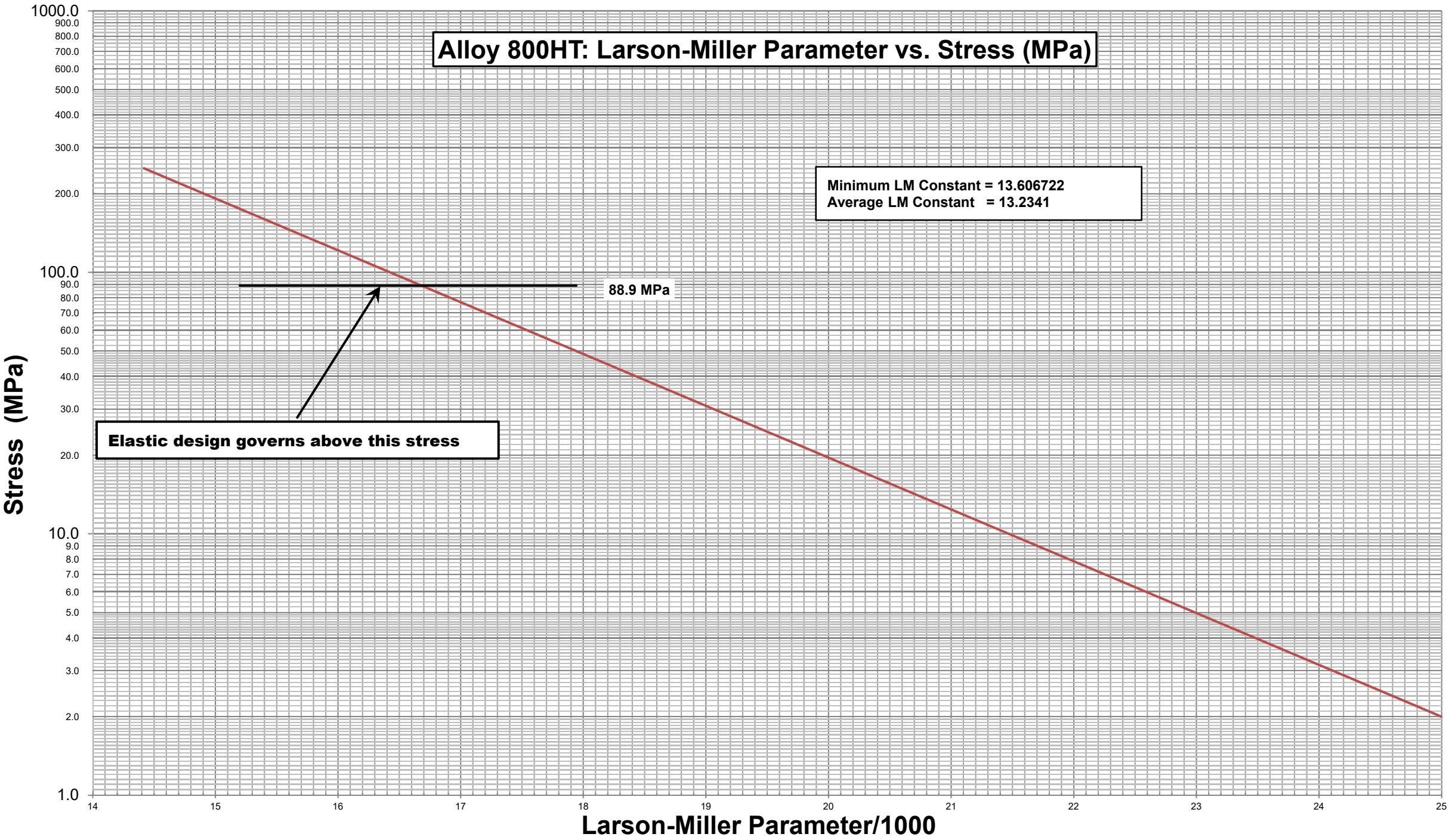


Figure E.63—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table E.21—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Alloy 800HT						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000$ h (MPa)	$t_{DL} = 60,000$ h (MPa)	$t_{DL} = 40,000$ h (MPa)	$t_{DL} = 20,000$ h (MPa)	
480	107.8					
490	107.0					6.6
500	106.0					6.5
510	105.0					6.4
520	104.0					6.4
530	102.9					6.3
540	101.7					6.2
550	100.4					6.1
560	99.1					6.1
570	97.7					6.0
580	96.2					5.9
590	94.6					5.8
600	93.0	108.5	118.5	127.1	143.3	5.8
610	91.3	99.6	109.0	117.0	132.1	5.7
620	89.6	91.5	100.2	107.7	121.7	5.6
630	87.7	84.1	92.1	99.1	112.2	5.6
640	85.8	77.2	84.7	91.2	103.4	5.5
650	83.8	70.9	77.9	83.9	95.2	5.5
660	81.8	65.2	71.6	77.2	87.8	5.4
670	79.7	59.9	65.9	71.1	80.9	5.3
680	77.5	55.0	60.6	65.4	74.5	5.3
690	75.3	50.5	55.7	60.2	68.7	5.2
700	73.0	46.4	51.2	55.4	63.3	5.2
710	70.7	42.6	47.1	51.0	58.3	5.1
720	68.3	39.2	43.3	46.9	53.7	5.1
730	65.9	36.0	39.8	43.2	49.5	5.0
740	63.5	33.0	36.6	39.7	45.6	5.0
750	61.1	30.3	33.7	36.5	42.1	4.9
760	58.6	27.9	31.0	33.6	38.8	4.9
770	56.1	25.6	28.5	31.0	35.7	4.8
780	53.6	23.5	26.2	28.5	32.9	4.8
790	51.1	21.6	24.1	26.2	30.3	4.7
800	48.7	19.8	22.1	24.1	28.0	4.7
810	46.2	18.2	20.3	22.2	25.8	4.7
820	43.8	16.7	18.7	20.4	23.7	4.6
830	41.4	15.4	17.2	18.8	21.9	4.6
840	39.0	14.1	15.8	17.3	20.2	4.5
850	36.7	13.0	14.5	15.9	18.6	4.5
860	34.5	11.9	13.4	14.7	17.1	4.5
870	32.3	11.0	12.3	13.5	15.8	4.4
880	30.1	10.1	11.3	12.4	14.5	4.4
890	28.0	9.2	10.4	11.4	13.4	4.3
900	26.0	8.5	9.6	10.5	12.3	4.3
910	24.1	7.8	8.8	9.7	11.4	4.3
920	22.2	7.2	8.1	8.9	10.5	4.2
930	20.5	6.6	7.4	8.2	9.7	4.2
940	18.8	6.0	6.8	7.5	8.9	4.2
950	17.2	5.6	6.3	6.9	8.2	4.1
960	15.7	5.1	5.8	6.4	7.6	4.1
970	14.2	4.7	5.3	5.9	7.0	4.1
980	12.9	4.3	4.9	5.4	6.4	4.0
990	11.6	4.0	4.5	5.0	5.9	4.0
1000	10.5	3.6	4.1	4.6	5.5	4.0
1010	9.4	3.3	3.8	4.2	5.0	3.9

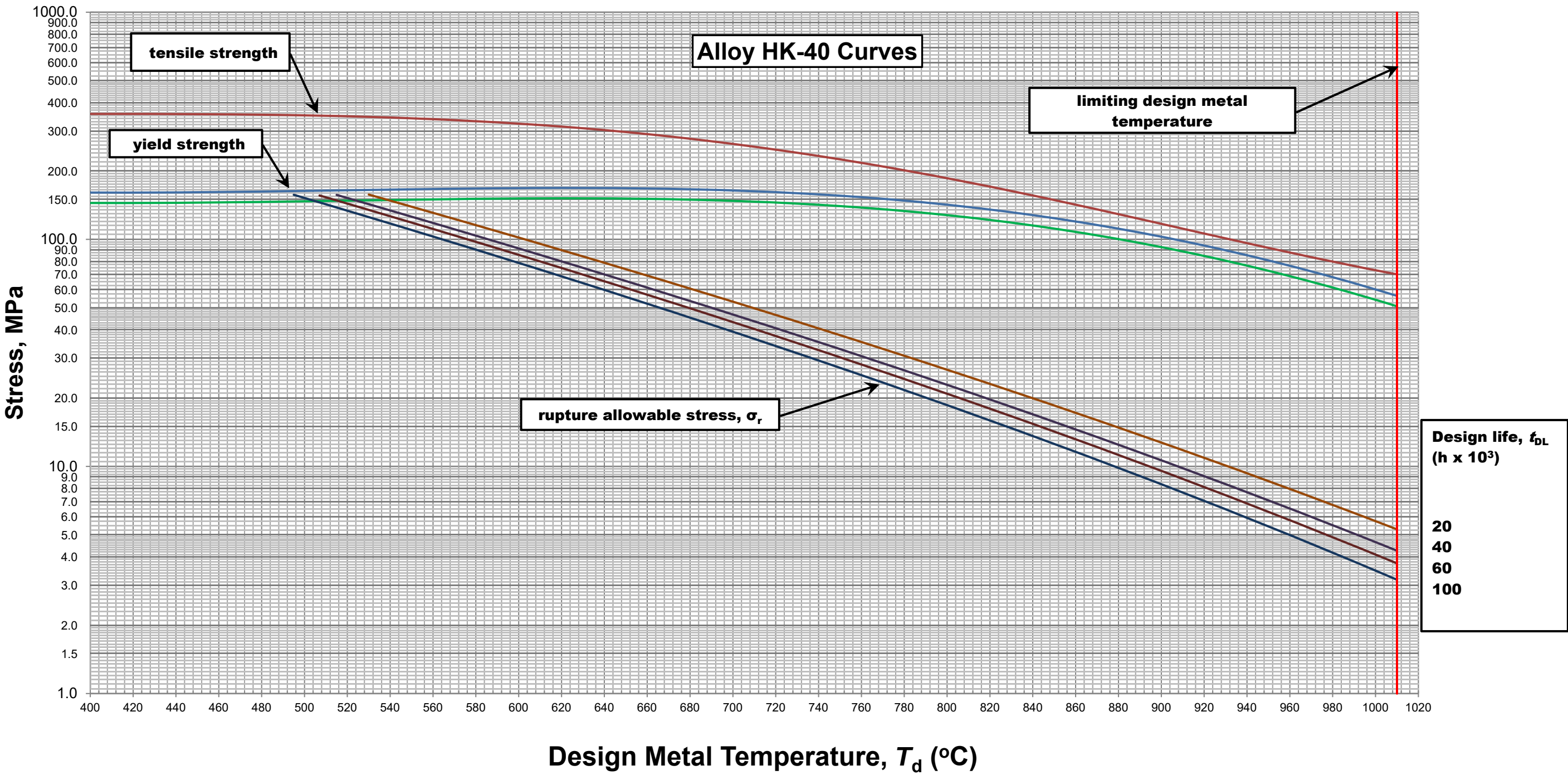


Figure E.64—Stress Curves (SI Units) for ASTM A608 Grade HK-40 Steels

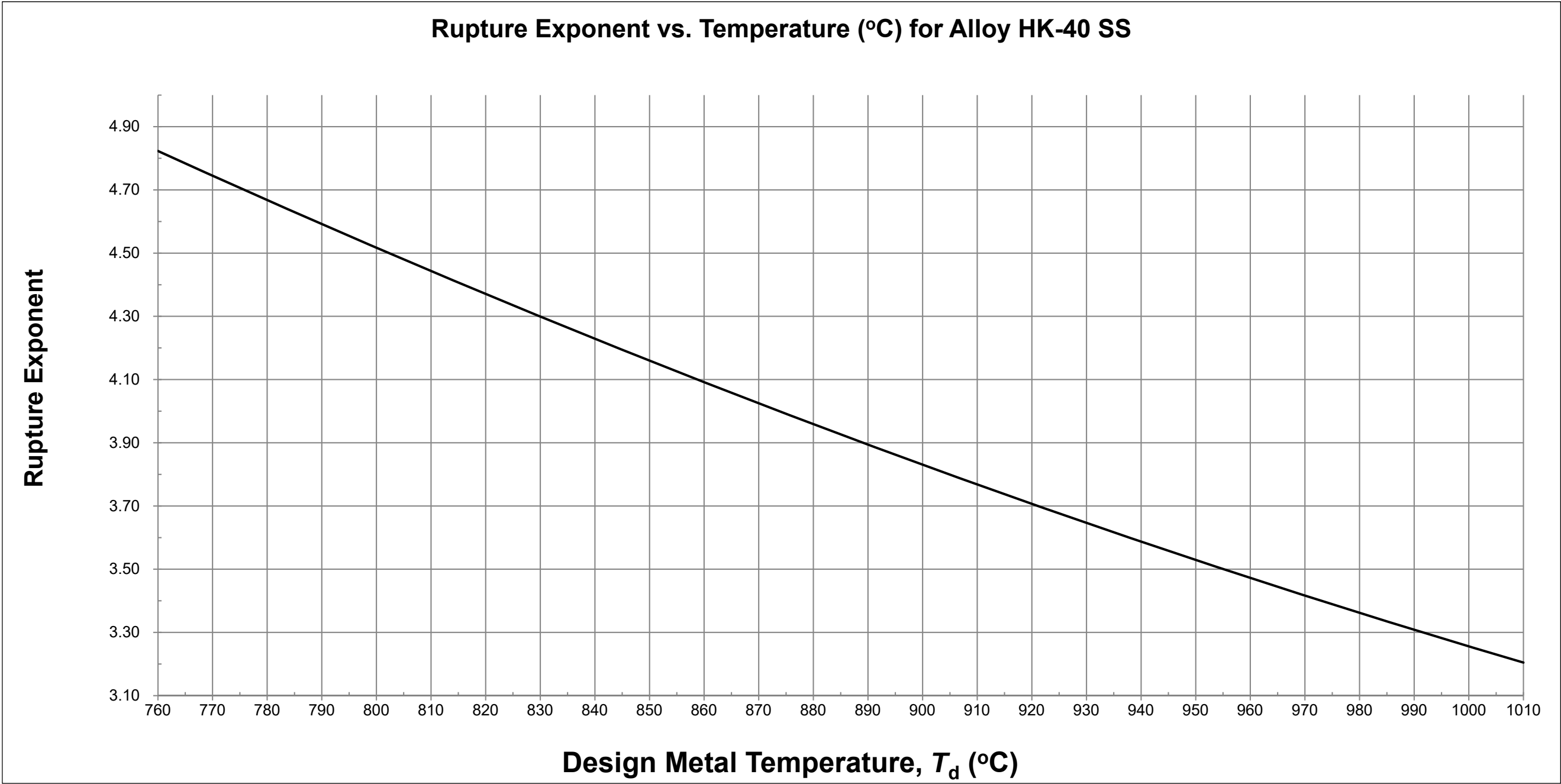


Figure E.65—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A608 Grade HK-40 Steels

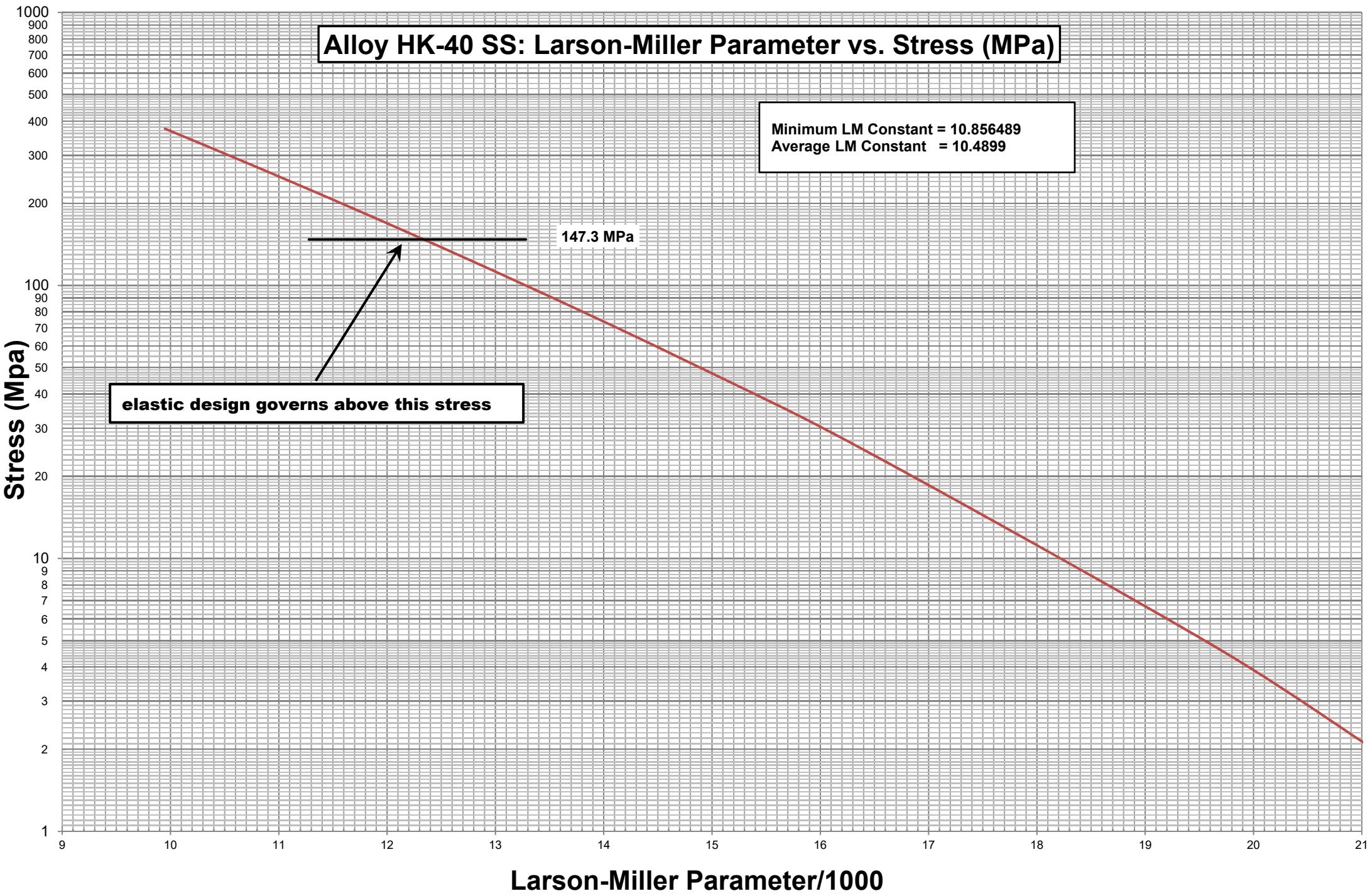


Figure E.66—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A608 Grade HK-40 Steels

Table E.22—Elastic, Rupture Allowable Stresses and Rupture Exponent (SI Units) for ASTM A608 Grade HK-40 Steels

Alloy HK-40						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
480	146.2					
490	146.6	162.2	173.6	183.2	200.7	
500	147.1	152.2	163.1	172.2	189.0	
510	147.6	142.7	153.1	161.9	177.9	
520	148.1	133.8	143.7	152.1	167.5	
530	148.6	125.4	134.9	142.9	157.5	
540	149.1	117.4	126.5	134.1	148.2	
550	149.6	110.0	118.6	125.9	139.3	
560	150.0	102.9	111.2	118.1	131.0	
570	150.4	96.3	104.2	110.8	123.1	
580	150.8	90.1	97.6	103.9	115.6	
590	151.1	84.3	91.4	97.4	108.6	
600	151.4	78.8	85.5	91.3	101.9	
610	151.5	73.6	80.0	85.5	95.7	
620	151.6	68.7	74.9	80.1	89.7	
630	151.6	64.2	70.0	74.9	84.2	
640	151.5	59.9	65.4	70.1	78.9	
650	151.2	55.9	61.1	65.6	73.9	
660	150.8	52.1	57.1	61.3	69.3	
670	150.3	48.6	53.3	57.3	64.9	
680	149.6	45.2	49.7	53.5	60.7	
690	148.8	42.1	46.4	50.0	56.8	
700	147.8	39.2	43.2	46.7	53.2	
710	146.6	36.5	40.3	43.6	49.7	
720	145.3	33.9	37.5	40.6	46.5	
730	143.8	31.5	34.9	37.9	43.4	
740	142.0	29.3	32.5	35.3	40.5	
750	140.1	27.2	30.2	32.9	37.8	
760	138.1	25.2	28.1	30.6	35.3	4.8
770	135.8	23.4	26.1	28.5	32.9	4.7
780	133.3	21.7	24.3	26.5	30.7	4.7
790	130.7	20.1	22.5	24.6	28.6	4.6
800	127.9	18.6	20.9	22.9	26.7	4.5
810	124.9	17.2	19.4	21.2	24.8	4.4
820	121.8	15.9	18.0	19.7	23.1	4.4
830	118.5	14.7	16.6	18.3	21.5	4.3
840	115.1	13.6	15.4	17.0	20.0	4.2
850	111.5	12.6	14.2	15.7	18.6	4.2
860	107.9	11.6	13.2	14.6	17.2	4.1
870	104.1	10.7	12.2	13.5	16.0	4.0
880	100.3	9.9	11.2	12.5	14.8	4.0
890	96.4	9.1	10.4	11.5	13.8	3.9
900	92.5	8.4	9.6	10.6	12.7	3.8
910	88.5	7.7	8.8	9.8	11.8	3.8
920	84.6	7.1	8.1	9.1	10.9	3.7
930	80.6	6.5	7.5	8.4	10.1	3.6
940	76.6	5.9	6.9	7.7	9.3	3.6
950	72.7	5.4	6.3	7.1	8.6	3.5
960	68.9	5.0	5.8	6.5	8.0	3.5
970	65.1	4.6	5.3	6.0	7.3	3.4
980	61.3	4.2	4.9	5.5	6.8	3.4
990	57.7	3.8	4.5	5.1	6.2	3.3
1000	54.2	3.5	4.1	4.6	5.7	3.3
1010	50.7	3.2	3.7	4.3	5.3	3.2

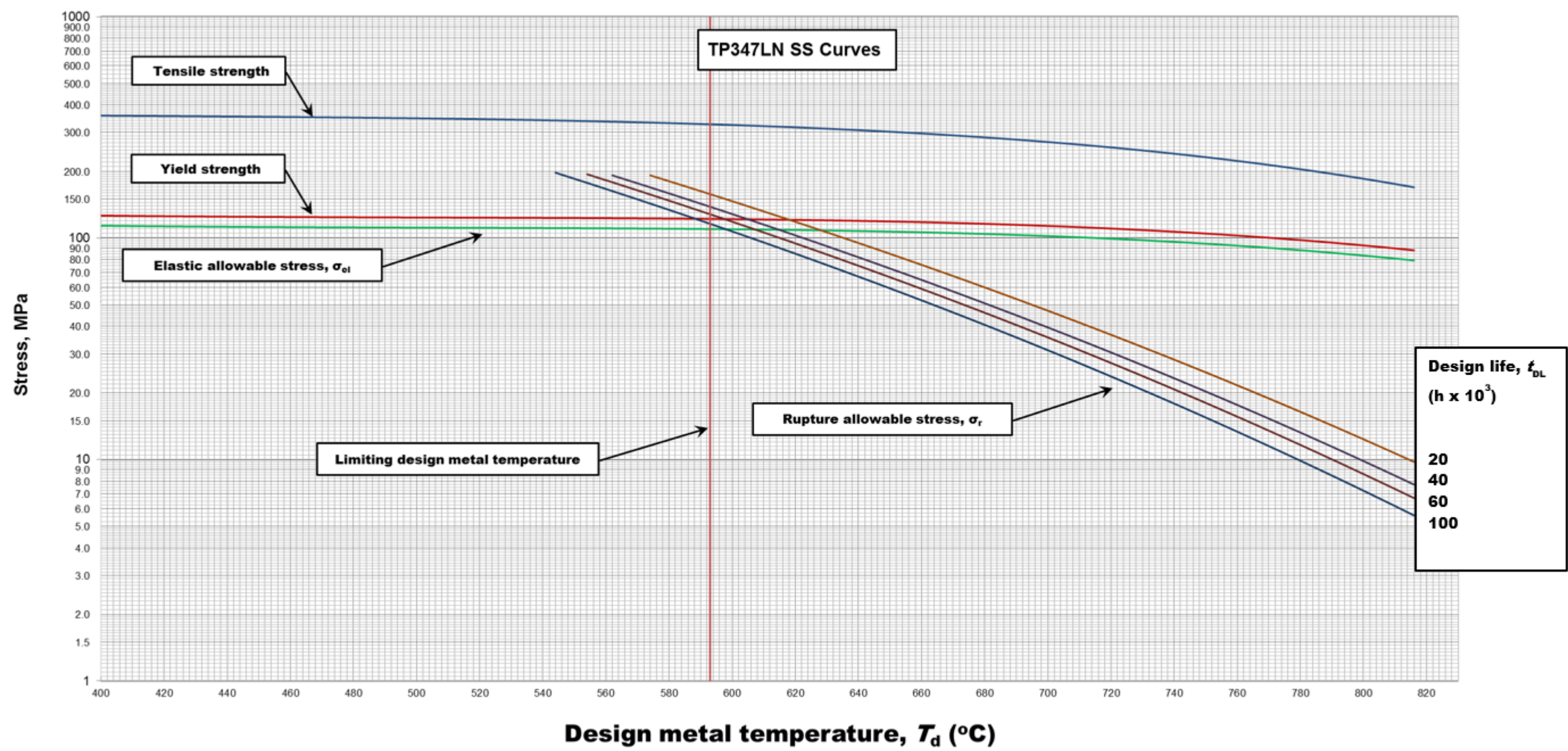


Figure E.67—Stress Curves (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

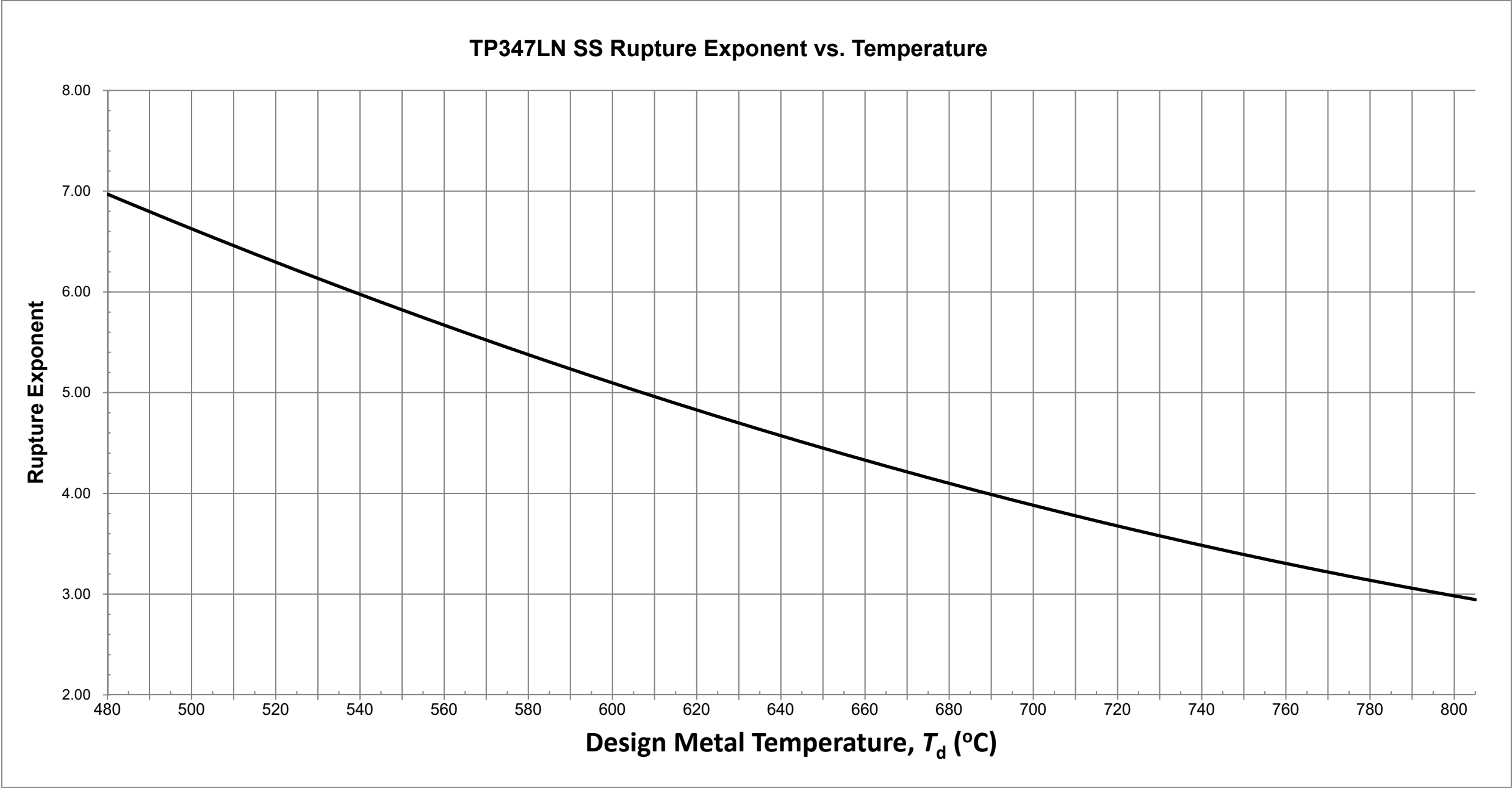


Figure E.68—Rupture Exponent vs. Temperature Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

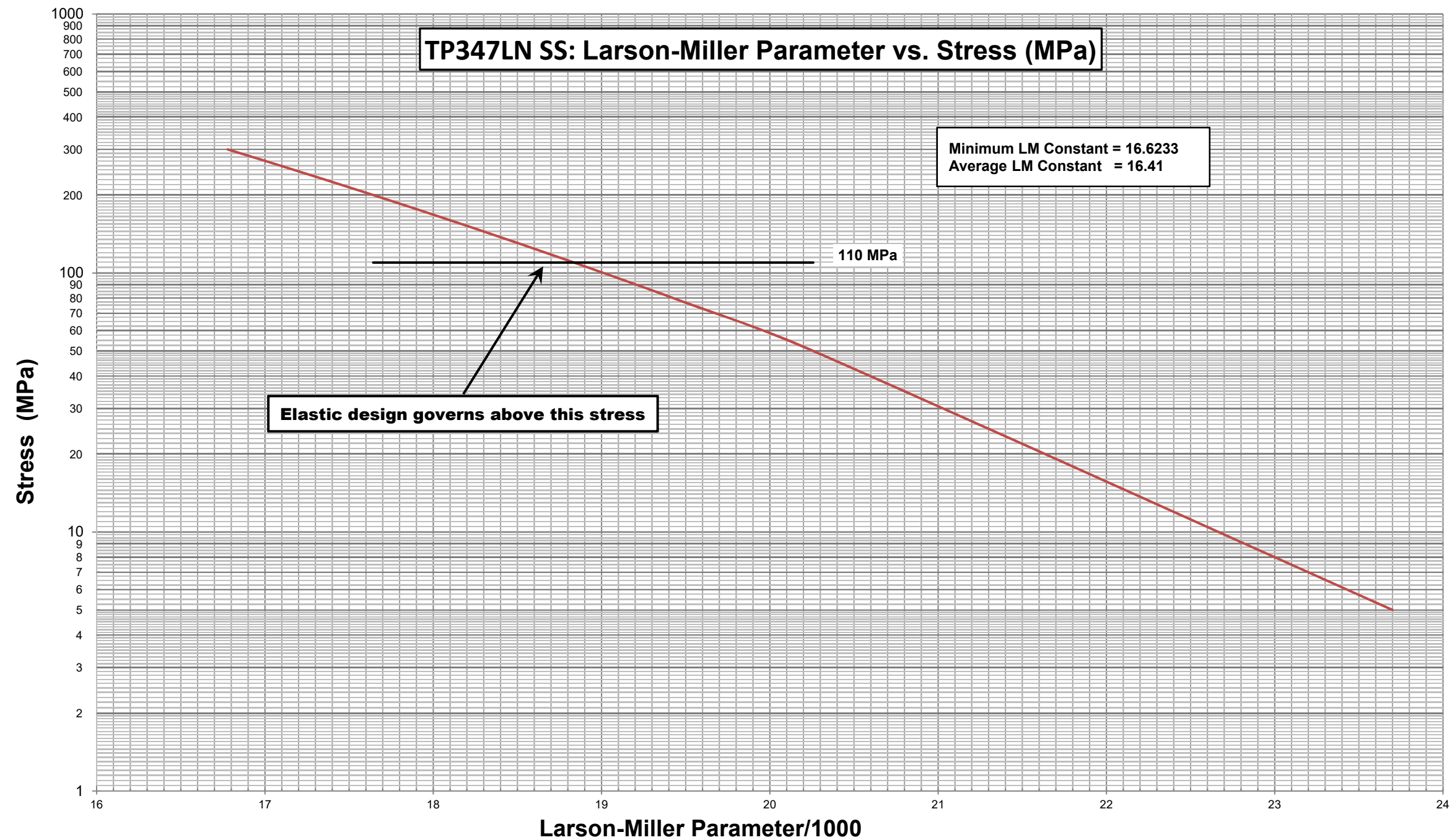


Figure E.69—Larson-Miller Parameter vs. Stress Curve (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table E.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (SI Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

TP347LN SS						
Design Metal Temperature, T_d (Centigrade)	Elastic Allowable Stress, σ_{el} (MPa)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (MPa)	$t_{DL} = 60,000\text{ h}$ (MPa)	$t_{DL} = 40,000\text{ h}$ (MPa)	$t_{DL} = 20,000\text{ h}$ (MPa)	
400	113.8					
410	113.4					
420	113.1					
430	112.8					
440	112.5					
450	112.3					
460	112.1					
470	111.9					
480	111.8					
490	111.7					6.8
500	111.5					6.7
510	111.4					6.5
520	111.3					6.3
530	111.2					6.2
540	111.1	205.9	224.4	240.2	269.2	6.0
550	110.9	185.4	202.6	217.2	244.2	5.9
560	110.7	166.8	182.6	196.1	221.2	5.7
570	110.5	149.7	164.4	176.9	200.1	5.6
580	110.3	134.2	147.7	159.2	180.8	5.4
590	110.0	120.1	132.5	143.1	163.0	5.3
600	109.7	107.2	118.7	128.5	146.8	5.1
610	109.3	95.6	106.1	115.1	132.1	5.0
620	108.9	85.1	94.7	103.0	118.6	4.9
630	108.3	75.6	84.4	92.0	106.3	4.7
640	107.7	67.0	75.0	82.0	95.1	4.6
650	107.1	59.3	66.6	72.9	85.0	4.5
660	106.3	52.4	59.0	64.8	75.8	4.4
670	105.4	46.2	52.2	57.4	67.4	4.2
680	104.5	40.6	46.0	50.8	59.9	4.1
690	103.4	35.6	40.5	44.8	53.1	4.0
700	102.2	31.2	35.6	39.5	47.0	3.9
710	100.9	27.2	31.2	34.7	41.5	3.8
720	99.5	23.7	27.3	30.5	36.6	3.7
730	97.9	20.6	23.8	26.7	32.2	3.6
740	96.2	17.9	20.8	23.3	28.3	3.5
750	94.4	15.5	18.0	20.3	24.8	3.4
760	92.5	13.4	15.6	17.7	21.7	3.3
770	90.4	11.5	13.5	15.3	18.9	3.2
780	88.2	9.9	11.7	13.2	16.4	3.2
790	85.9	8.5	10.0	11.4	14.3	3.1
800	83.5	7.2	8.6	9.8	12.4	3.0
810	80.9	6.2	7.4	8.5	10.7	2.9
816	79.3	5.6	6.7	7.7	9.8	2.9

Annex F
(normative)

Stress Curves and Data Tables (USC Units)

Stress curves and data table (in USC units) are presented in Figures F.1 to F.66 and Tables F.1 to F.22.

List of Figures and Tables (USC Units)

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- Figure F.2—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A192 Low-carbon Steels
- Figure F.3—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A192 Low-carbon Steels
- Table F.1—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A192 Low-carbon Steels

Medium Carbon Steels

- Figure F.4—Stress Curves (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
- Figure F.5—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
- Figure F.6—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels
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- Figure F.8—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels
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1-1/4Cr-1/2Moly Steels

- Figure F.10—Stress Curves (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels
- Figure F.11—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels
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- Table F.5—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

3Cr-1Moly Steels

Figure F.16—Stress Curves (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Figure F.17—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Figure F.18—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Table F.6—Elastic and Rupture Allowable Stresses (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

5Cr-1/2Moly Steels

Figure F.19—Stress Curves (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Figure F.20—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Figure F.21—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Table F.7—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

5Cr-1/2Moly-Si Steels

Figure F.22—Stress Curves (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Figure F.23—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Figure F.24—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Table F.8—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

9Cr-1Moly Steels

Figure F.25—Stress Curves (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Figure F.26—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Figure F.27—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Table F.9—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

9Cr-1Moly-V Steels

Figure F.28—Stress Curves (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Figure F.29—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Figure F.30—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Table F.10—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

TP 304-304H Stainless Steels

Figure F.31—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Figure F.32—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Figure F.33—Larson-Miller Parameter vs. Stress Curve (USC Units) for A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Table F.11—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

TP 304L Stainless Steels

Figure F.34—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Figure F.35—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Figure F.36—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Table F.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

TP 316-316H Stainless Steels

Figure F.37—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Figure F.38—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Figure F.39—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Table F.13—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

TP 316L—317L Stainless Steels

Figure F.40—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

Figure F.41—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Figure F.42—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table F.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

TP 321 Stainless Steels

Figure F.43—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Figure F.44—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Figure F.45—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Table F.15—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

TP 321H Stainless Steels

Figure F.46—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Figure F.47—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Figure F.48—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Table F.16—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

TP 347 Stainless Steels

Figure F.49—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Figure F.50—Rupture Exponent vs. Temperature Surve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Figure F.51—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Table F.17—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

TP 347H Stainless Steels

Figure F.52—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Figure F.53—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Figure F.54—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Table F.18—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Alloy 800 Steels

Figure F.55—Stress Curves (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Figure F.56—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Figure F.57—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Table F.19—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Alloy 800H Steels

Figure F.58—Stress Curves (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Figure F.59—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Figure F.60—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Table F.20—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Alloy 800HT Steels

Figure F.61—Stress Curves (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Figure F.62—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Figure F.63—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table F.21—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Alloy HK-40 Steels

Figure F.64—Stress Curves (USC Units) for ASTM A608 Grade HK-40 Steels

Figure F.65—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A608 Grade HK-40 Steels

Figure F.66—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A608 Grade HK-40 Steels

Table F.22—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A608 Grade HK-40 Steels

TP 347LN Stainless Steels

Figure F.67—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.68—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Figure F.69—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table F.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

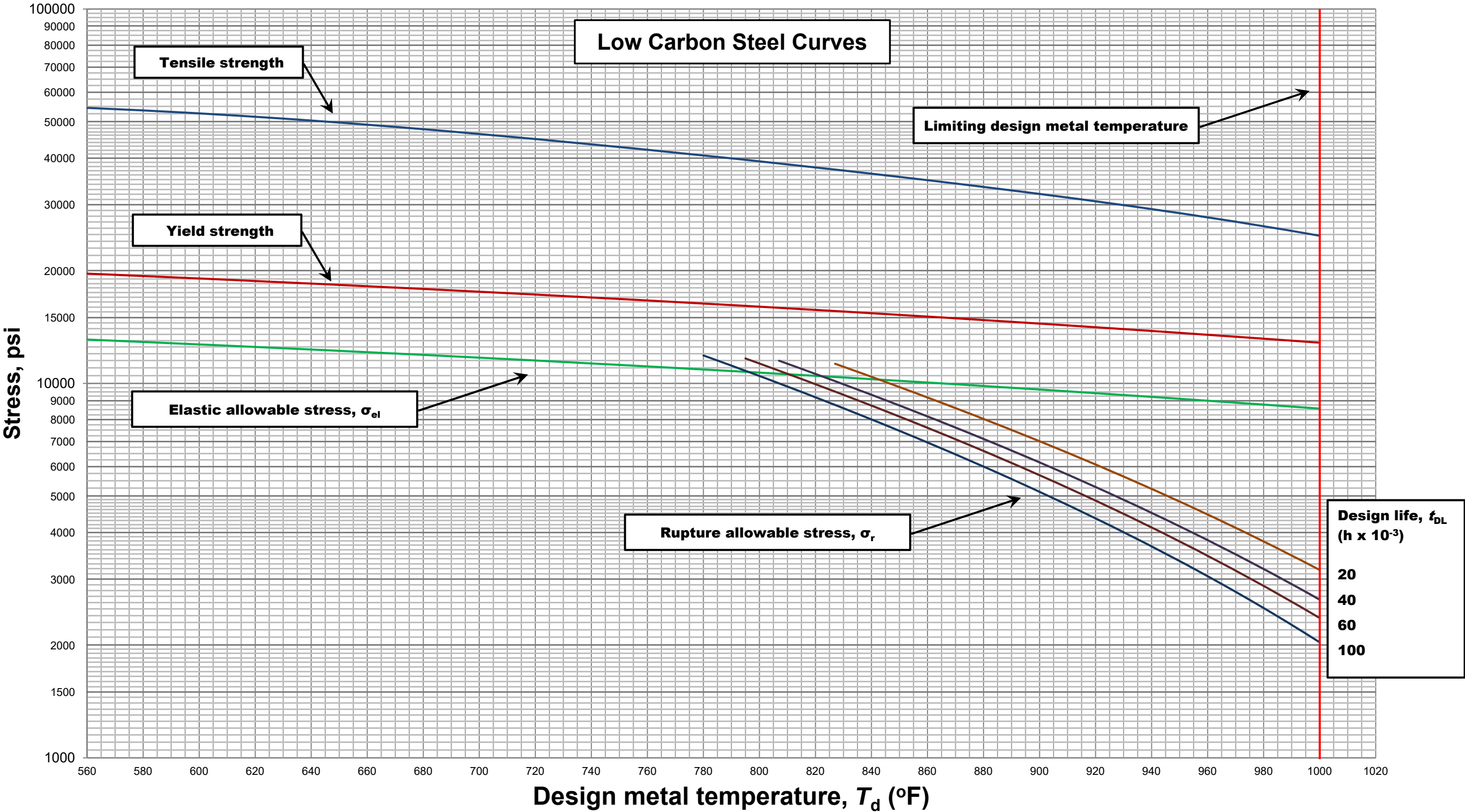


Figure F.1—Stress Curves (USC Units) for ASTM A192 Low-carbon Steels

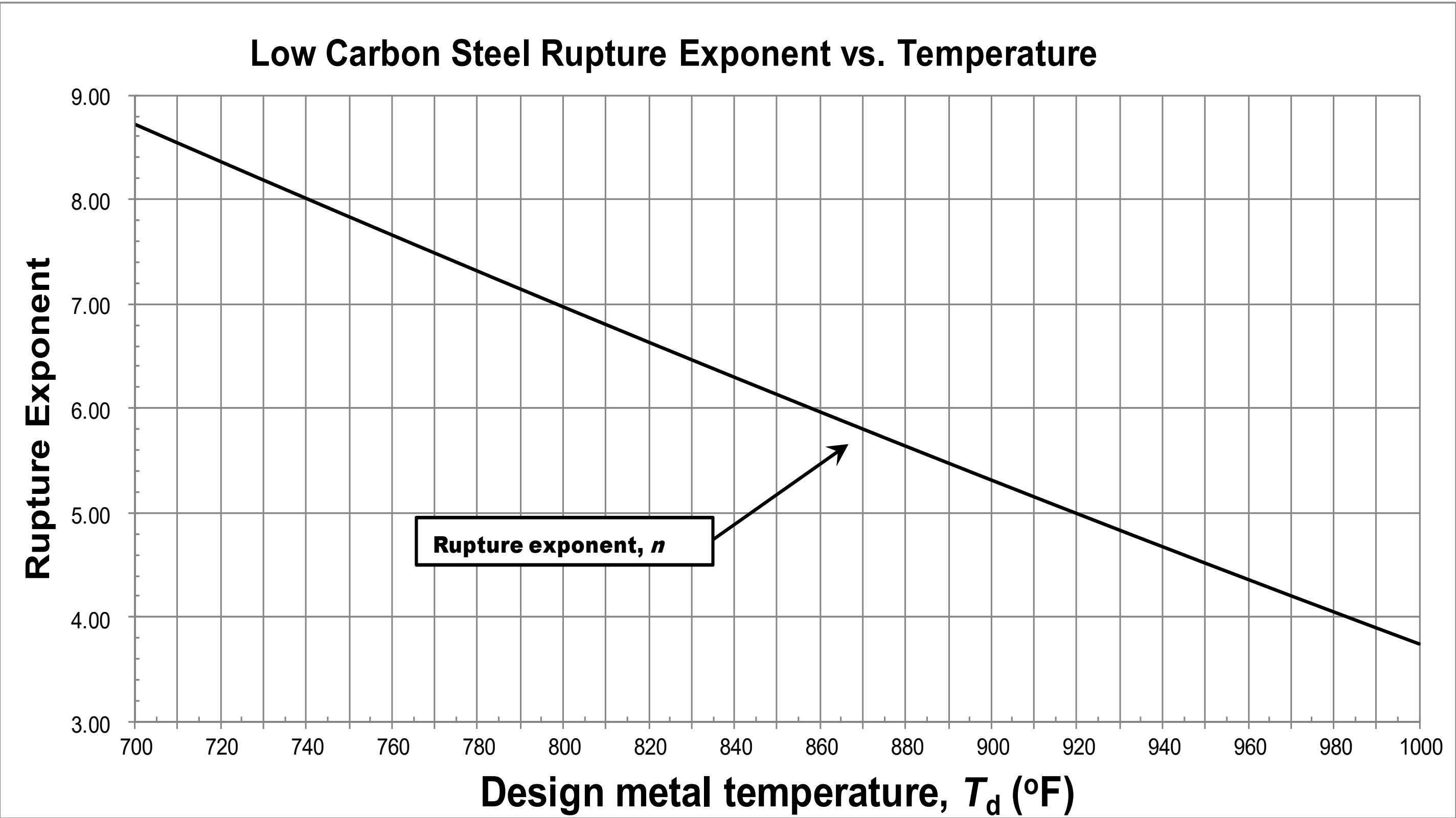


Figure F.2—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A192 Low-carbon Steels

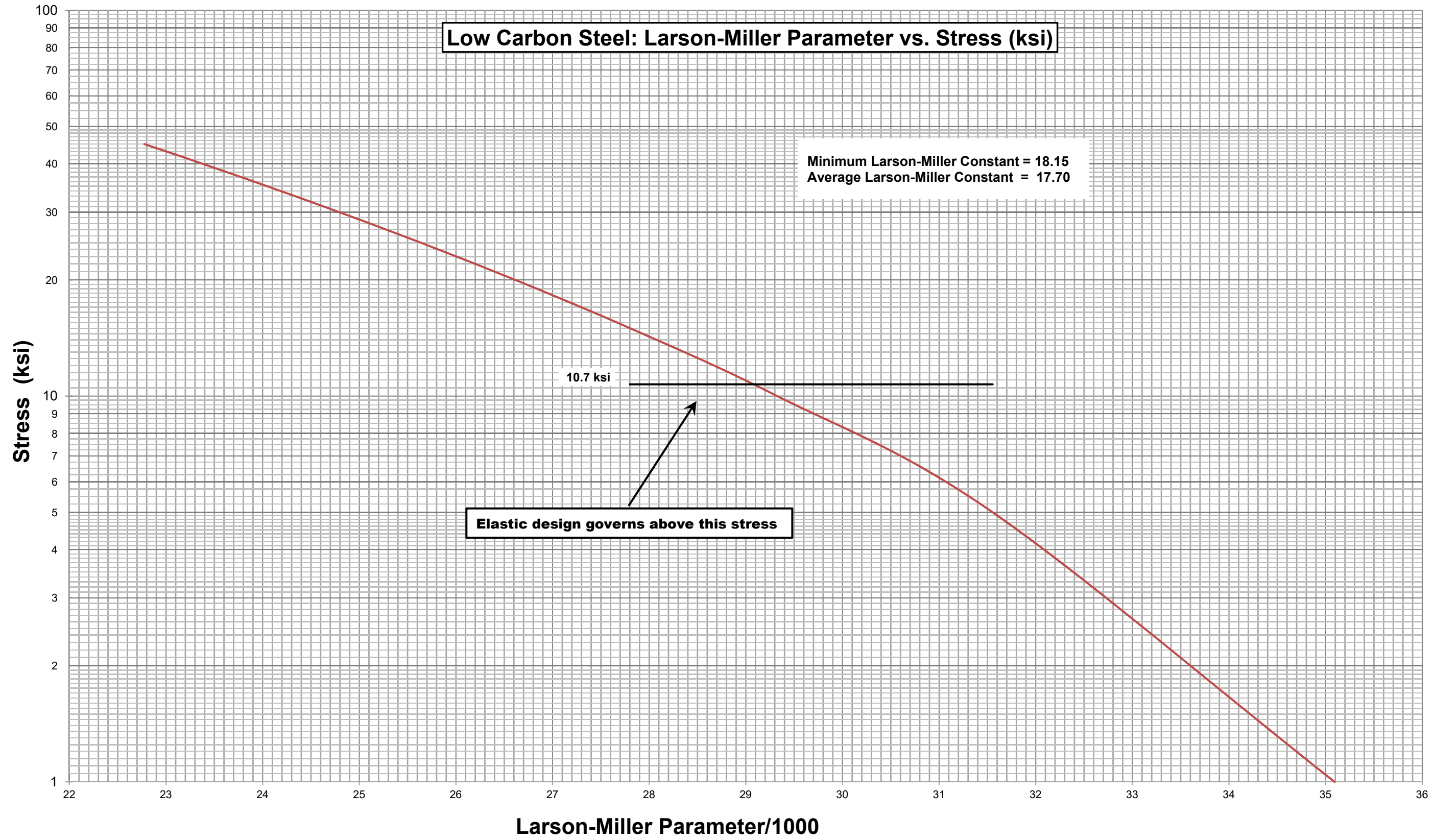


Figure F.3—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A192 Low-carbon Steels

Table F.1—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A192 Low-carbon Steels

Low Carbon Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
560	13.1					
580	12.9					
600	12.7					
620	12.5					
640	12.3					
660	12.1					
680	11.9					
700	11.7					
720	11.5					8.7
740	11.3					8.4
760	11.1					8.0
780	10.9					7.7
800	10.7					7.3
820	10.5	10.5	11.3	12.0	13.3	7.0
840	10.3	9.2	10.0	10.6	11.8	6.6
860	10.1	8.0	8.7	9.3	10.4	6.3
880	9.8	7.0	7.6	8.2	9.2	6.0
900	9.6	6.0	6.6	7.1	8.0	5.6
920	9.4	5.1	5.7	6.2	7.0	5.3
940	9.2	4.4	4.9	5.3	6.1	5.0
960	9.0	3.7	4.1	4.5	5.2	4.7
980	8.8	3.1	3.5	3.8	4.5	4.4
1000	8.6	2.5	2.9	3.2	3.8	4.1
		2.0	2.4	2.6	3.2	3.7

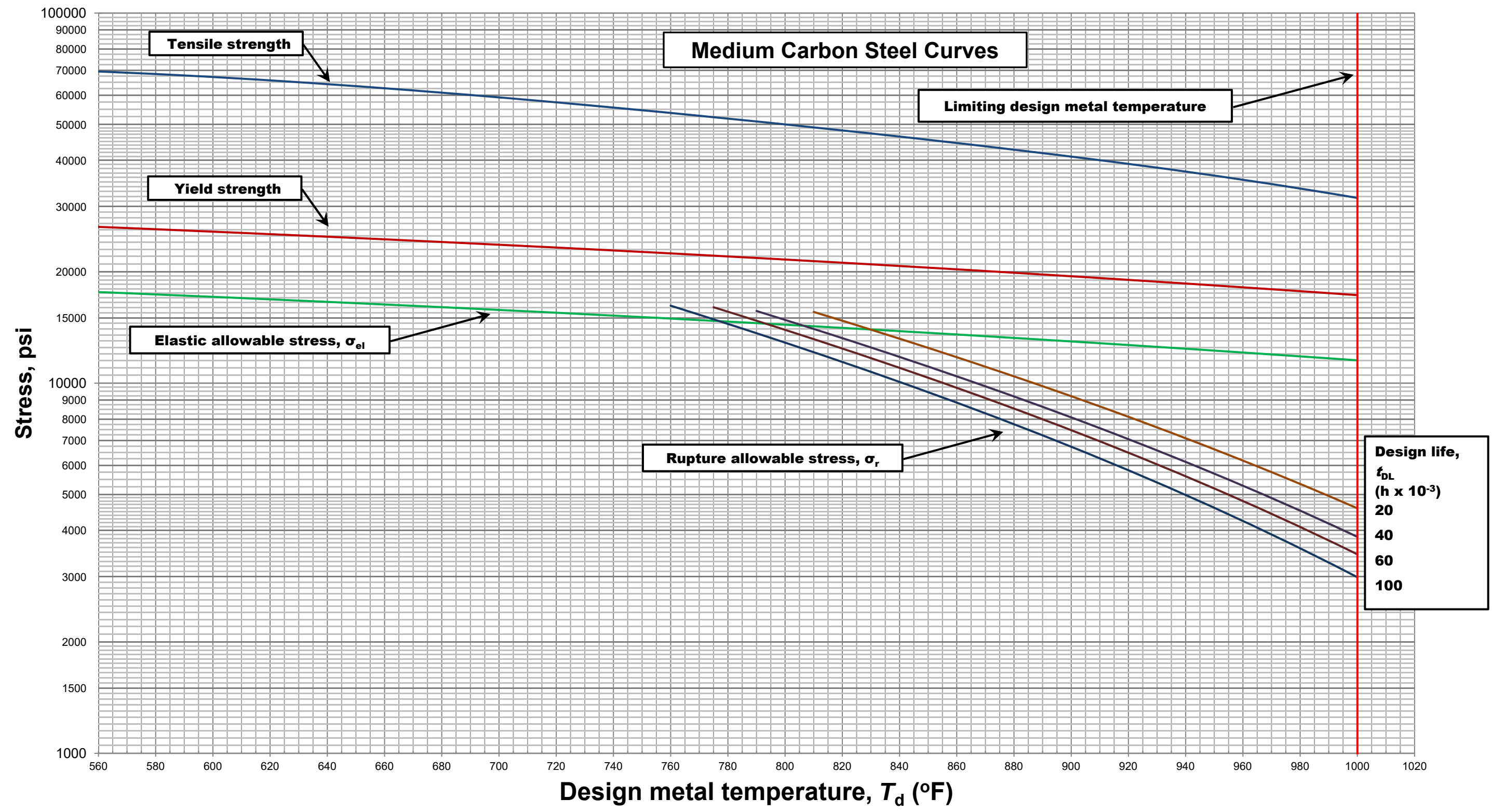


Figure F.4—Stress Curves (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

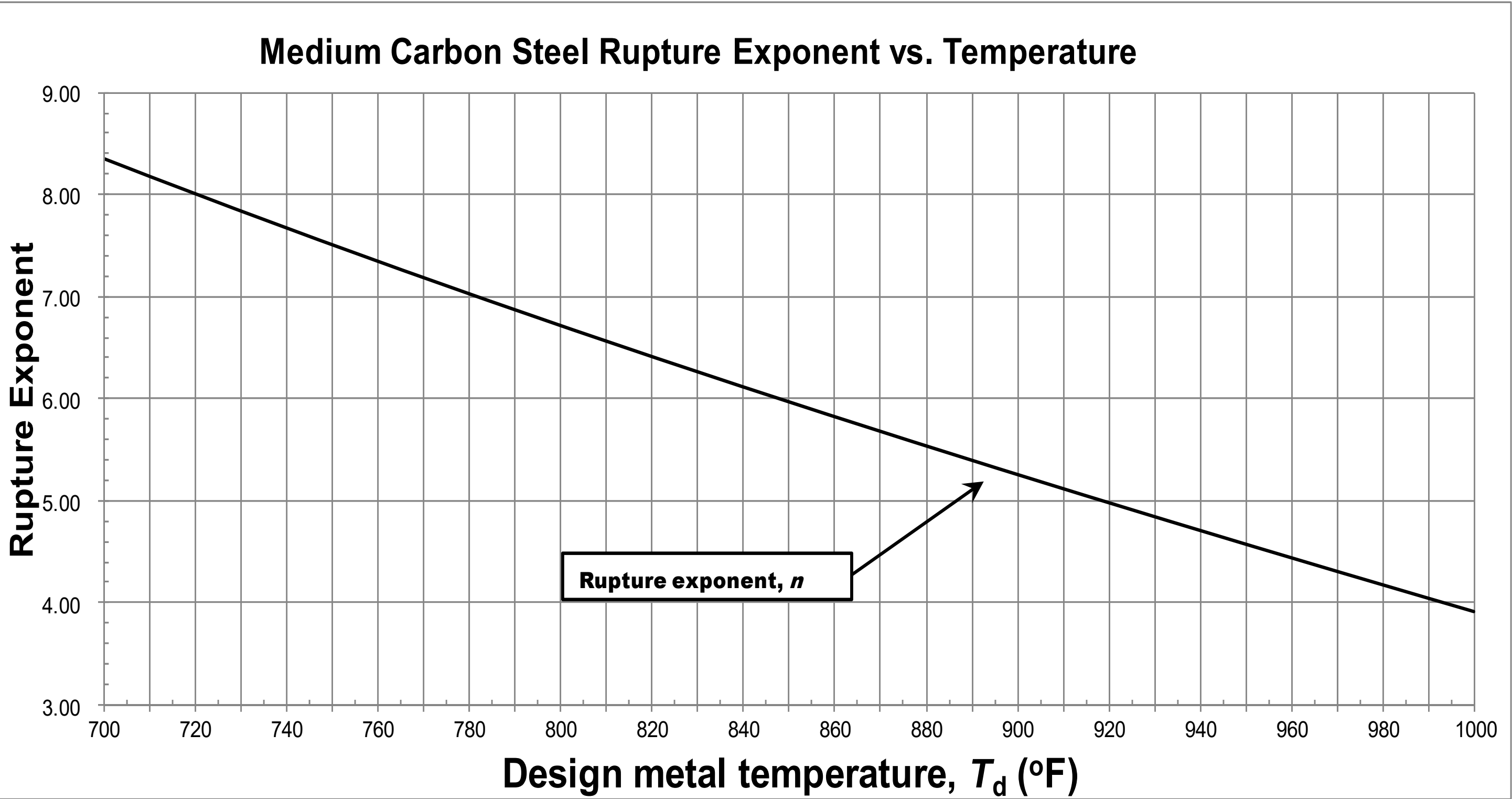


Figure F.5—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

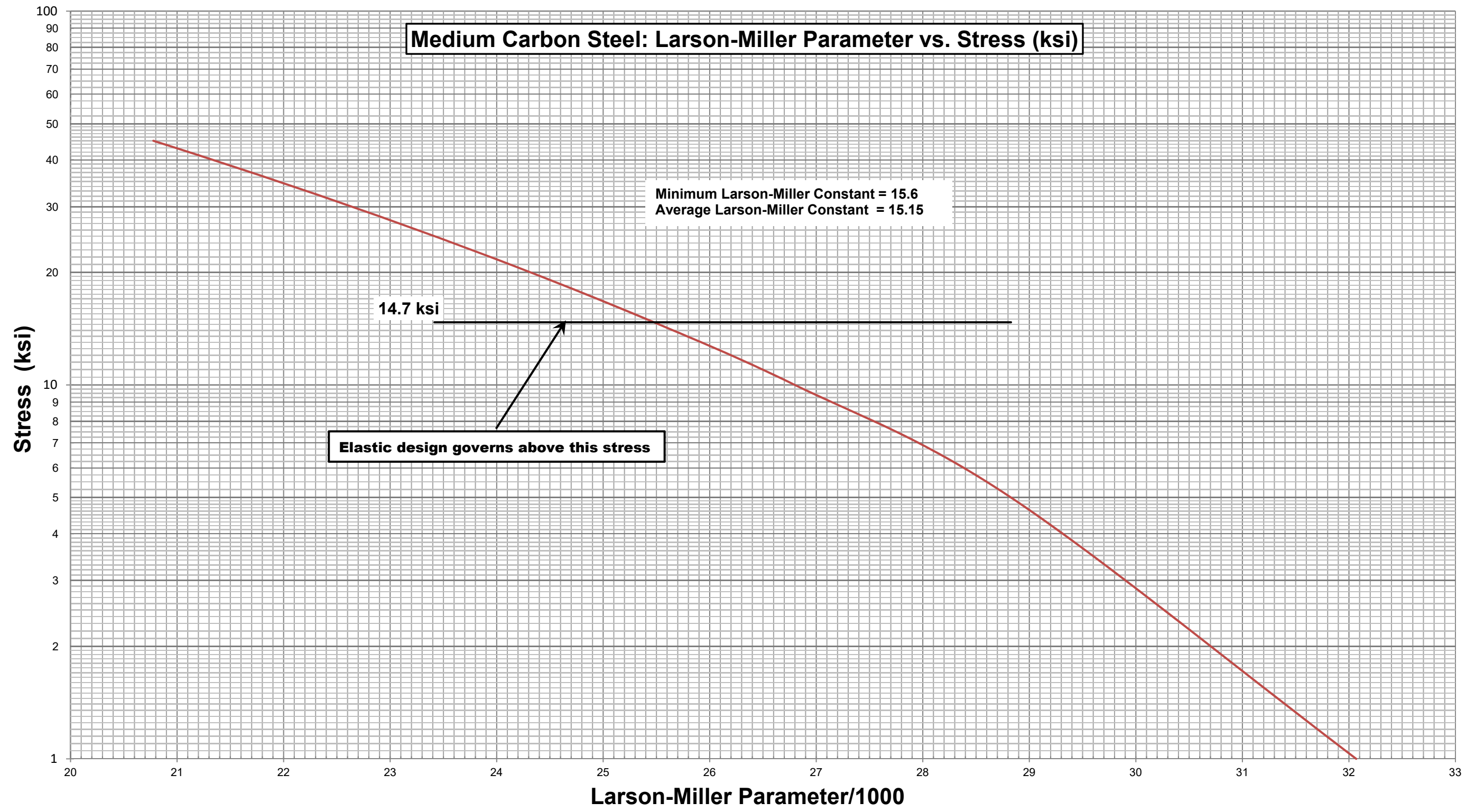


Figure F.6—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Table F.2—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Medium Carbon Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
560	17.6					
580	17.4					
600	17.1					
620	16.9					
640	16.6					
660	16.3					
680	16.0					
700	15.8					8.4
720	15.5					8.0
740	15.2					7.7
760	15.0					7.3
780	14.7					7.0
800	14.4					6.7
820	14.1					6.4
840	13.8					6.1
860	13.5					5.8
880	13.3					5.5
900	13.0					5.3
920	12.7					5.0
940	12.4					4.7
960	12.1					4.4
980	11.8					4.2
1000	11.5					3.9

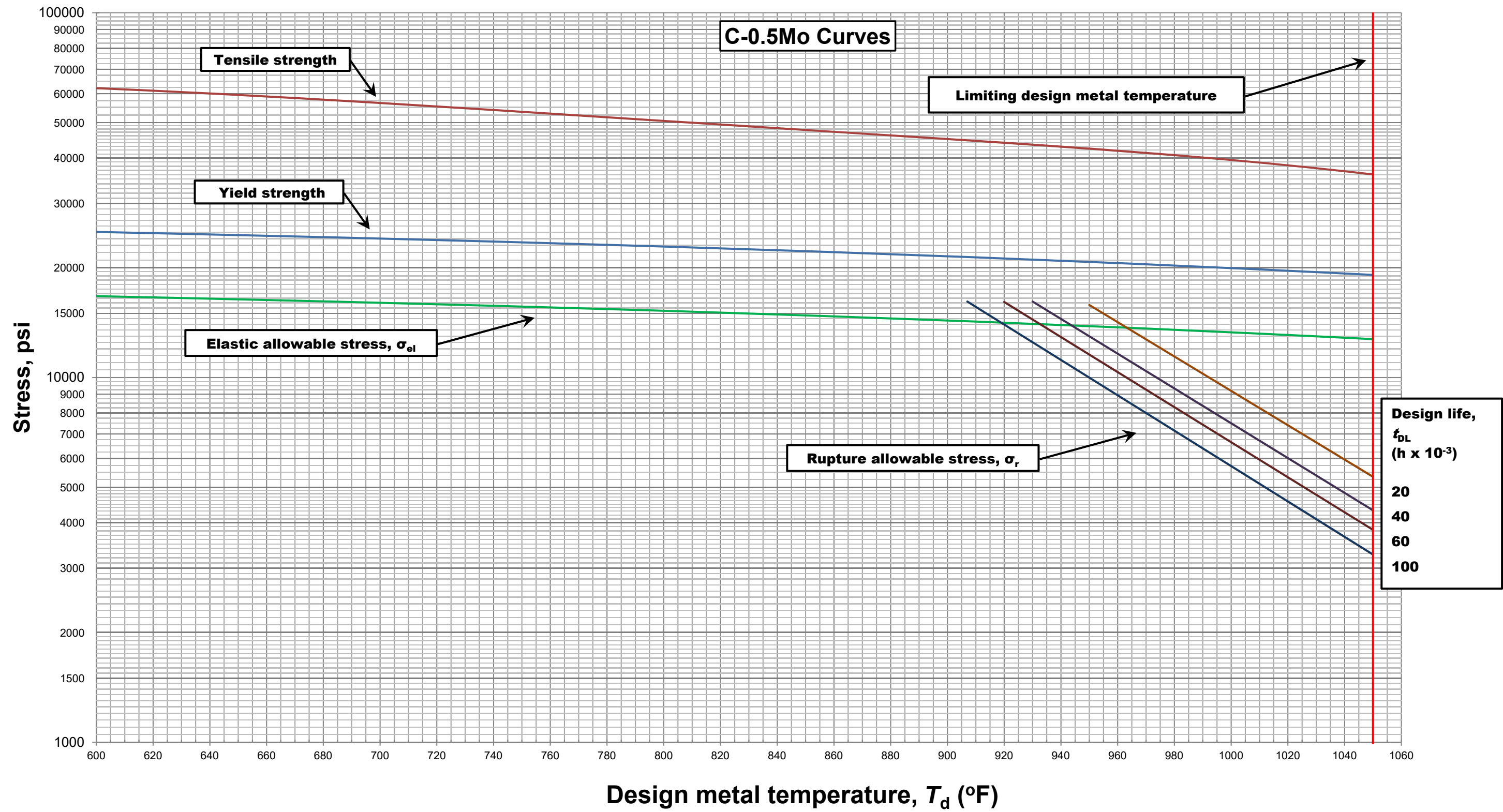


Figure F.7—Stress Curves (USC Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

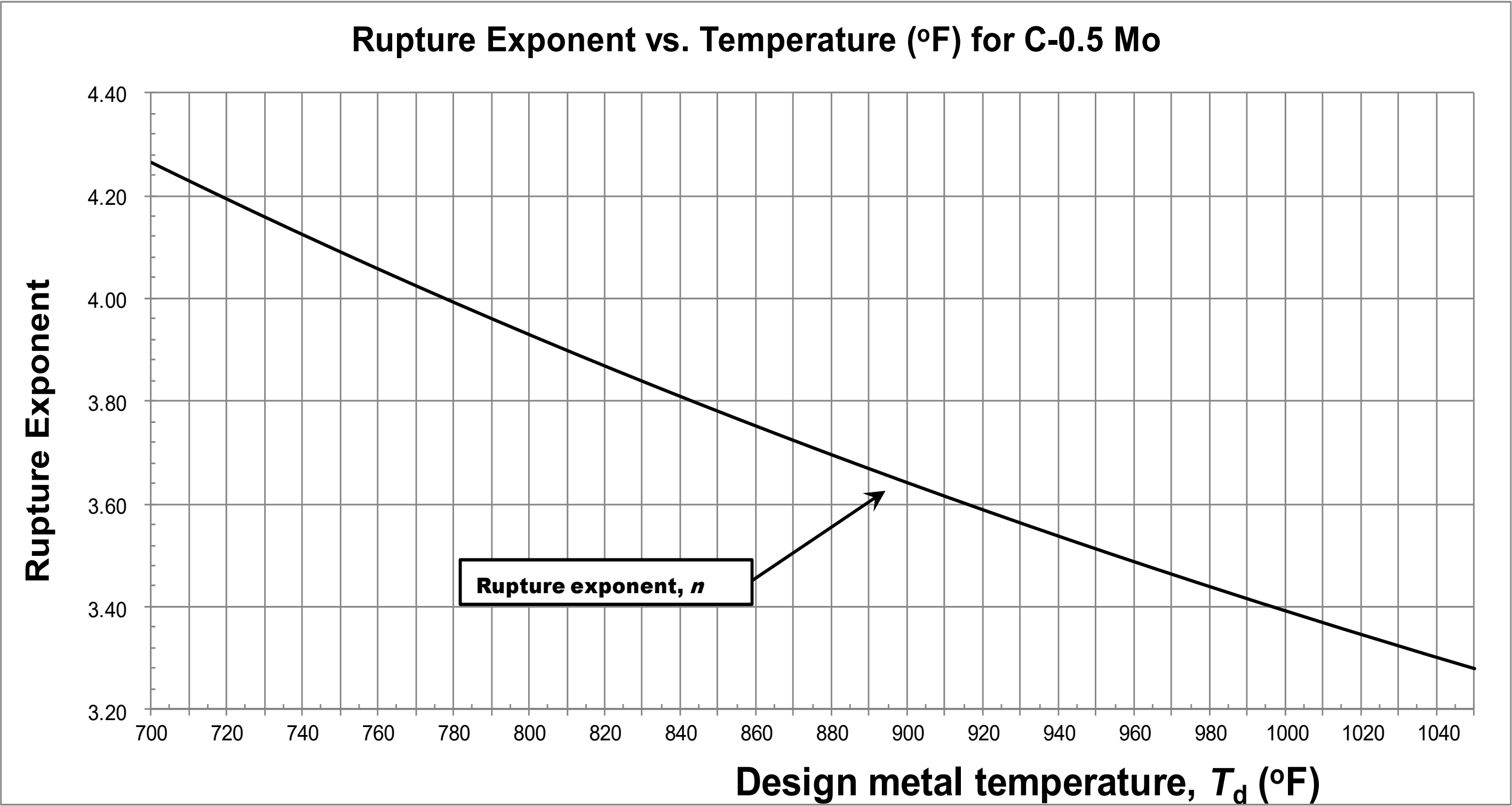


Figure F.8—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

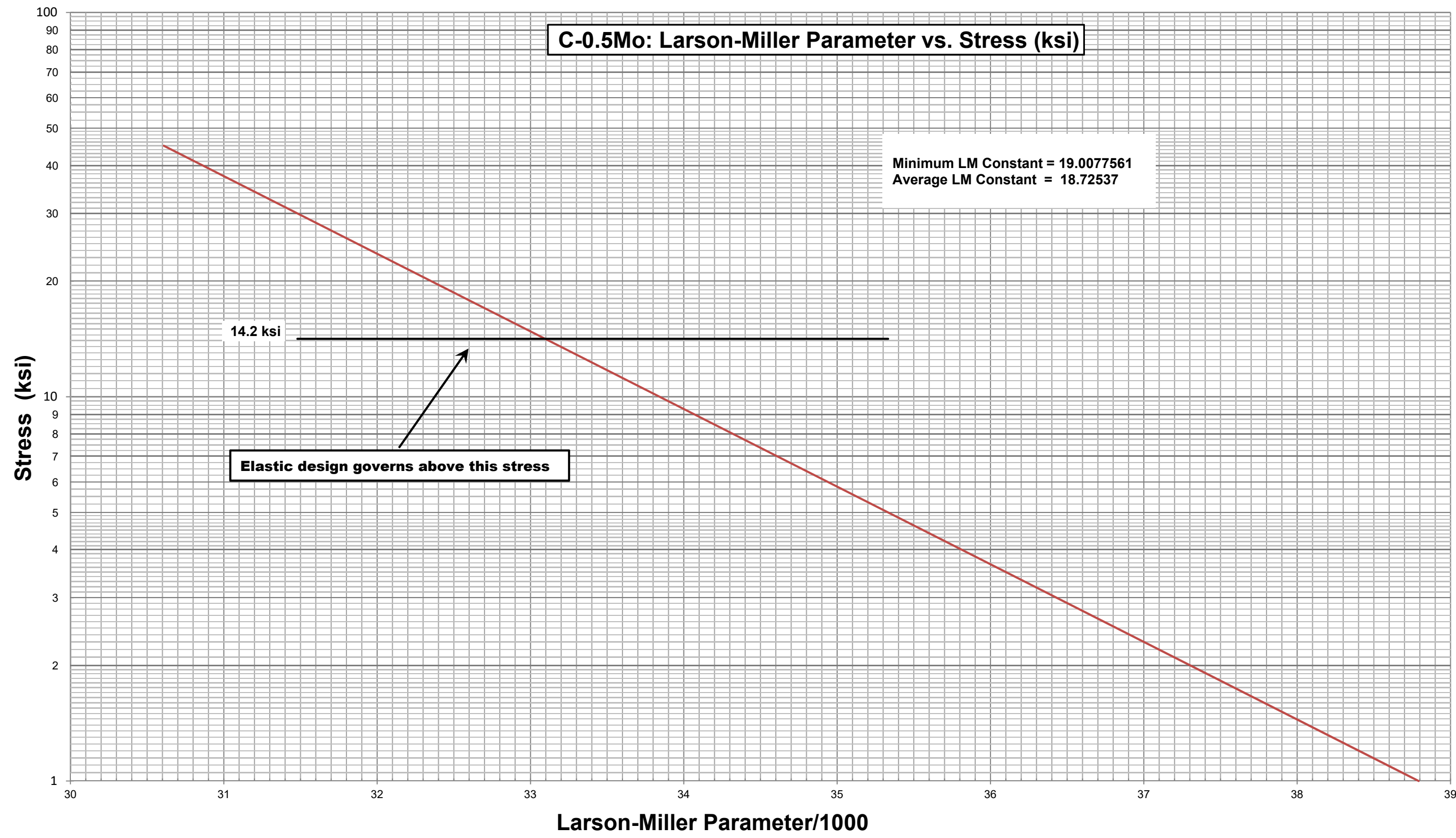


Figure F.9—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

Table F.3—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A209 T1 and ASTM A335 P1 Carbon-1/2Mo Steels

C-0.5Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	16.7					
620	16.6					
640	16.5					
660	16.3					
680	16.2					
700	16.0					4.3
720	15.9					4.2
740	15.7					4.1
760	15.6					4.1
780	15.4					4.0
800	15.2					3.9
820	15.1					3.9
840	14.9					3.8
860	14.7					3.8
880	14.5					3.7
900	14.3	17.5	20.1	22.5	27.2	3.6
920	14.1	14.0	16.1	18.0	21.9	3.6
940	13.9	11.2	12.9	14.5	17.6	3.5
960	13.7	8.9	10.3	11.6	14.2	3.5
980	13.5	7.1	8.3	9.3	11.4	3.4
1000	13.3	5.7	6.6	7.5	9.2	3.4
1020	13.1	4.6	5.3	6.0	7.4	3.3
1040	12.9	3.7	4.3	4.8	6.0	3.3
1050	12.7	3.3	3.8	4.3	5.3	3.3

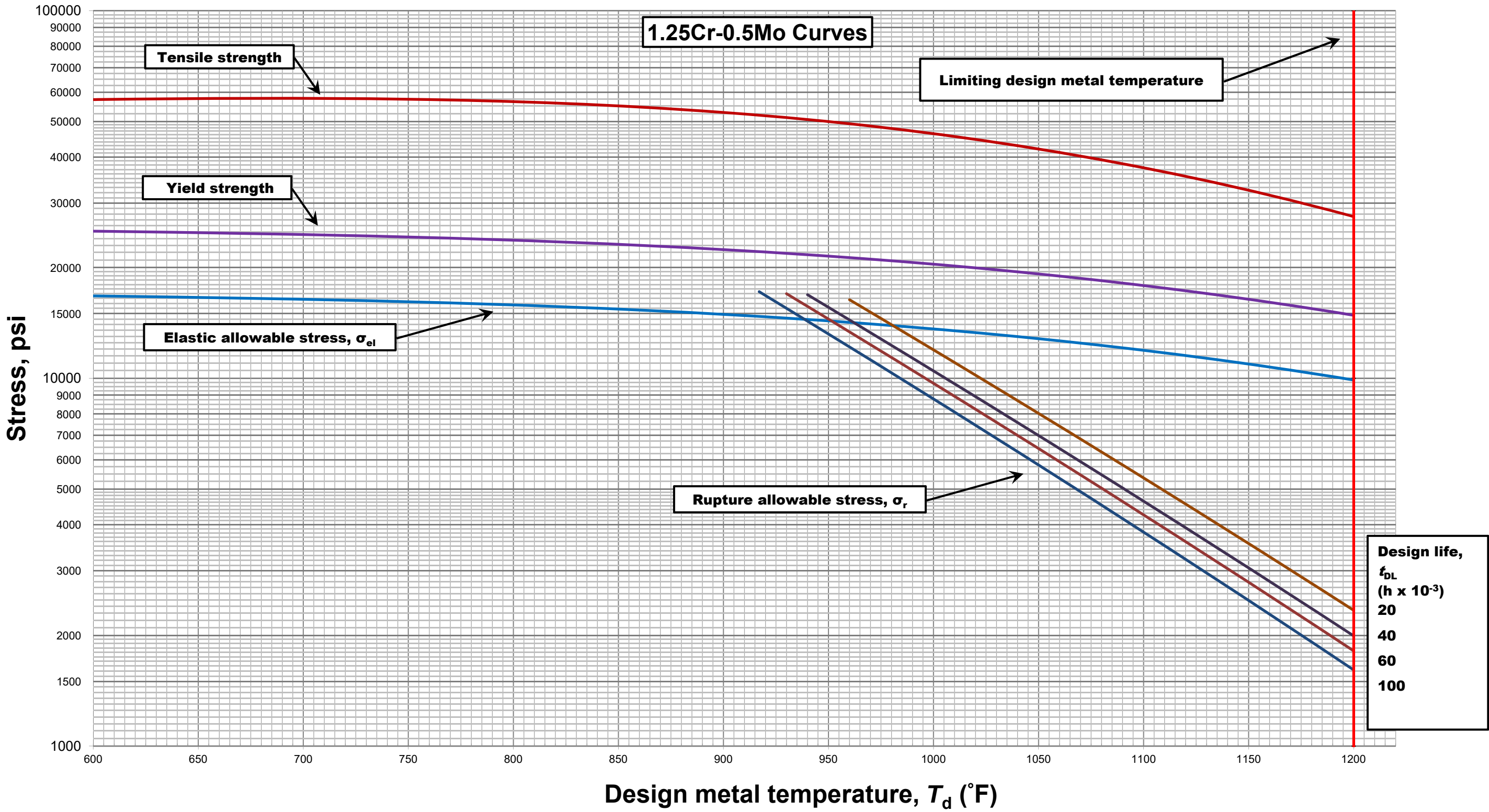


Figure F.10—Stress Curves (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

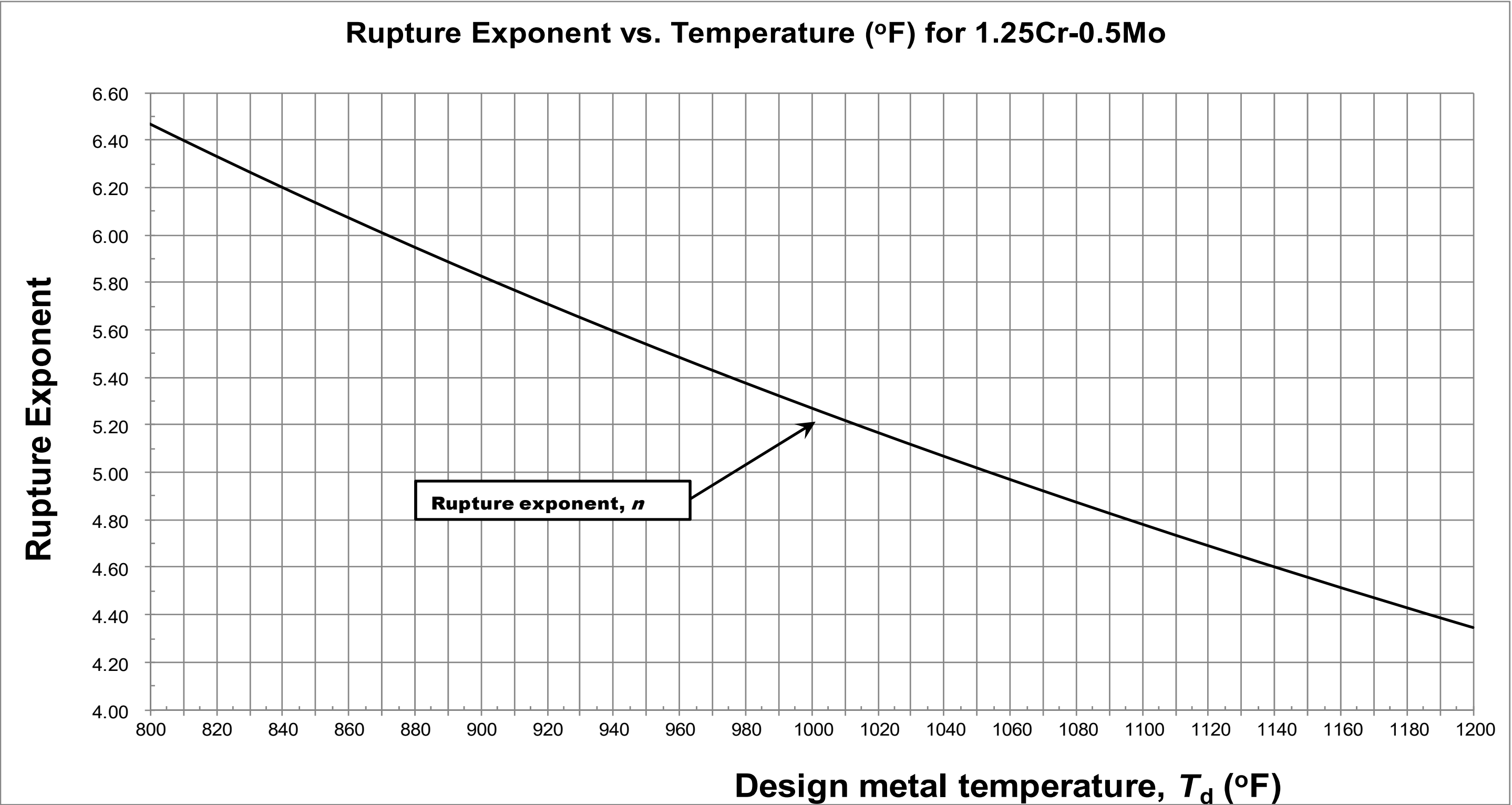


Figure F.11—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

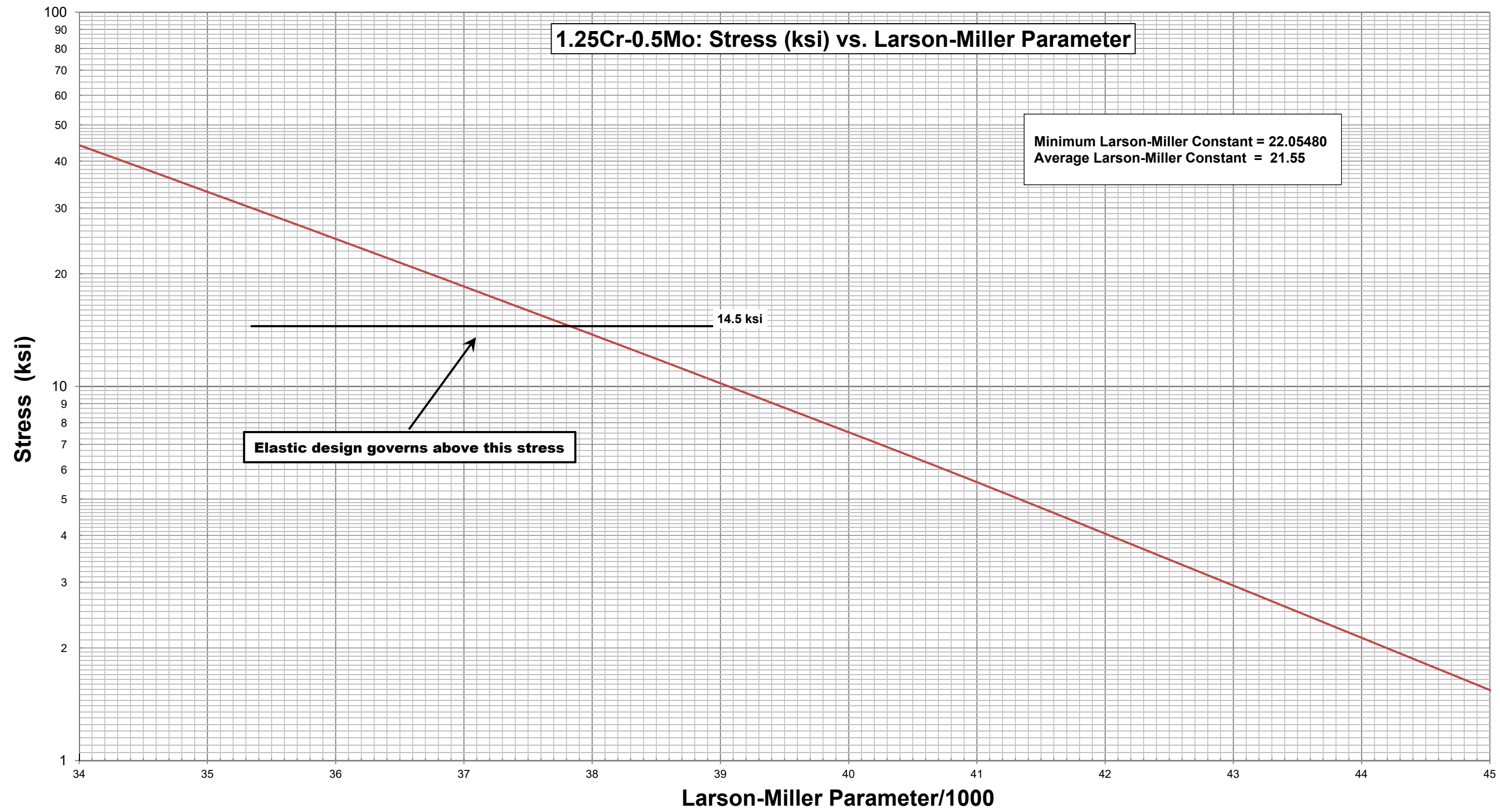


Figure F.12—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

Table F.4—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T11 and ASTM A335 P11 1-1/4Cr-1/2Mo Steels

1.25Cr-0.5Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	16.8					
620	16.7					
640	16.6					
660	16.6					
680	16.5					
700	16.4					
720	16.3					
740	16.2					
760	16.1					
780	16.0					
800	15.8					6.5
820	15.7					6.3
840	15.5					6.2
860	15.3					6.1
880	15.2					6.0
900	14.9	19.7	21.5	23.1	26.0	5.8
920	14.7	16.8	18.4	19.8	22.3	5.7
940	14.5	14.3	15.7	16.9	19.1	5.6
960	14.2	12.2	13.4	14.4	16.4	5.5
980	13.9	10.4	11.4	12.3	14.0	5.4
1000	13.6	8.8	9.7	10.5	12.0	5.3
1020	13.3	7.5	8.2	8.9	10.2	5.2
1040	13.0	6.3	7.0	7.6	8.7	5.1
1060	12.6	5.3	5.9	6.4	7.4	5.0
1080	12.3	4.5	5.0	5.5	6.3	4.9
1100	11.9	3.8	4.3	4.6	5.4	4.8
1120	11.5	3.2	3.6	3.9	4.6	4.7
1140	11.1	2.7	3.0	3.3	3.9	4.6
1160	10.7	2.3	2.6	2.8	3.3	4.5
1180	10.3	1.9	2.2	2.4	2.8	4.4
1200	9.9	1.6	1.8	2.0	2.3	4.3

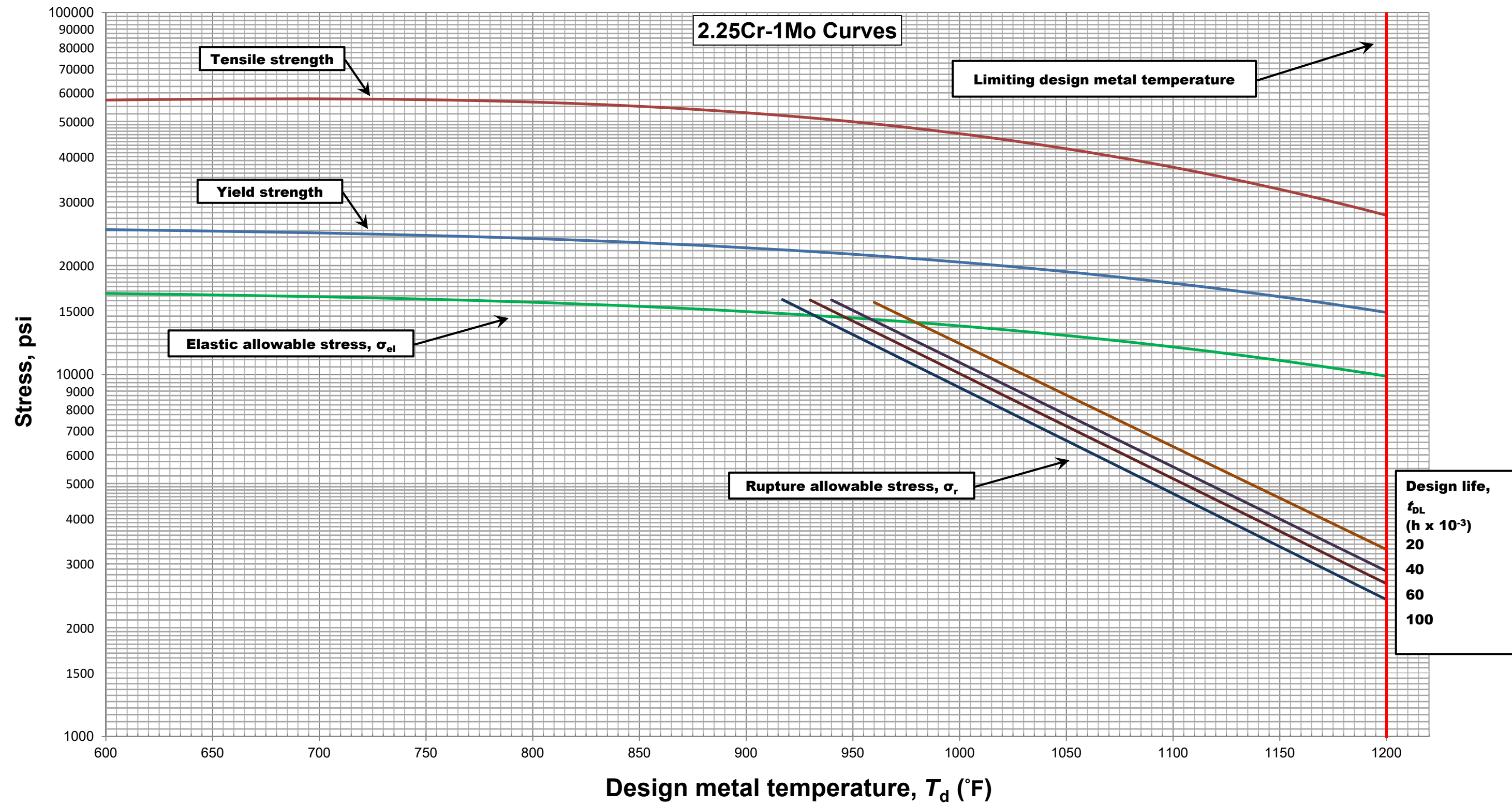


Figure F.13—Stress Curves (USC Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

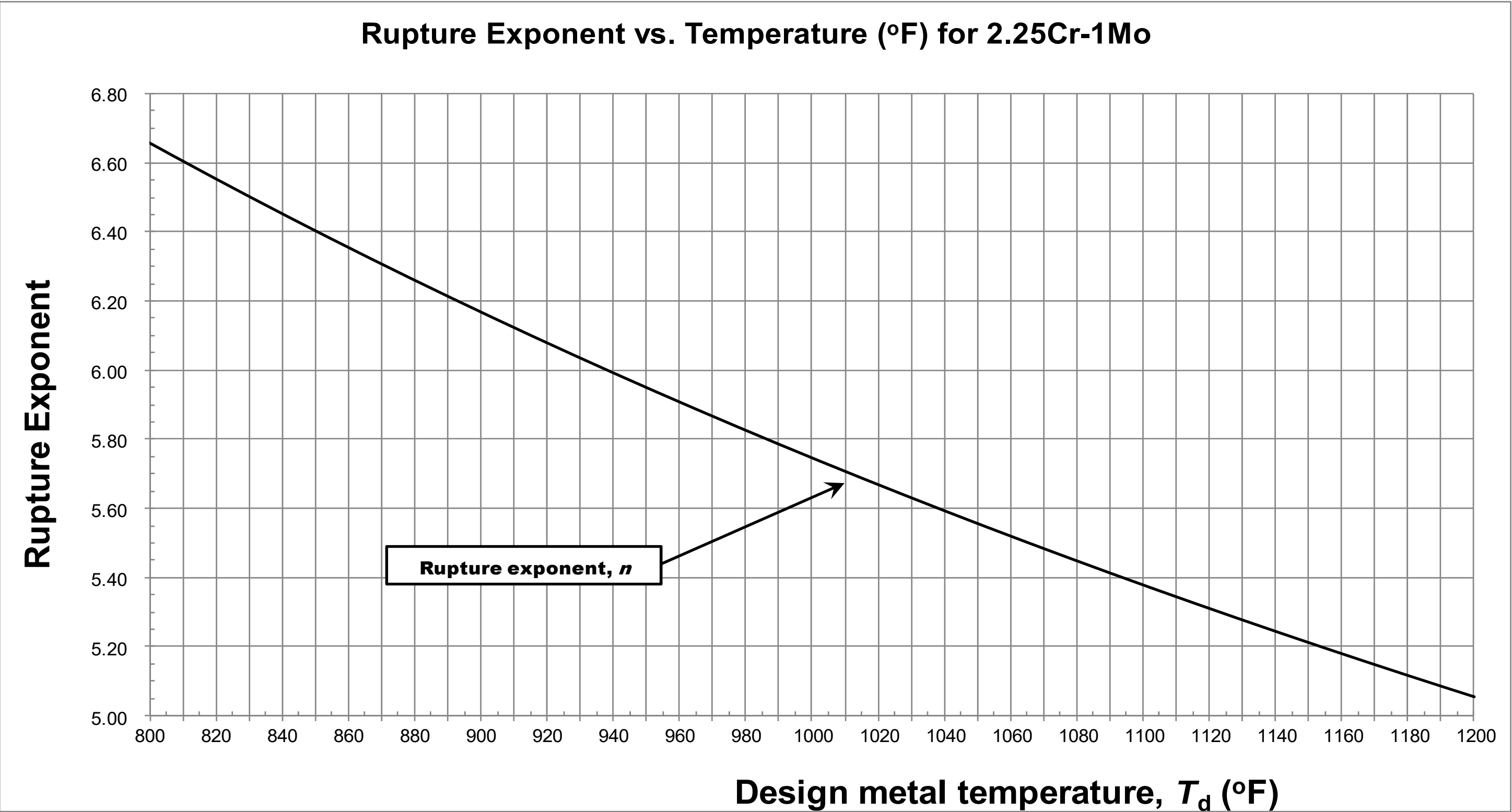


Figure F.14—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

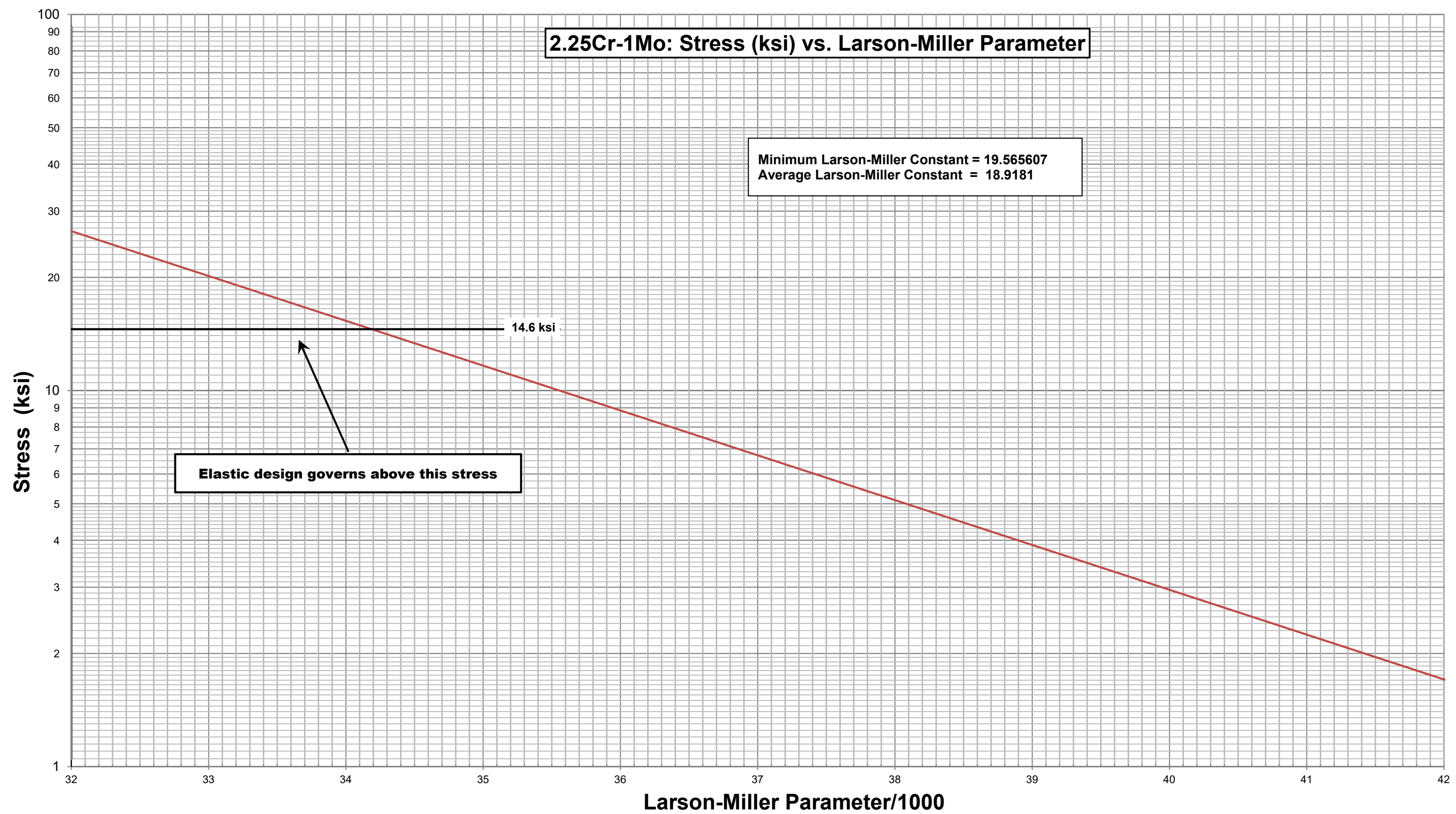


Figure F.15—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

Table F.5—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T22 and ASTM A335 P22 2-1/4Cr-1Mo Steels

2.25Cr-1Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	16.8					
620	16.7					
640	16.6					
660	16.6					
680	16.5					
700	16.4					
720	16.3					
740	16.2					
760	16.1					
780	16.0					
800	15.8					6.7
820	15.7					6.6
840	15.5					6.5
860	15.3					6.4
880	15.2					6.3
900	14.9	18.1	19.6	21.0	23.5	6.2
920	14.7	15.8	17.2	18.4	20.6	6.1
940	14.5	13.8	15.0	16.1	18.0	6.0
960	14.2	12.1	13.1	14.1	15.8	5.9
980	13.9	10.5	11.5	12.3	13.9	5.8
1000	13.6	9.2	10.1	10.8	12.2	5.7
1020	13.3	8.0	8.8	9.5	10.7	5.7
1040	13.0	7.0	7.7	8.3	9.4	5.6
1060	12.6	6.1	6.7	7.3	8.2	5.5
1080	12.3	5.4	5.9	6.4	7.2	5.4
1100	11.9	4.7	5.2	5.6	6.3	5.4
1120	11.5	4.1	4.5	4.9	5.6	5.3
1140	11.1	3.6	3.9	4.3	4.9	5.2
1160	10.7	3.1	3.5	3.7	4.3	5.2
1180	10.3	2.7	3.0	3.3	3.7	5.1
1200	9.9	2.4	2.6	2.9	3.3	5.1

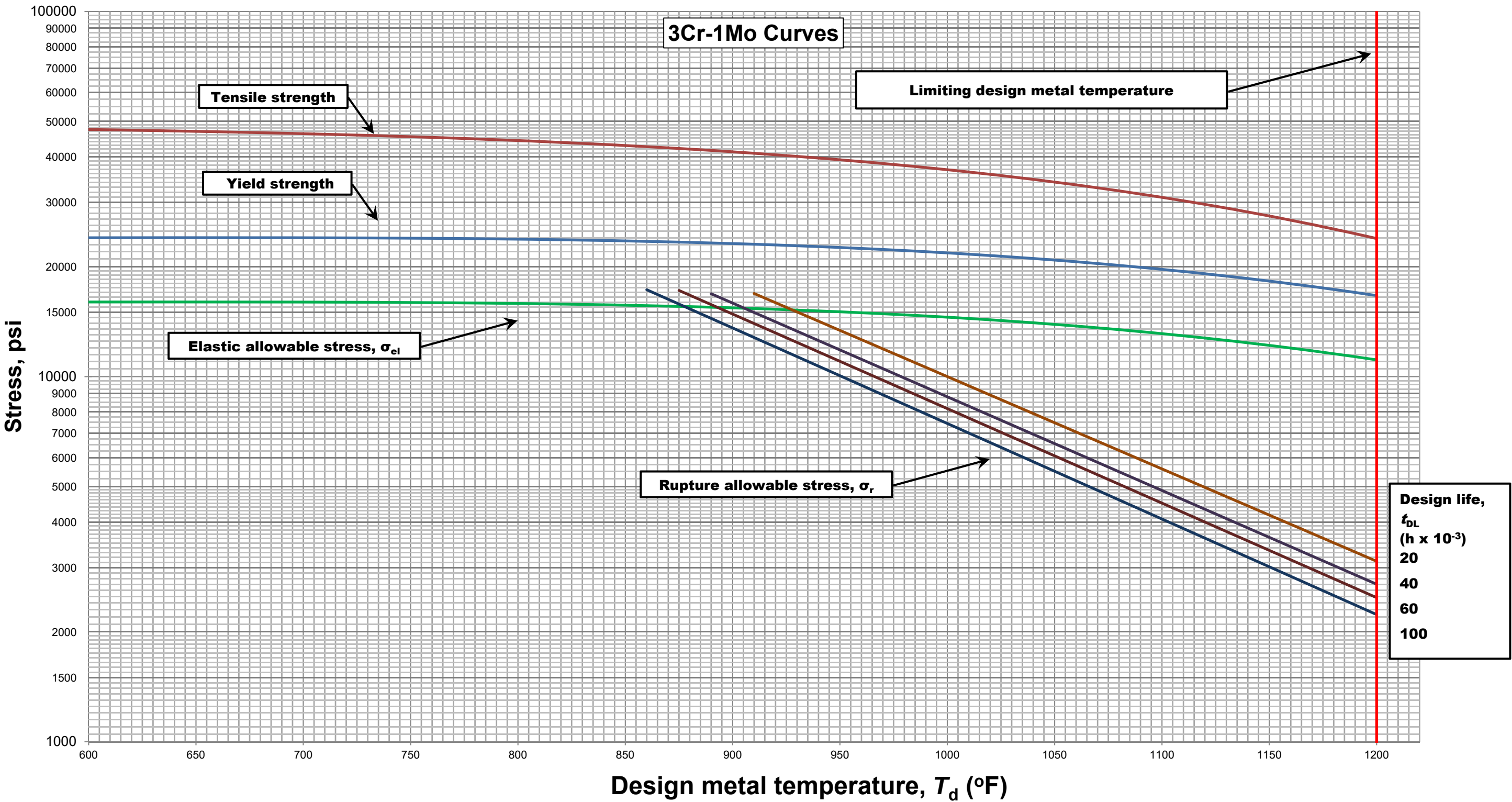


Figure F.16—Stress Curves (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

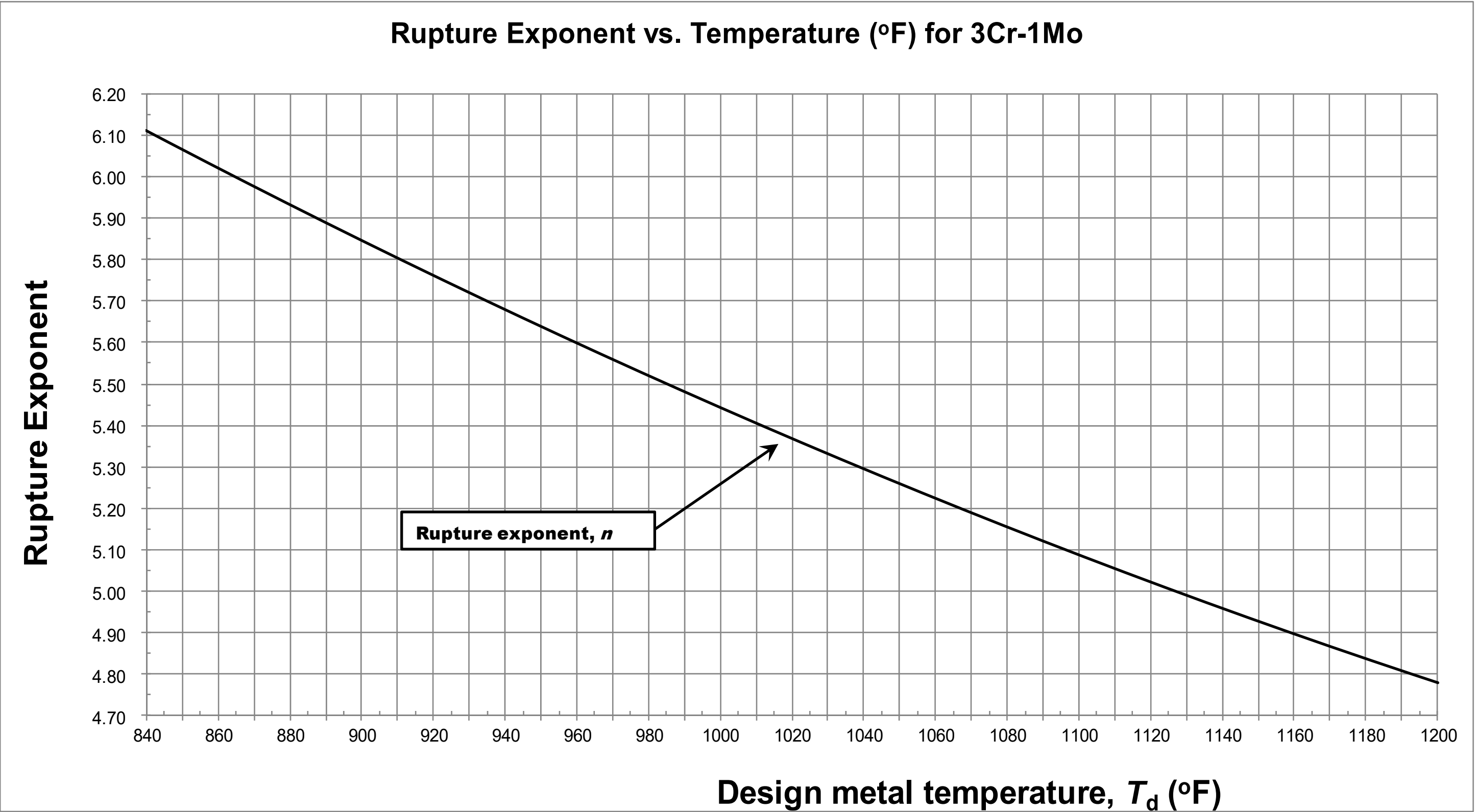


Figure F.17—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

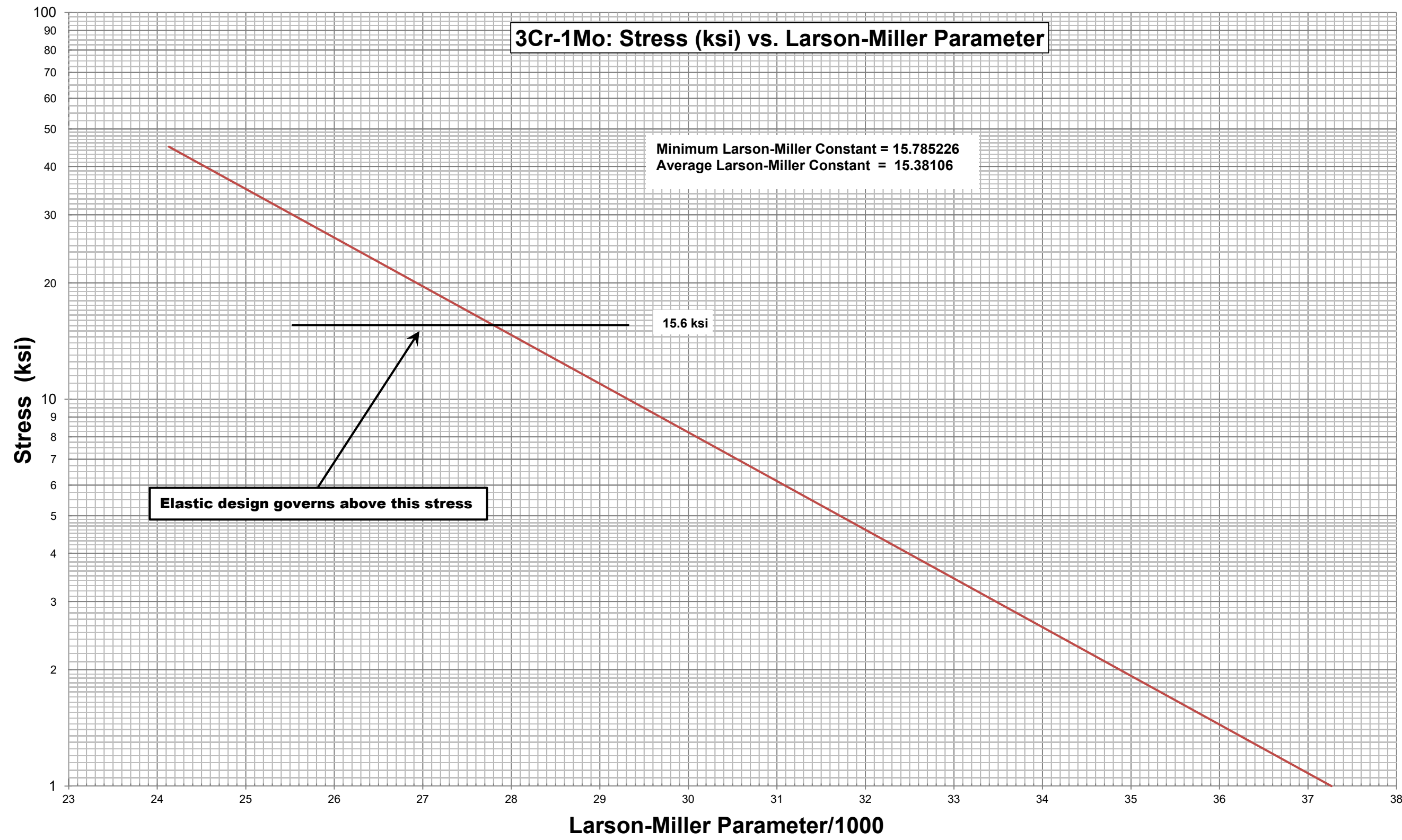


Figure F.18—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

Table F.6—Elastic and Rupture Allowable Stresses (USC Units) for ASTM A213 T21 and ASTM A335 P21 3Cr-1Mo Steels

3Cr-1Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	16.0					
620	16.0					
640	16.0					
660	16.0					
680	16.0					
700	16.0					
720	16.0					
740	16.0					
760	15.9					
780	15.9					
800	15.9					
820	15.8					
840	15.7	19.5	21.2	22.7	25.4	6.1
860	15.7	17.3	18.8	20.1	22.6	6.0
880	15.6	15.3	16.7	17.9	20.1	5.9
900	15.4	13.6	14.8	15.9	17.9	5.8
920	15.3	12.1	13.2	14.1	15.9	5.8
940	15.1	10.7	11.7	12.6	14.2	5.7
960	15.0	9.5	10.4	11.2	12.6	5.6
980	14.8	8.4	9.2	9.9	11.2	5.5
1000	14.6	7.4	8.2	8.8	10.0	5.4
1020	14.3	6.6	7.3	7.8	8.9	5.4
1040	14.0	5.8	6.4	7.0	7.9	5.3
1060	13.8	5.2	5.7	6.2	7.1	5.2
1080	13.4	4.6	5.1	5.5	6.3	5.2
1100	13.1	4.1	4.5	4.9	5.6	5.1
1120	12.8	3.6	4.0	4.3	5.0	5.0
1140	12.4	3.2	3.5	3.9	4.4	5.0
1160	12.0	2.8	3.2	3.4	3.9	4.9
1180	11.6	2.5	2.8	3.0	3.5	4.8
1200	11.1	2.2	2.5	2.7	3.1	4.8

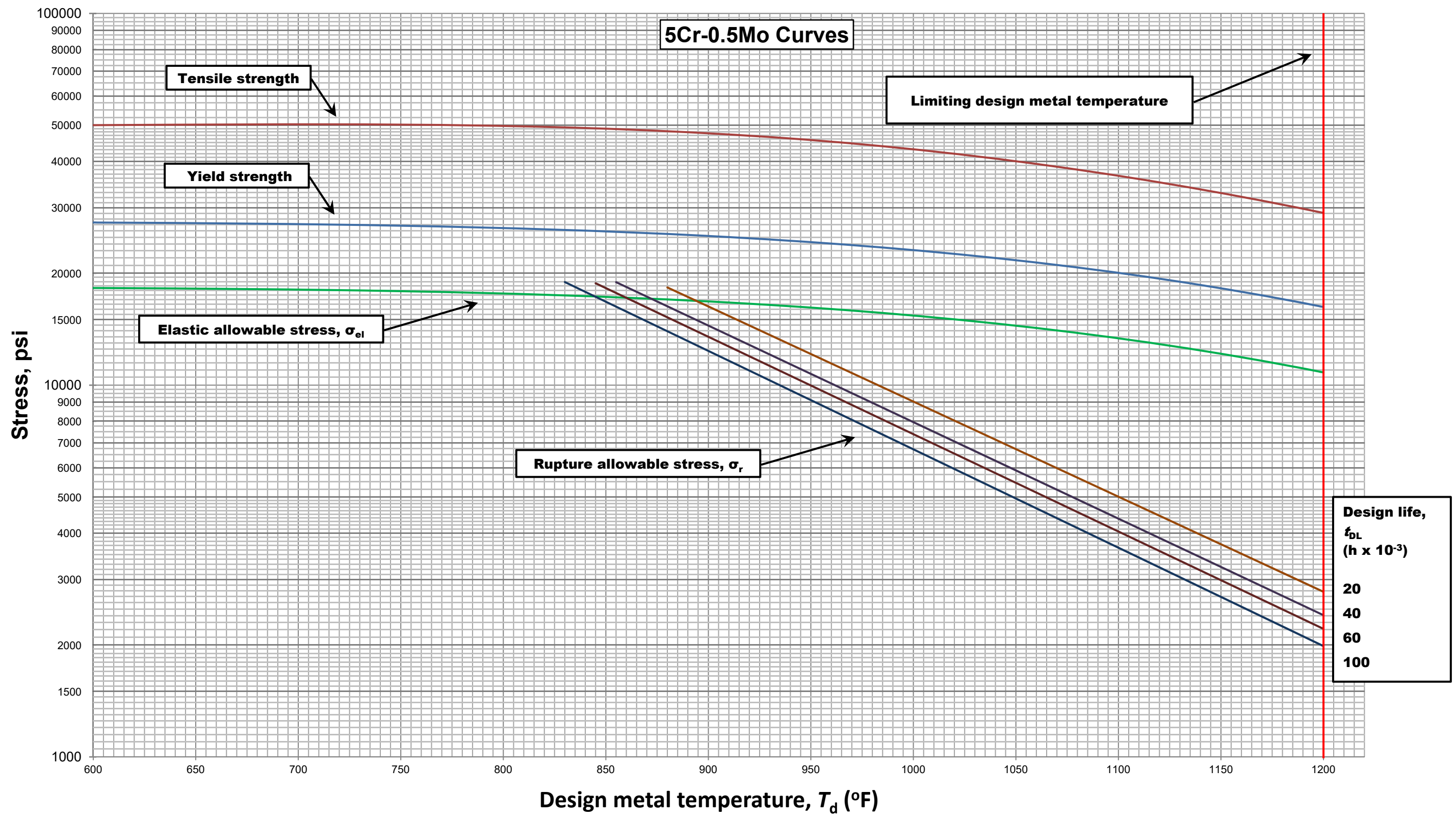


Figure F.19—Stress Curves (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

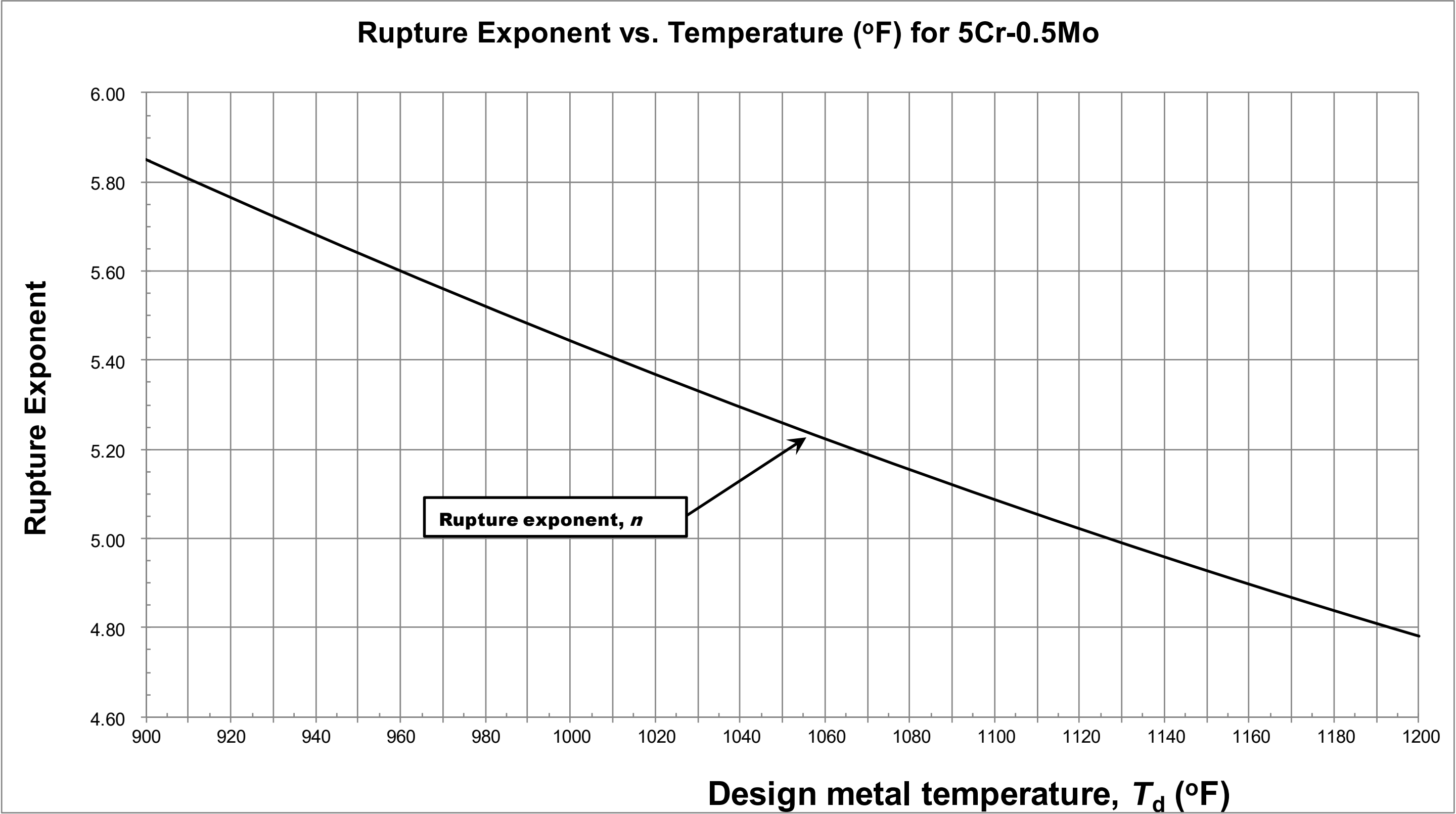


Figure F.20—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

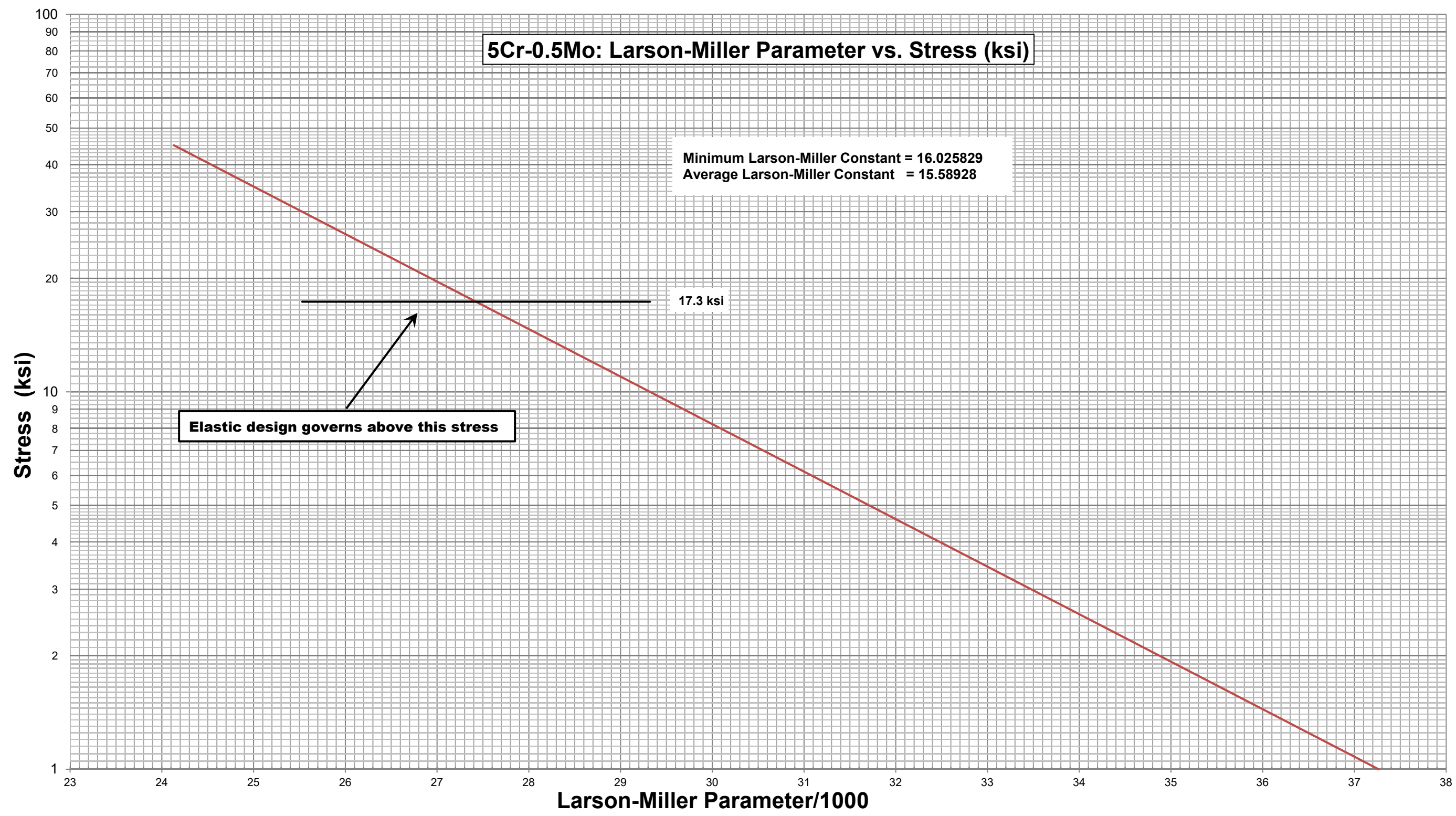


Figure F.21—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

Table F.7—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T5 and ASTM A335 P5 5Cr-1/2Mo Steels

5Cr-0.5Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	18.3					
620	18.2					
640	18.2					
660	18.2					
680	18.1					
700	18.1					
720	18.0					
740	17.9					
760	17.9					
780	17.8					
800	17.6					
820	17.5	20.1	21.9	23.3	26.1	5.8
840	17.4	17.8	19.4	20.7	23.2	
860	17.2	15.8	17.2	18.4	20.6	
880	17.0	14.0	15.2	16.3	18.3	
900	16.8	12.4	13.5	14.5	16.3	
920	16.6	10.9	12.0	12.8	14.5	
940	16.3	9.7	10.6	11.4	12.9	
960	16.0	8.6	9.4	10.1	11.4	
980	15.7	7.6	8.3	9.0	10.2	
1000	15.4	6.7	7.4	8.0	9.0	
1020	15.0	6.0	6.5	7.1	8.0	
1040	14.7	5.3	5.8	6.3	7.1	
1060	14.3	4.7	5.1	5.6	6.3	
1080	13.8	4.1	4.6	4.9	5.6	
1100	13.4	3.7	4.0	4.4	5.0	
1120	12.9	3.2	3.6	3.9	4.5	
1140	12.4	2.9	3.2	3.4	4.0	
1160	11.9	2.5	2.8	3.1	3.5	
1180	11.4	2.2	2.5	2.7	3.1	
1200	10.8	2.0	2.2	2.4	2.8	

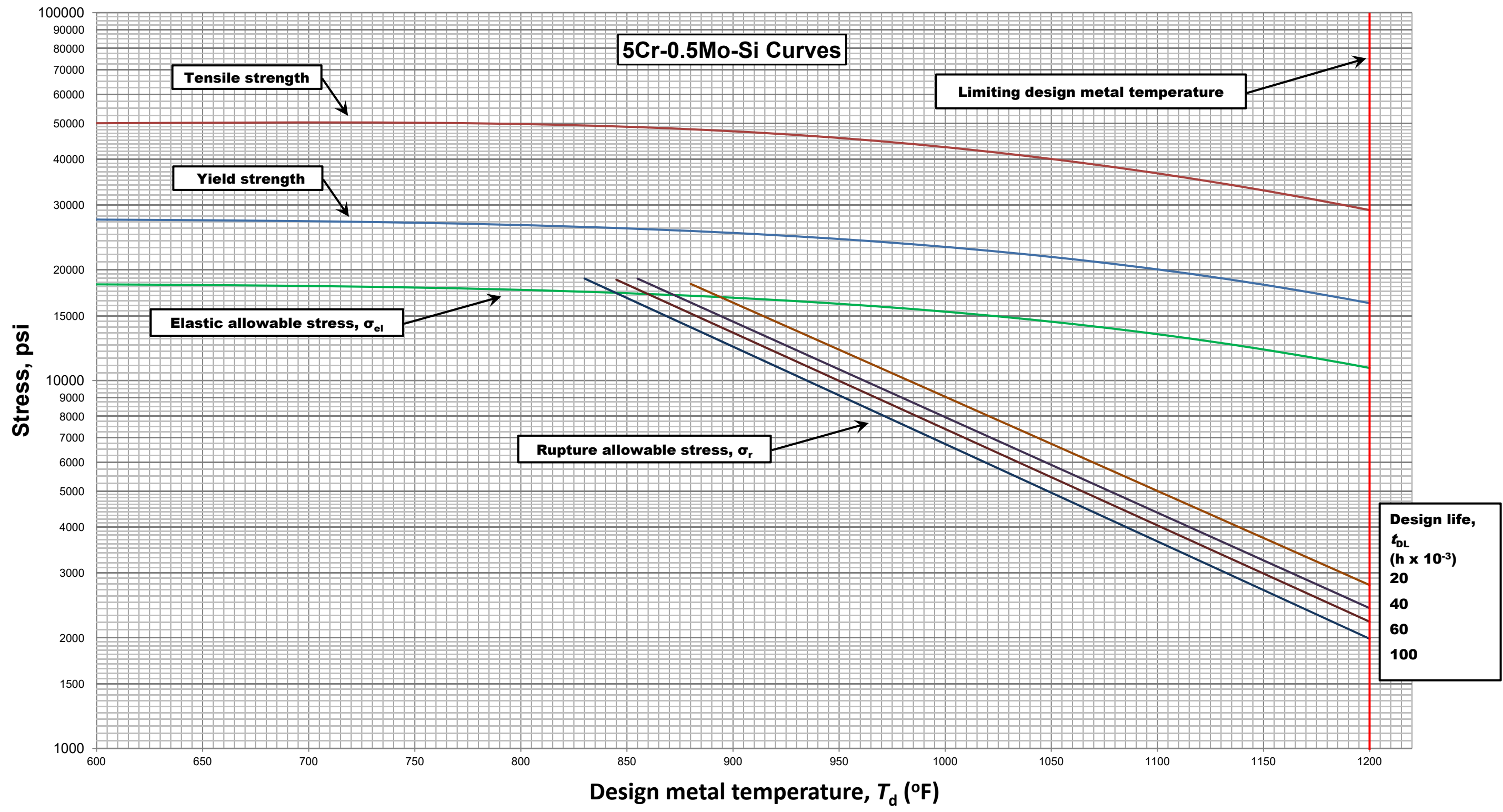


Figure F.22—Stress Curves (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

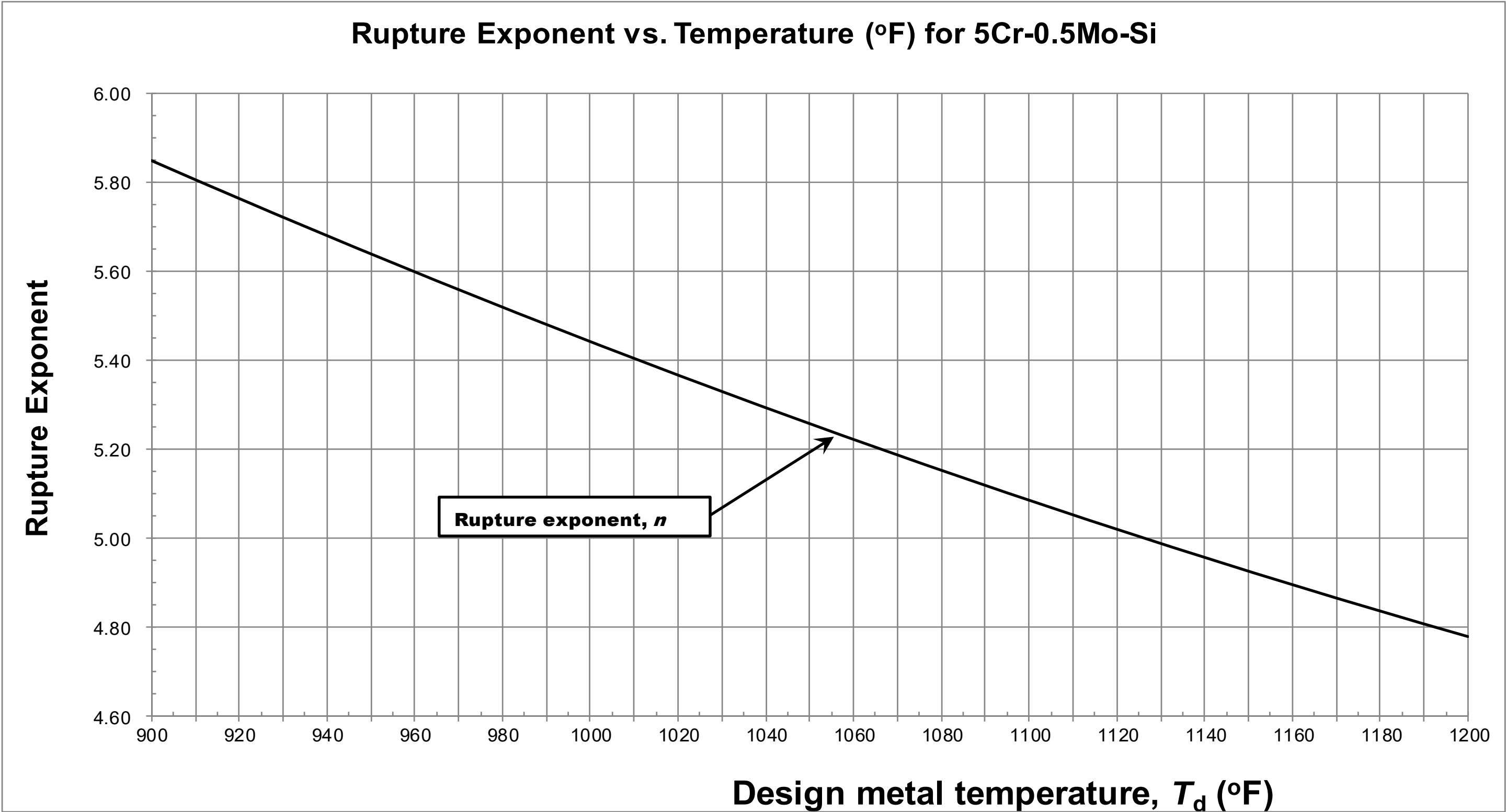


Figure F.23—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

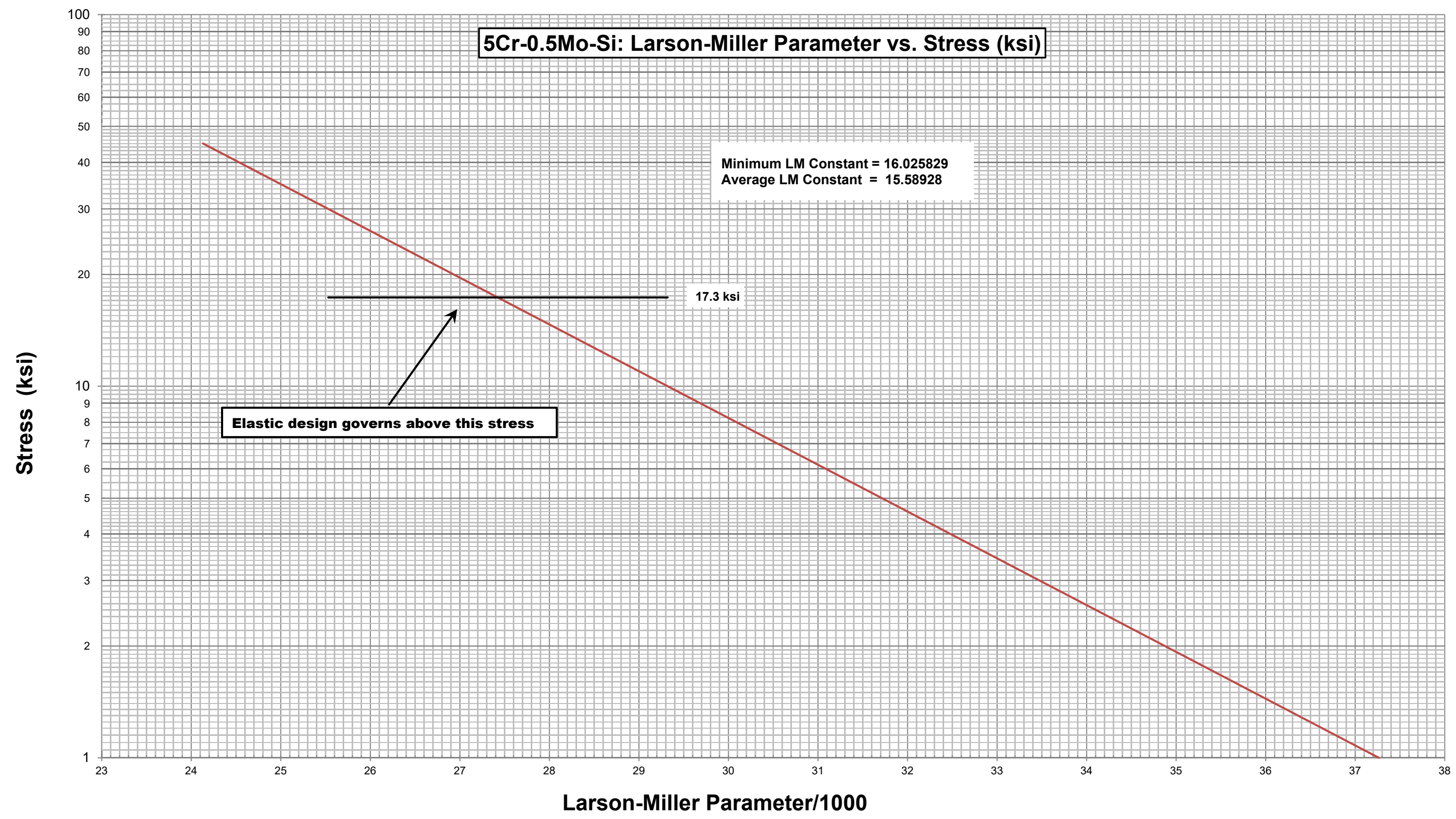


Figure F.24—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

Table F.8—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T5b and ASTM A335 P5b 5Cr-1/2Mo-Si Steels

5Cr-0.5Mo-Si Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
600	18.3					
620	18.2					
640	18.2					
660	18.2					
680	18.1					
700	18.1					
720	18.0					
740	17.9					
760	17.9					
780	17.8					
800	17.6					
820	17.5	20.1	21.9	23.3	26.1	5.8
840	17.4	17.8	19.4	20.7	23.2	
860	17.2	15.8	17.2	18.4	20.6	
880	17.0	14.0	15.2	16.3	18.3	
900	16.8	12.4	13.5	14.5	16.3	
920	16.6	10.9	12.0	12.8	14.5	
940	16.3	9.7	10.6	11.4	12.9	
960	16.0	8.6	9.4	10.1	11.4	
980	15.7	7.6	8.3	9.0	10.2	
1000	15.4	6.7	7.4	8.0	9.0	
1020	15.0	6.0	6.5	7.1	8.0	
1040	14.7	5.3	5.8	6.3	7.1	
1060	14.3	4.7	5.1	5.6	6.3	
1080	13.8	4.1	4.6	4.9	5.6	
1100	13.4	3.7	4.0	4.4	5.0	
1120	12.9	3.2	3.6	3.9	4.5	
1140	12.4	2.9	3.2	3.4	4.0	
1160	11.9	2.5	2.8	3.1	3.5	
1180	11.4	2.2	2.5	2.7	3.1	
1200	10.8	2.0	2.2	2.4	2.8	

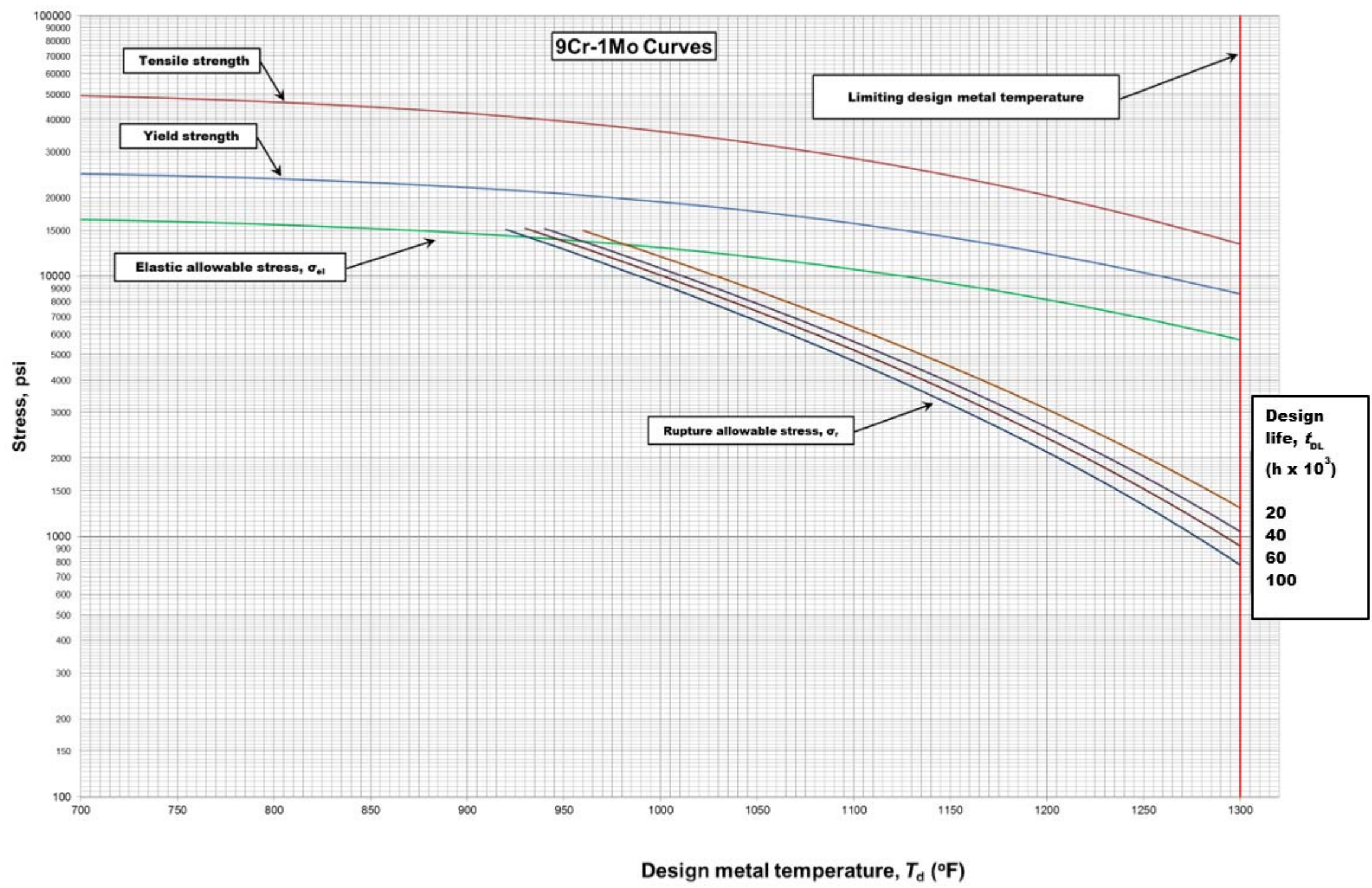


Figure F.25—Stress Curves (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

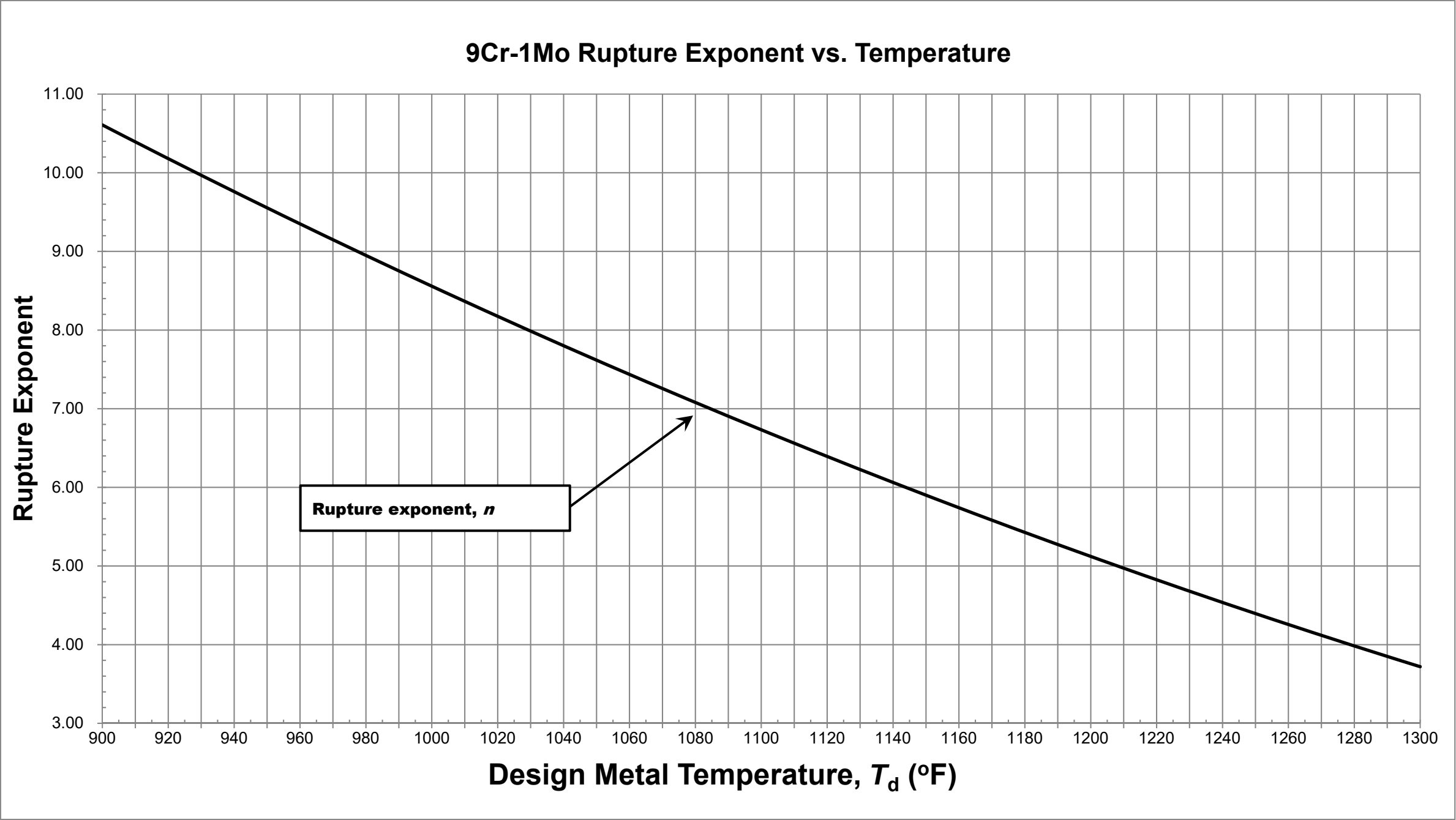


Figure F.26—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

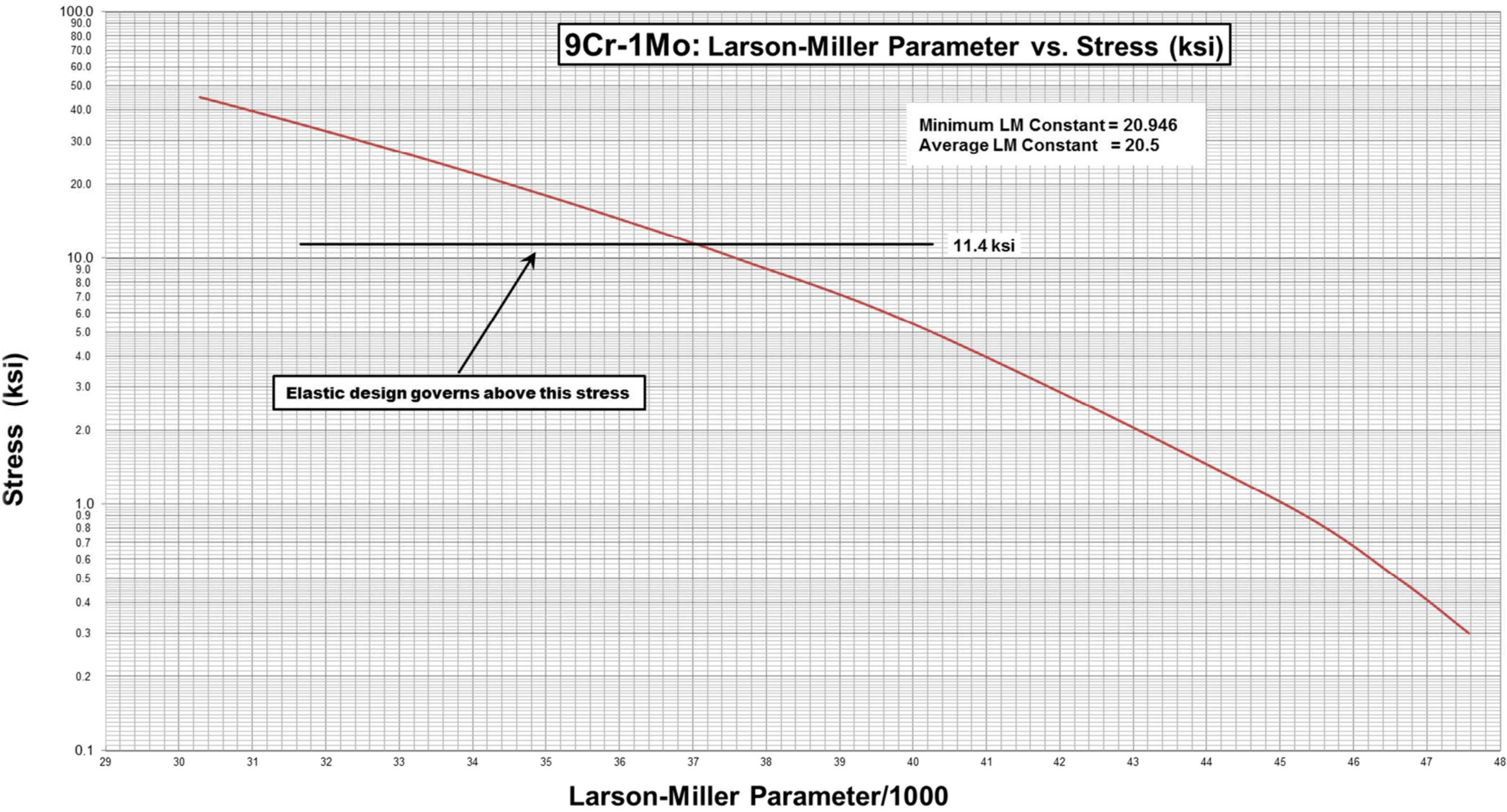


Figure F.27—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

Table F.9—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213 T9 and ASTM A335 P9 9Cr-1Mo Steels

9Cr-1Mo Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	16.5					
720	16.4					
740	16.3					
760	16.1					
780	16.0					
800	15.8					
820	15.6					
840	15.4					
860	15.1					
880	14.9					
900	14.6					
920	14.3	15.1	16.2	17.0	18.6	10.6
940	14.0	13.5	14.4	15.2	16.7	10.2
960	13.6	11.9	12.8	13.6	15.0	9.8
980	13.3	10.6	11.4	12.1	13.4	9.4
1000	12.9	9.3	10.1	10.7	11.9	8.9
1020	12.5	8.2	8.9	9.5	10.6	8.6
1040	12.0	7.2	7.8	8.4	9.4	8.2
1060	11.6	6.3	6.9	7.4	8.3	7.8
1080	11.1	5.5	6.0	6.4	7.3	7.4
1100	10.6	4.7	5.2	5.6	6.4	7.1
1120	10.1	4.1	4.5	4.9	5.6	6.7
1140	9.6	3.5	3.9	4.2	4.8	6.4
1160	9.1	3.0	3.3	3.6	4.2	6.1
1180	8.6	2.5	2.8	3.1	3.6	5.7
1200	8.1	2.1	2.4	2.6	3.1	5.4
1220	7.6	1.8	2.0	2.2	2.6	5.1
1240	7.1	1.5	1.7	1.9	2.2	4.8
1260	6.6	1.2	1.4	1.6	1.9	4.5
1280	6.2	1.0	1.1	1.3	1.6	4.3
1300	5.7	0.8	0.9	1.0	1.3	4.0
						3.7

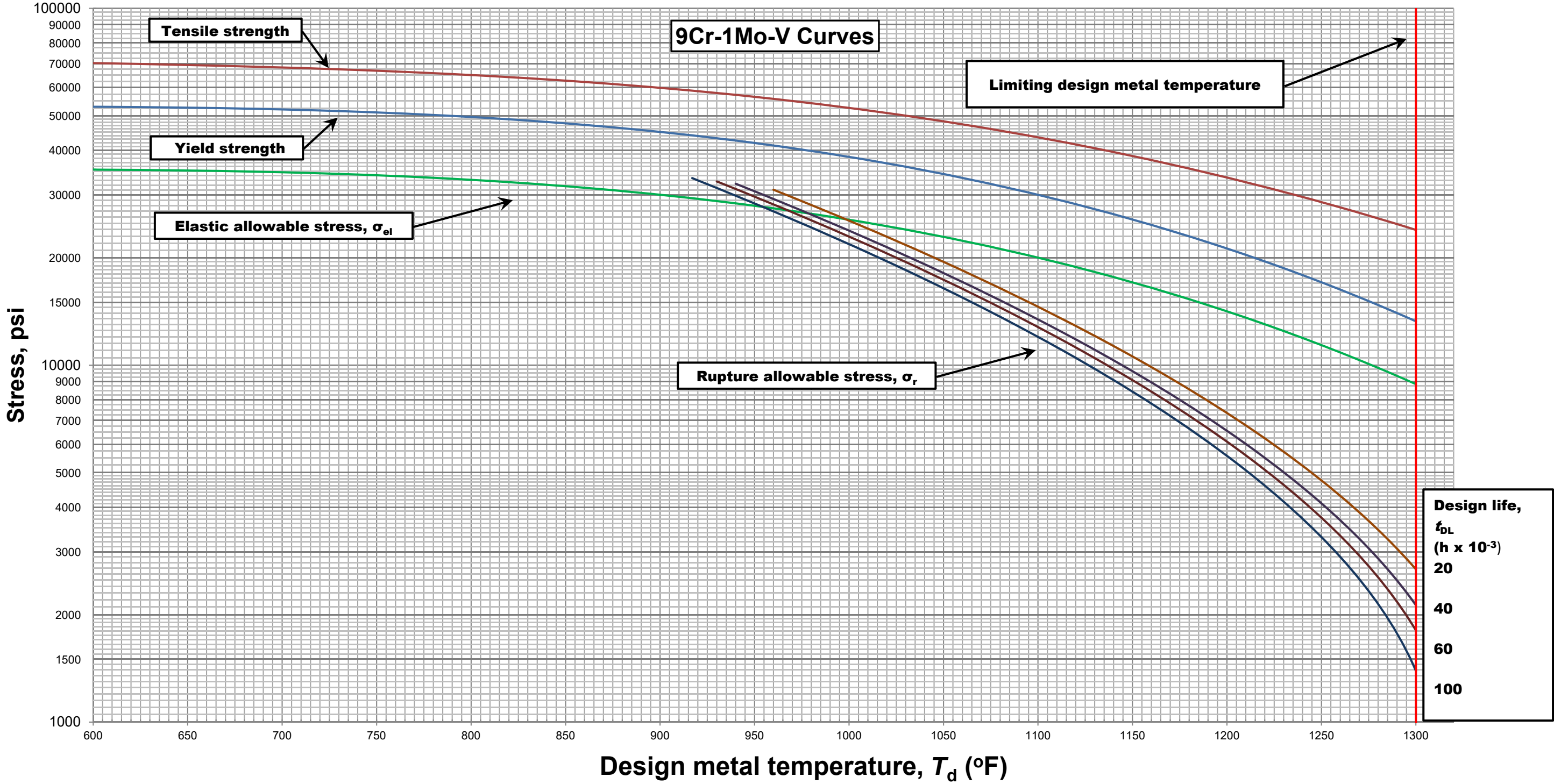


Figure F.28—Stress Curves (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

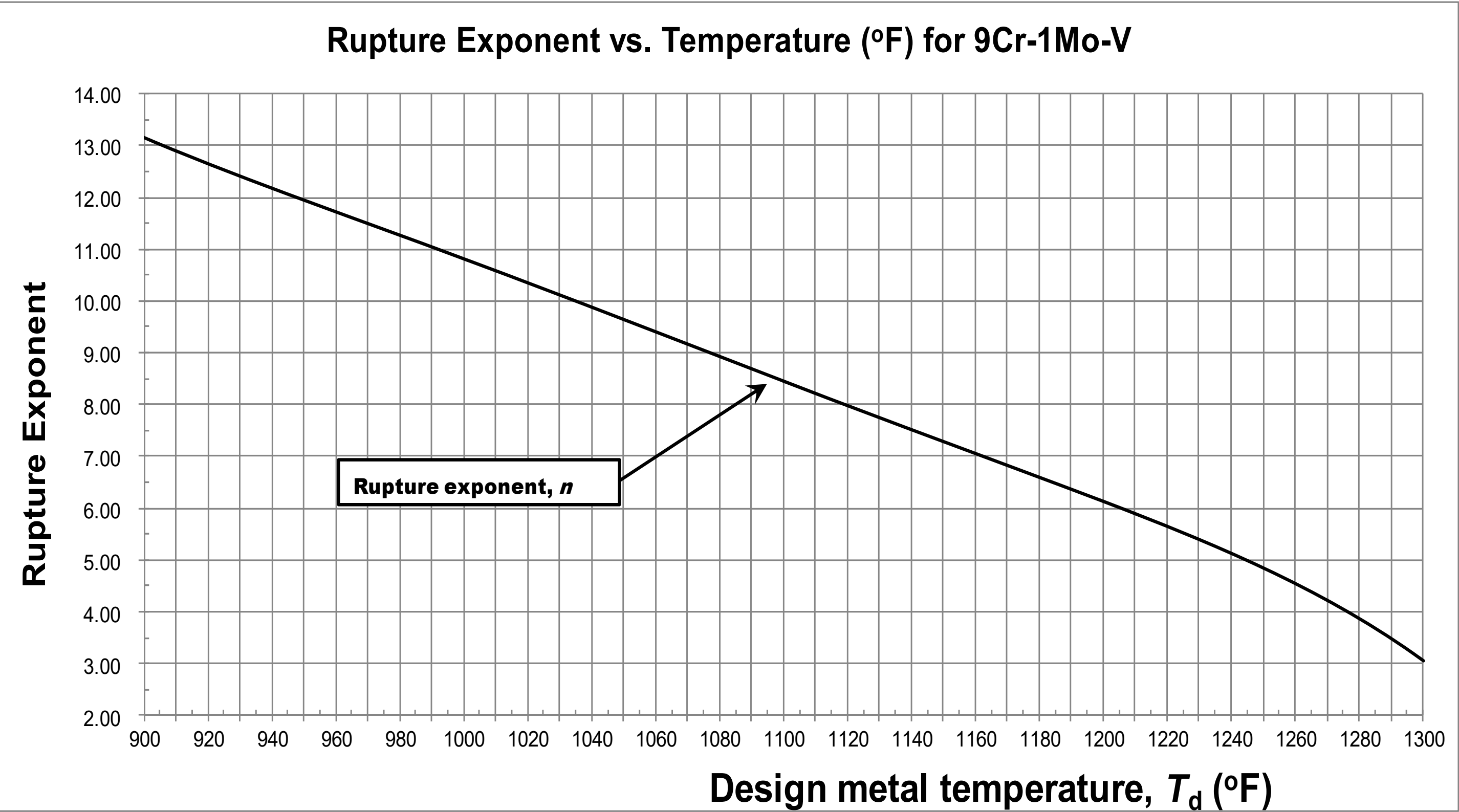


Figure F.29—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

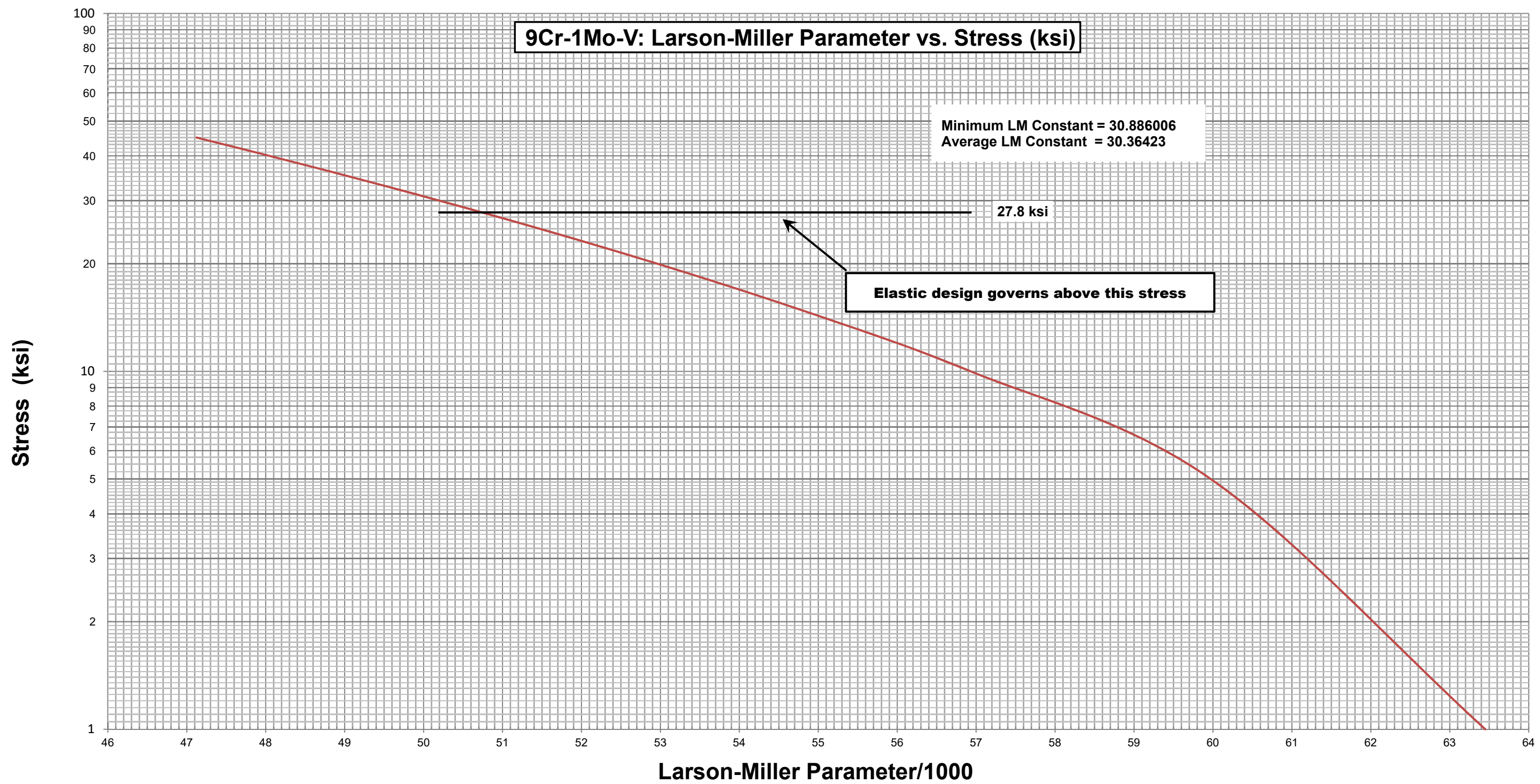


Figure F.30—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

Table F.10—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) ASTM A213 T91 and ASTM A335 P91 9Cr-1Mo-V Steels

9Cr-1Mo-V Steel						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	34.7					
720	34.5					
740	34.2					
760	33.9					
780	33.5					
800	33.1					
820	32.6					
840	32.0					
860	31.4					
880	30.8					
900	30.0	36.3	37.8	39.0	41.1	13.2
920	29.3	33.0	34.4	35.5	37.5	12.7
940	28.4	29.9	31.2	32.3	34.1	12.2
960	27.5	27.0	28.2	29.2	31.0	11.7
980	26.6	24.3	25.5	26.4	28.1	11.3
1000	25.6	21.8	22.9	23.8	25.4	10.8
1020	24.5	19.6	20.6	21.4	22.9	10.4
1040	23.4	17.4	18.4	19.2	20.6	9.9
1060	22.3	15.5	16.4	17.1	18.4	9.4
1080	21.2	13.7	14.5	15.2	16.4	8.9
1100	20.0	12.0	12.8	13.4	14.6	8.5
1120	18.9	10.5	11.2	11.8	12.9	8.0
1140	17.7	9.1	9.8	10.3	11.3	7.5
1160	16.5	7.8	8.4	9.0	9.9	7.1
1180	15.3	6.6	7.2	7.7	8.6	6.6
1200	14.2	5.6	6.1	6.6	7.3	6.1
1220	13.0	4.6	5.1	5.5	6.2	5.6
1240	11.9	3.7	4.2	4.5	5.2	5.1
1250	11.4	3.3	3.7	4.1	4.8	4.8
1260	10.9	2.9	3.3	3.7	4.3	4.5
1280	9.8	2.1	2.5	2.9	3.5	3.9
1300	8.9	1.4	1.8	2.1	2.7	3.0

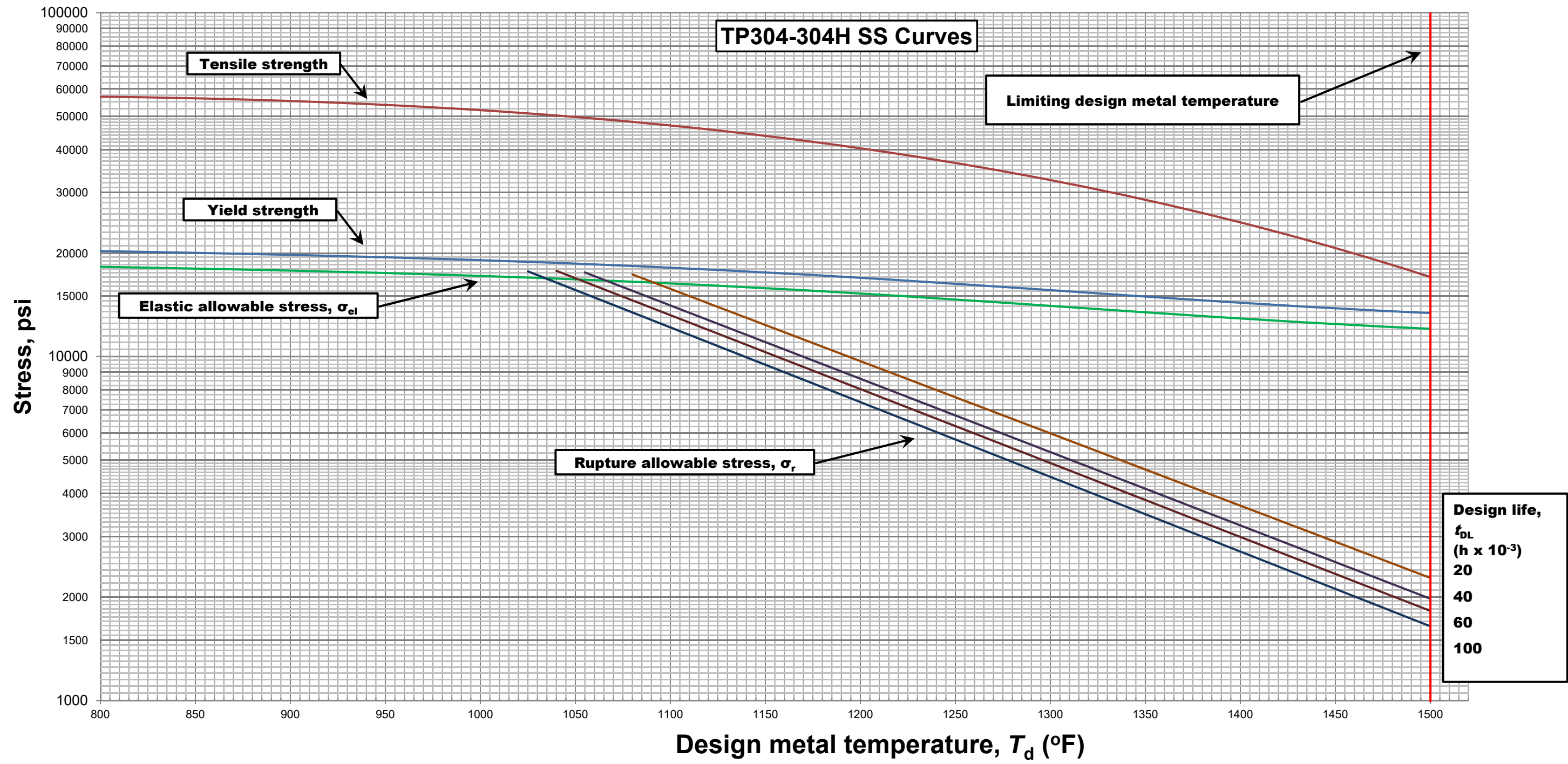


Figure F.31—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

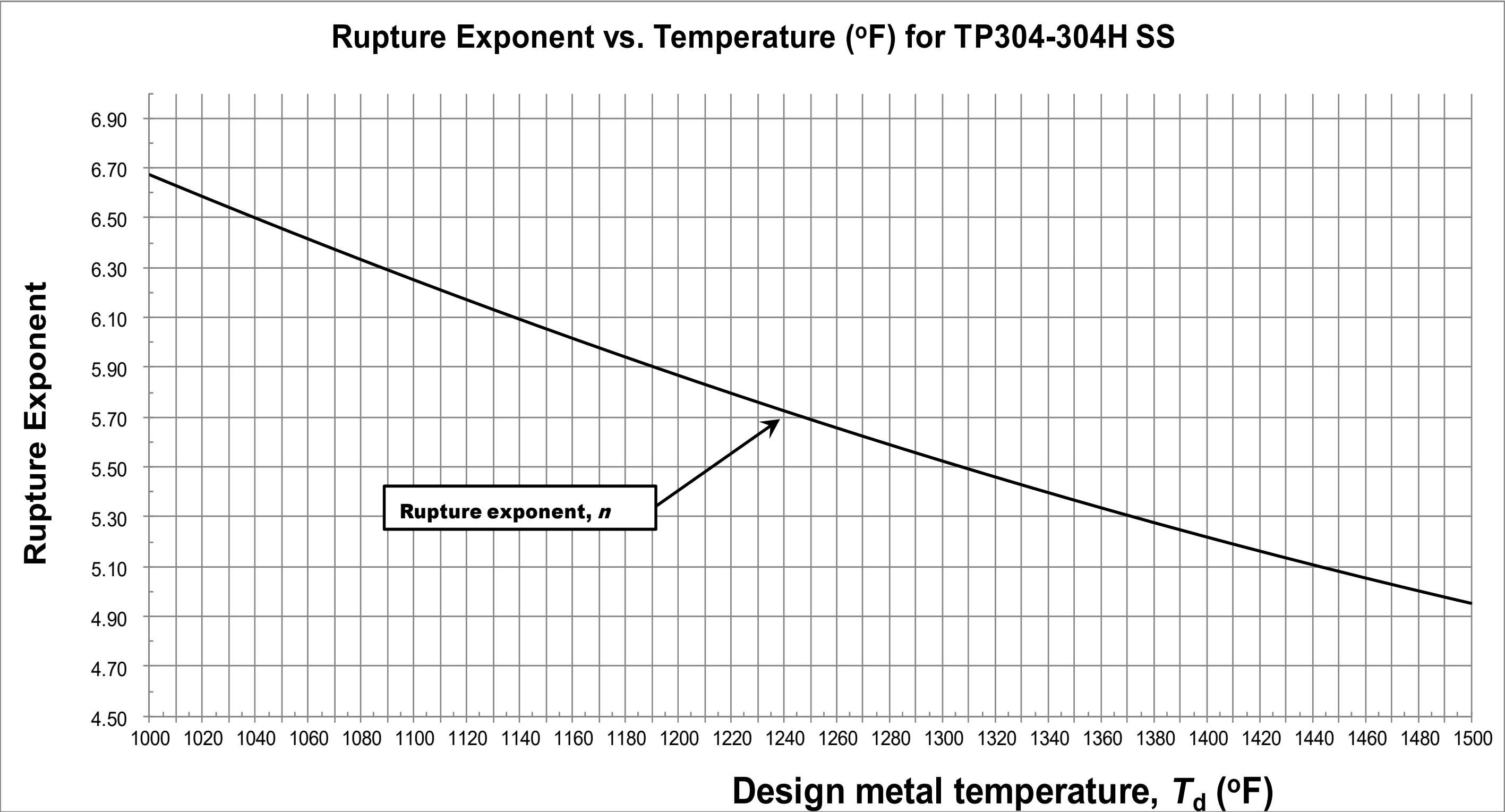


Figure F.32—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

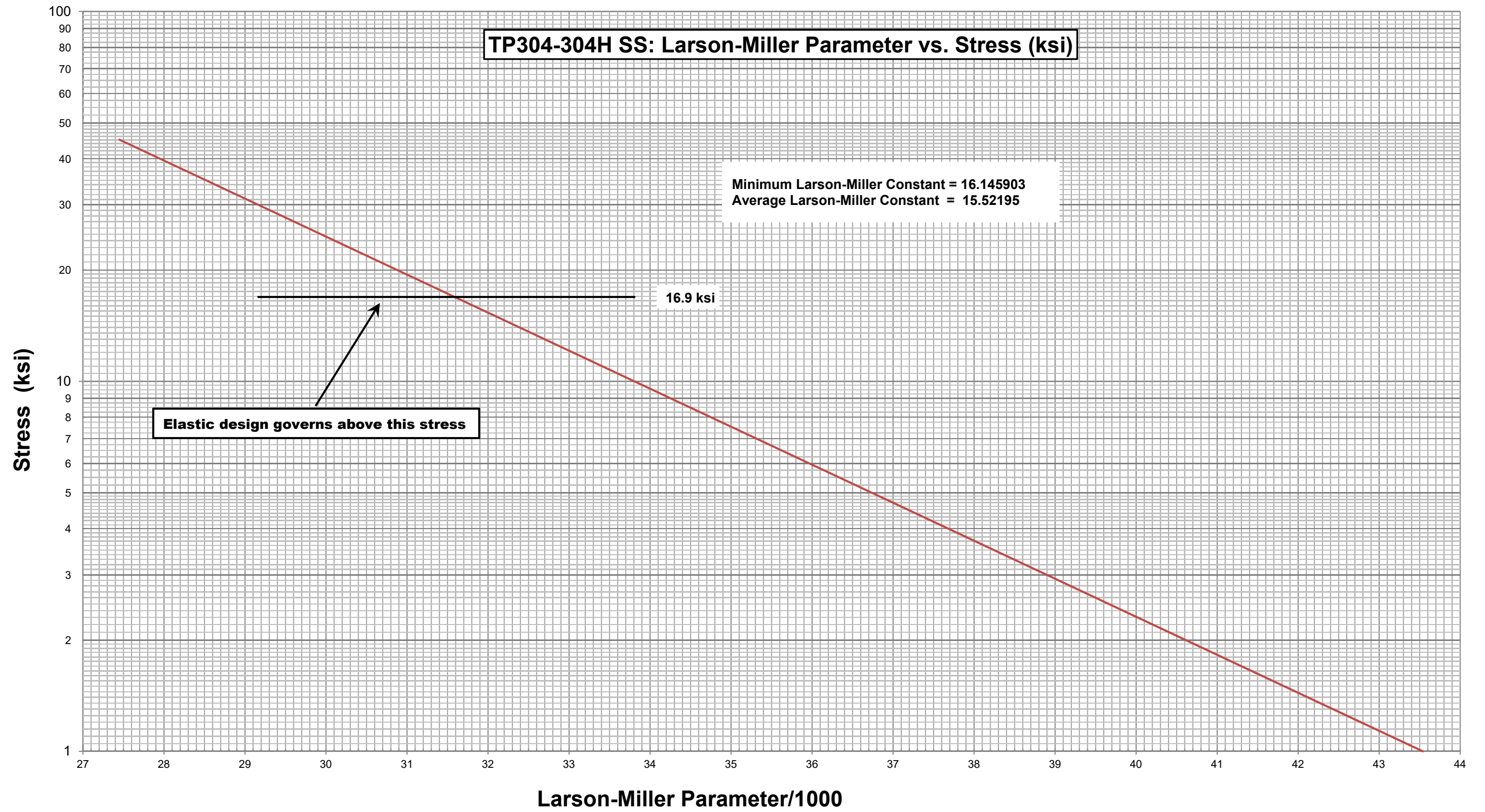


Figure F.33—Larson-Miller Parameter vs. Stress Curve (USC Units) for A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

Table F.11—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for A213, ASTM A271, ASTM A312, and ASTM 376 TP 304 and 304H (18Cr-8Ni) Stainless Steels

TP304-304H SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	18.2					
820	18.2					
840	18.1					
860	18.0					
880	17.9					
900	17.8					
920	17.7					
940	17.6					
960	17.4					
980	17.3					
1000	17.2	20.1	21.7	23.0	25.5	6.7
1020	17.0	18.1	19.6	20.9	23.2	6.6
1040	16.9	16.4	17.8	18.9	21.0	6.5
1060	16.7	14.9	16.1	17.1	19.1	6.4
1080	16.5	13.4	14.6	15.5	17.3	6.3
1100	16.3	12.2	13.2	14.1	15.7	6.3
1120	16.1	11.0	12.0	12.8	14.3	6.2
1140	15.9	10.0	10.8	11.6	13.0	6.1
1160	15.7	9.0	9.8	10.5	11.8	6.0
1180	15.5	8.1	8.9	9.5	10.7	5.9
1200	15.2	7.4	8.0	8.6	9.7	5.9
1220	15.0	6.7	7.3	7.8	8.8	5.8
1240	14.8	6.0	6.6	7.1	8.0	5.7
1260	14.5	5.5	6.0	6.4	7.3	5.7
1280	14.3	4.9	5.4	5.8	6.6	5.6
1300	14.1	4.5	4.9	5.3	6.0	5.5
1320	13.8	4.0	4.4	4.8	5.4	5.5
1340	13.6	3.7	4.0	4.3	4.9	5.4
1360	13.3	3.3	3.6	3.9	4.5	5.3
1380	13.1	3.0	3.3	3.6	4.1	5.3
1400	12.9	2.7	3.0	3.2	3.7	5.2
1420	12.7	2.5	2.7	2.9	3.3	5.2
1440	12.5	2.2	2.5	2.7	3.0	5.1
1460	12.3	2.0	2.2	2.4	2.8	5.1
1480	12.2	1.8	2.0	2.2	2.5	5.0
1500	12.1	1.6	1.8	2.0	2.3	5.0

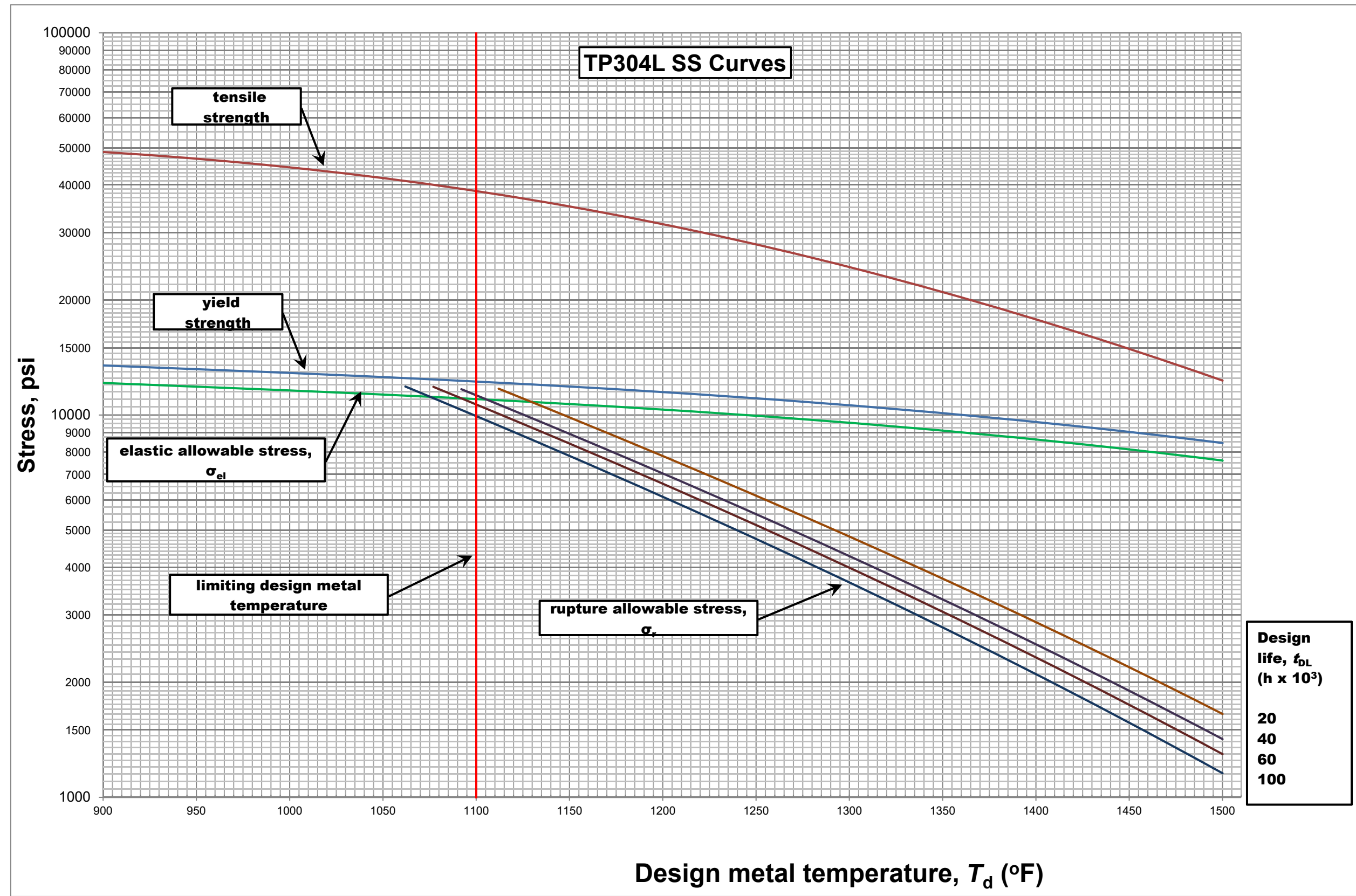


Figure F.34—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

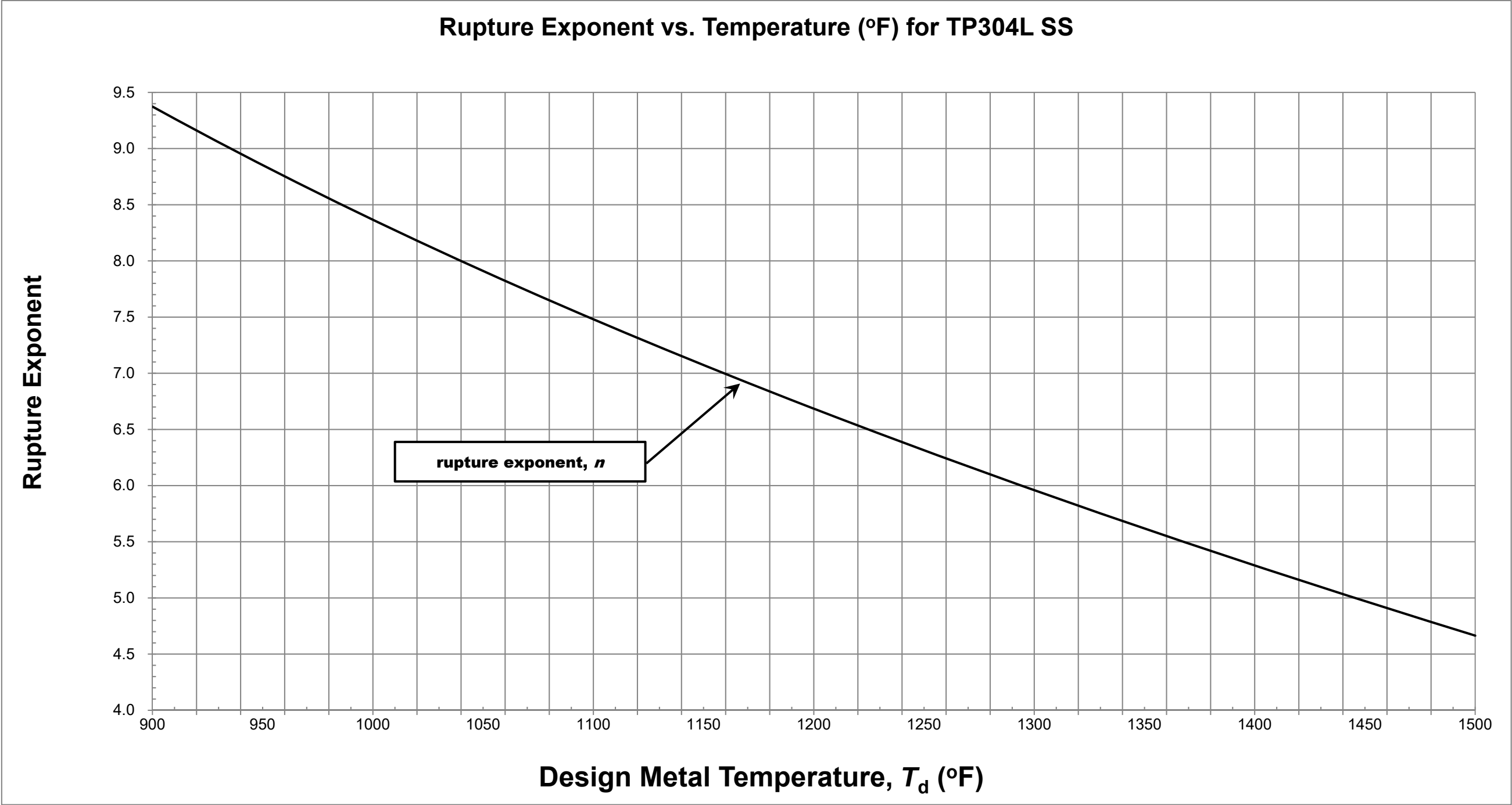


Figure F.35—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

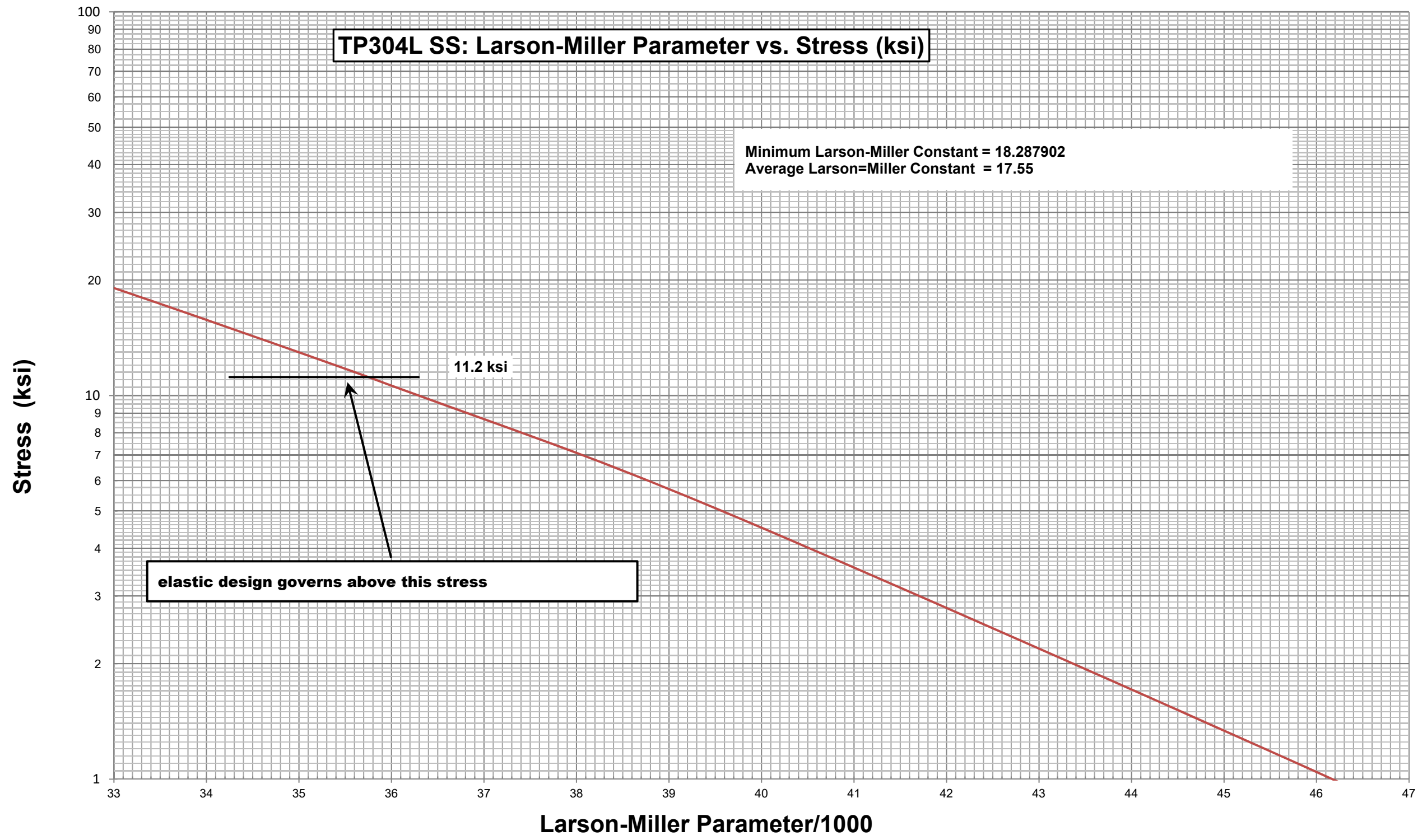


Figure F.36—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

Table F.12—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP304L (18Cr-8Ni) Stainless Steels

TP304L SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	12.7					
820	12.6					
840	12.5					
860	12.4					
880	12.2					
900	12.1					9.4
920	12.0					9.2
940	11.9					9.0
960	11.8					8.8
980	11.7					8.6
1000	11.6					8.4
1020	11.5					8.2
1040	11.4					8.0
1060	11.3					7.8
1080	11.1					7.6
1100	11.0					7.5
1120	10.9					7.3
1140	10.8					7.2
1160	10.6					7.0
1180	10.5					6.8
1200	10.3	13.1	14.0	14.8	16.1	6.7
1220	10.2	12.0	12.8	13.5	14.8	6.5
1240	10.0	10.9	11.7	12.3	13.5	6.4
1260	9.9	9.9	10.7	11.3	12.4	6.2
1280	9.7	9.0	9.7	10.3	11.3	6.1
1300	9.5	8.2	8.8	9.4	10.3	6.0
1320	9.4	7.4	8.0	8.5	9.4	5.8
1340	9.2	6.8	7.3	7.7	8.6	5.7
1360	9.0	6.1	6.6	7.0	7.8	5.6
1380	8.8	5.5	6.0	6.4	7.1	5.4
1400	8.6	5.0	5.4	5.8	6.5	5.3
1420	8.4	4.5	4.9	5.2	5.9	5.2
1440	8.2	4.1	4.4	4.7	5.3	5.0
1460	8.0	3.6	4.0	4.3	4.8	4.9
1480	7.8	3.3	3.6	3.9	4.4	4.8
1500	7.6	2.9	3.2	3.5	3.9	4.7

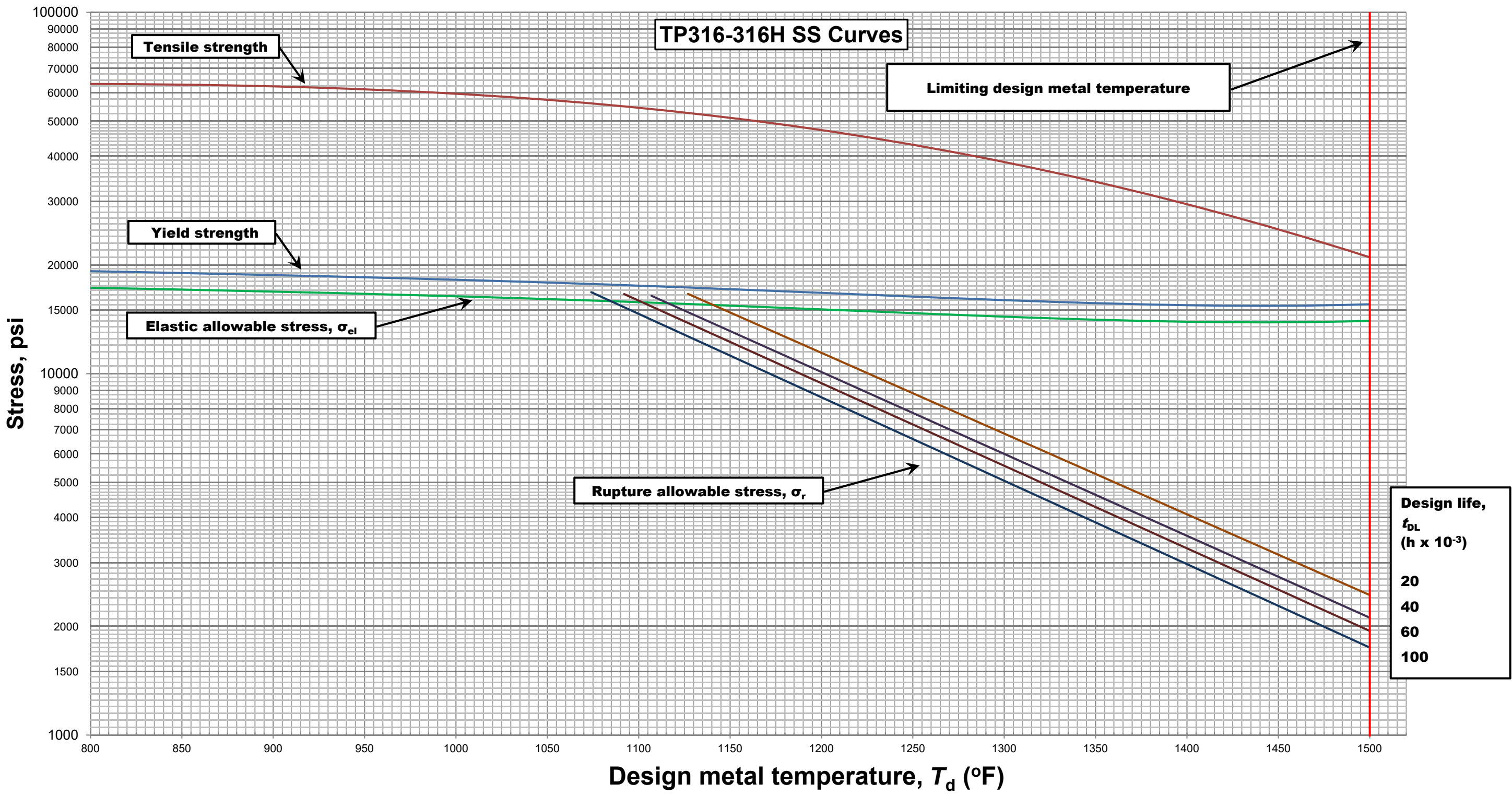


Figure F.37—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

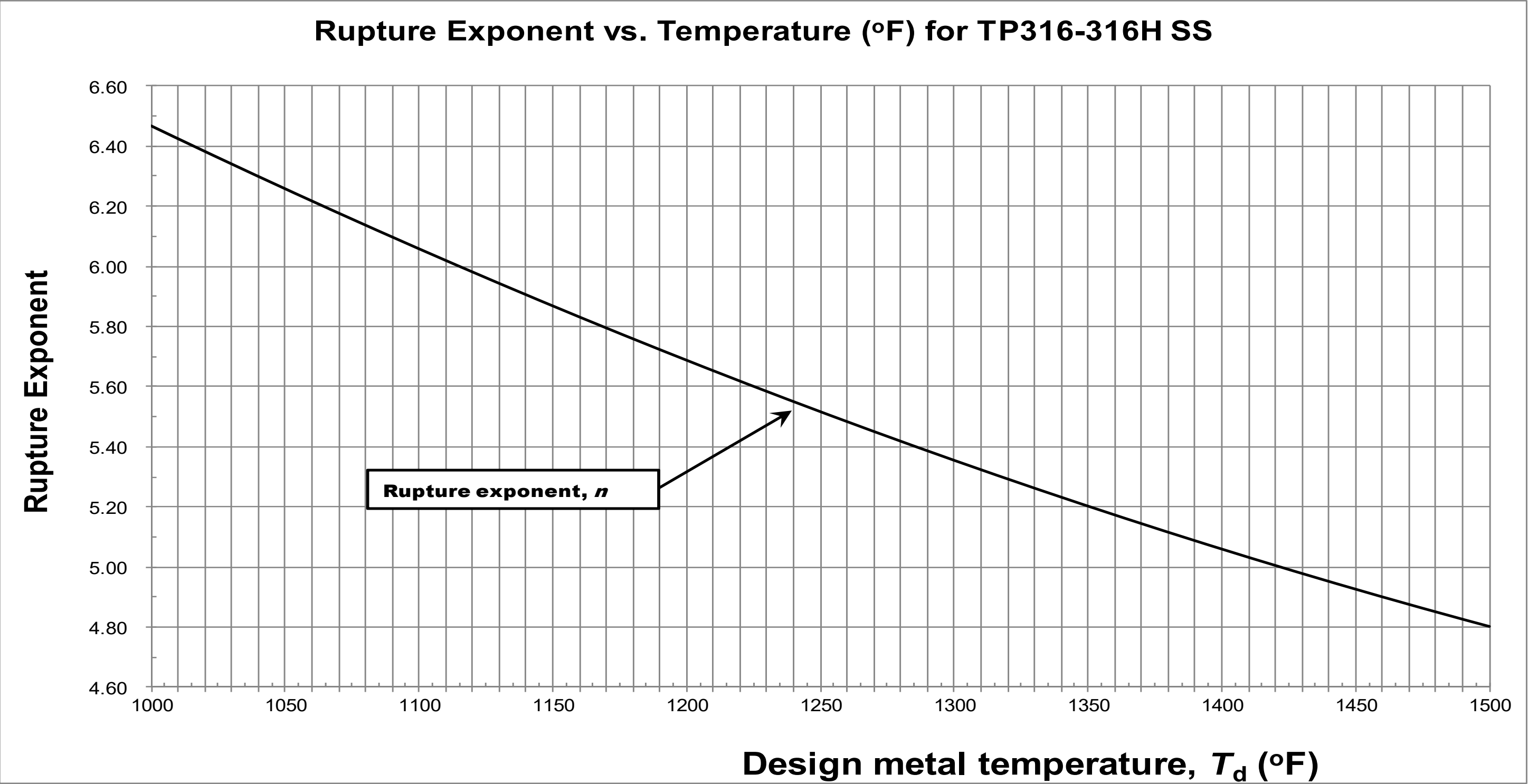


Figure F.38—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

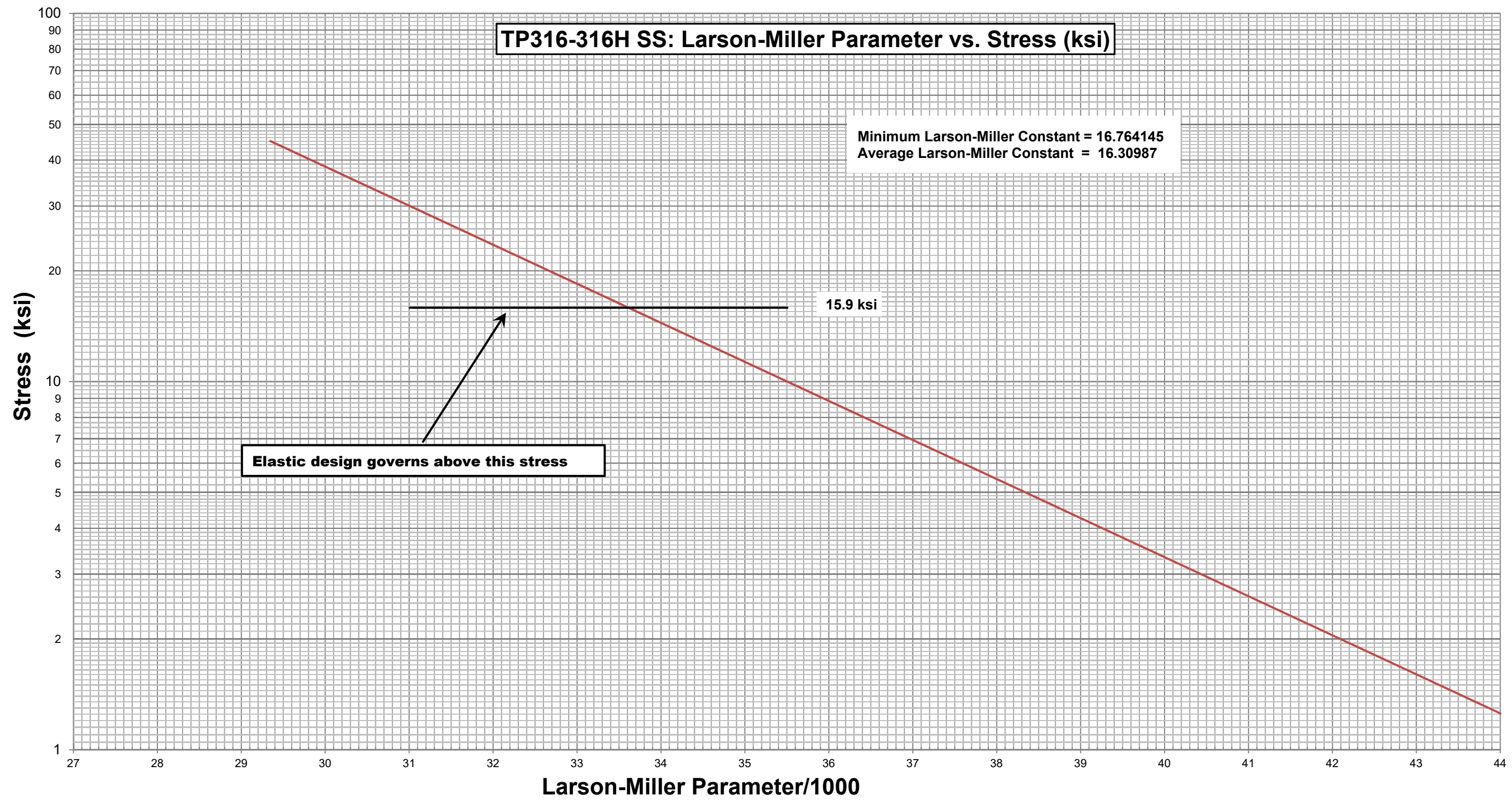


Figure F.39—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

Table F.13—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 316 and 316H (16Cr-12Ni-2Mo) Stainless Steels

TP316-316H SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	17.3					
820	17.2					
840	17.1					
860	17.0					
880	17.0					
900	16.9					
920	16.8					
940	16.7					
960	16.6					
980	16.5					
1000	16.4					6.5
1020	16.3					6.4
1040	16.2					6.3
1060	16.0	18.1	19.7	21.0	23.5	6.2
1080	15.9	16.3	17.7	18.9	21.2	6.1
1100	15.8	14.6	15.9	17.0	19.1	6.1
1120	15.6	13.2	14.3	15.3	17.2	6.0
1140	15.5	11.8	12.9	13.8	15.6	5.9
1160	15.4	10.6	11.6	12.5	14.0	5.8
1180	15.2	9.6	10.5	11.2	12.7	5.8
1200	15.1	8.6	9.4	10.1	11.4	5.7
1220	14.9	7.7	8.5	9.1	10.3	5.6
1240	14.8	7.0	7.6	8.2	9.3	5.5
1260	14.6	6.3	6.9	7.4	8.4	5.5
1280	14.5	5.6	6.2	6.7	7.6	5.4
1300	14.4	5.1	5.6	6.0	6.8	5.4
1320	14.3	4.5	5.0	5.4	6.2	5.3
1340	14.2	4.1	4.5	4.9	5.6	5.2
1360	14.1	3.7	4.1	4.4	5.0	5.2
1380	14.0	3.3	3.7	4.0	4.5	5.1
1400	13.9	3.0	3.3	3.6	4.1	5.1
1420	13.9	2.7	3.0	3.2	3.7	5.0
1440	13.9	2.4	2.7	2.9	3.3	5.0
1460	13.9	2.2	2.4	2.6	3.0	4.9
1480	13.9	1.9	2.2	2.3	2.7	4.8
1500	14.0	1.7	1.9	2.1	2.4	4.8

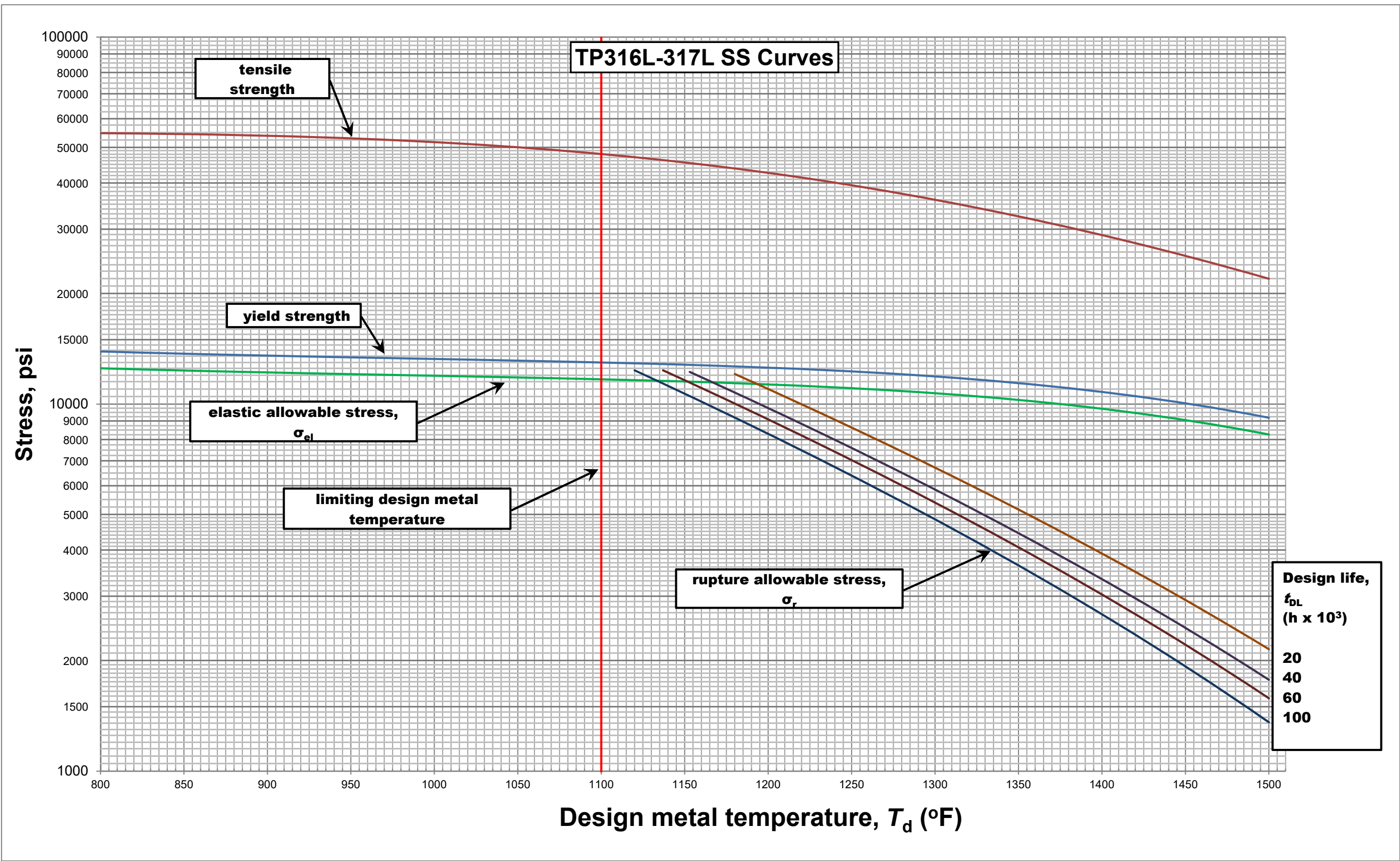


Figure F.40—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASMT A379 TP316L (18Cr-8Ni) Stainless Steels

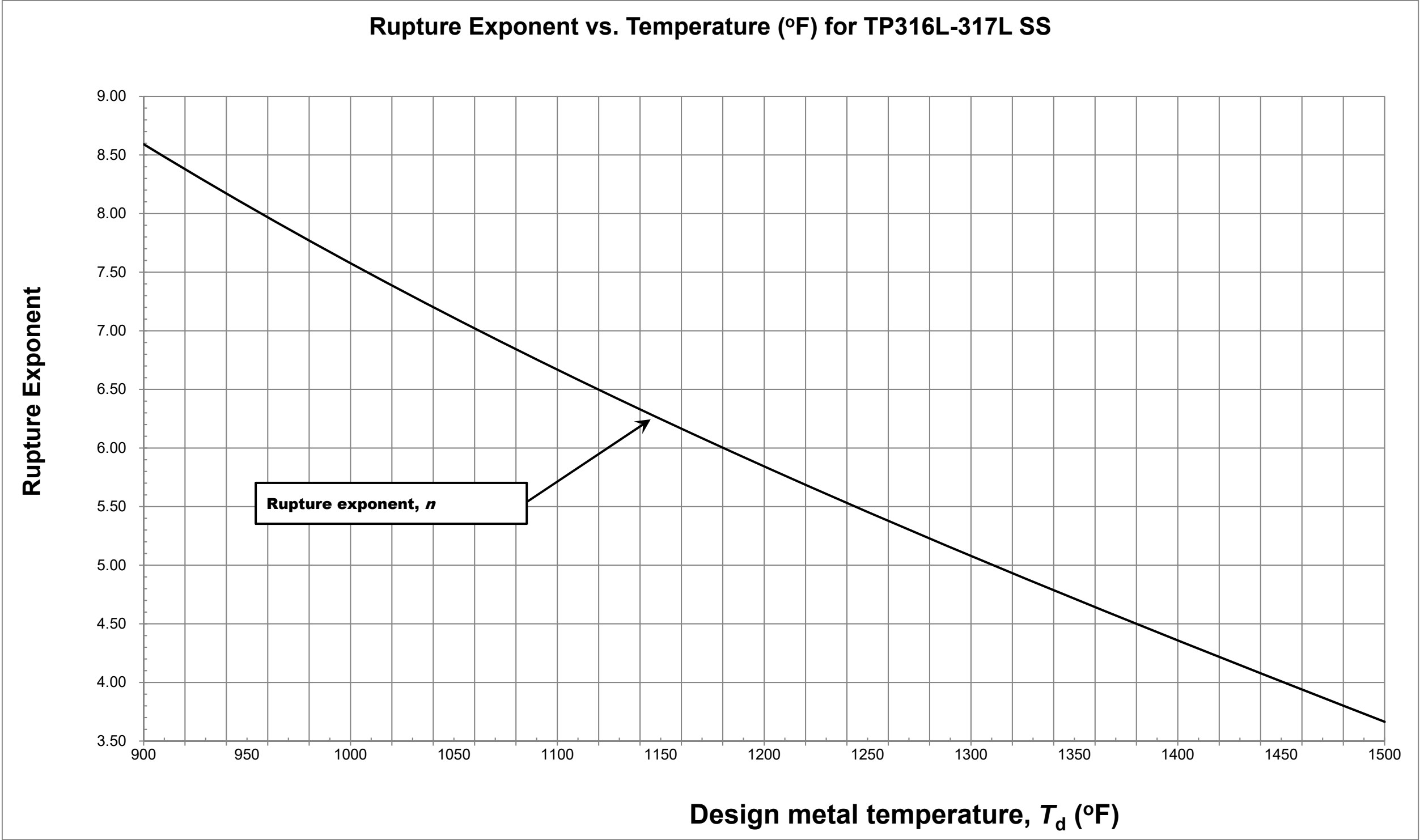


Figure F.41—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

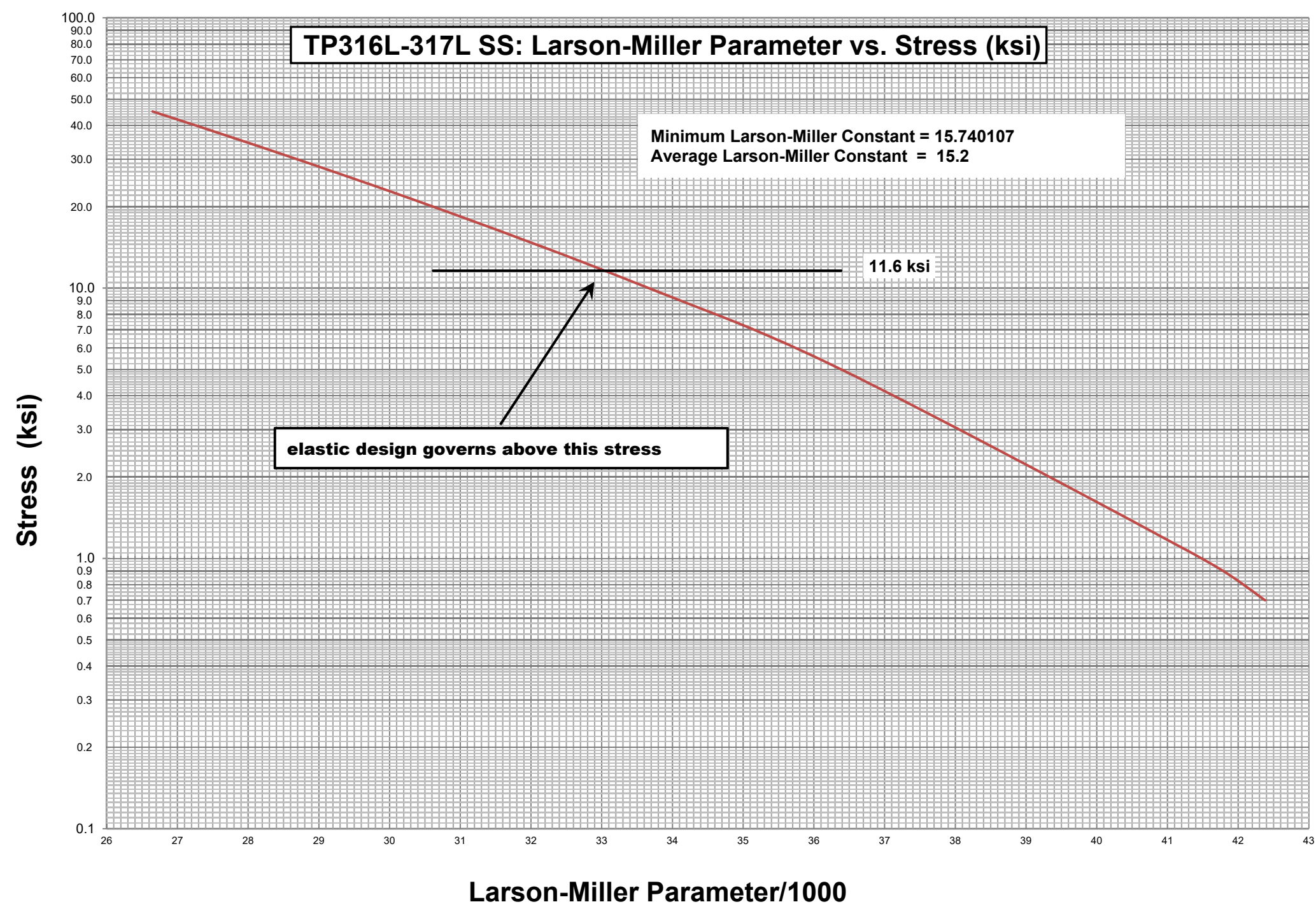


Figure F.42—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

Table F.14—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP316L-317L Stainless Steels

TP316L-317L SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	12.5					
820	12.5					
840	12.4					
860	12.3					
880	12.3					
900	12.2					8.6
920	12.2					8.4
940	12.1					8.2
960	12.0					8.0
980	12.0					7.8
1000	12.0					7.6
1020	11.9					7.4
1040	11.9					7.2
1060	11.8					7.0
1080	11.7					6.8
1100	11.7	13.6	14.7	15.7	17.4	6.7
1120	11.6	12.4	13.4	14.3	15.9	6.5
1140	11.6	11.2	12.2	13.0	14.5	6.3
1160	11.5	10.2	11.1	11.8	13.3	6.2
1180	11.4	9.2	10.0	10.8	12.1	6.0
1200	11.3	8.3	9.1	9.8	11.0	5.8
1220	11.2	7.5	8.2	8.8	10.0	5.7
1240	11.1	6.7	7.4	8.0	9.1	5.5
1260	11.0	6.1	6.7	7.2	8.2	5.4
1280	10.9	5.4	6.0	6.5	7.4	5.2
1300	10.7	4.9	5.4	5.9	6.7	5.1
1320	10.5	4.3	4.8	5.3	6.1	4.9
1340	10.4	3.9	4.3	4.7	5.4	4.8
1360	10.2	3.4	3.8	4.2	4.9	4.6
1380	10.0	3.0	3.4	3.8	4.4	4.5
1400	9.7	2.7	3.0	3.3	3.9	4.4
1420	9.5	2.4	2.7	3.0	3.5	4.2
1440	9.2	2.1	2.4	2.6	3.1	4.1
1460	8.9	1.8	2.1	2.3	2.8	3.9
1480	8.6	1.6	1.8	2.0	2.4	3.8
1500	8.3	1.4	1.6	1.8	2.1	3.7

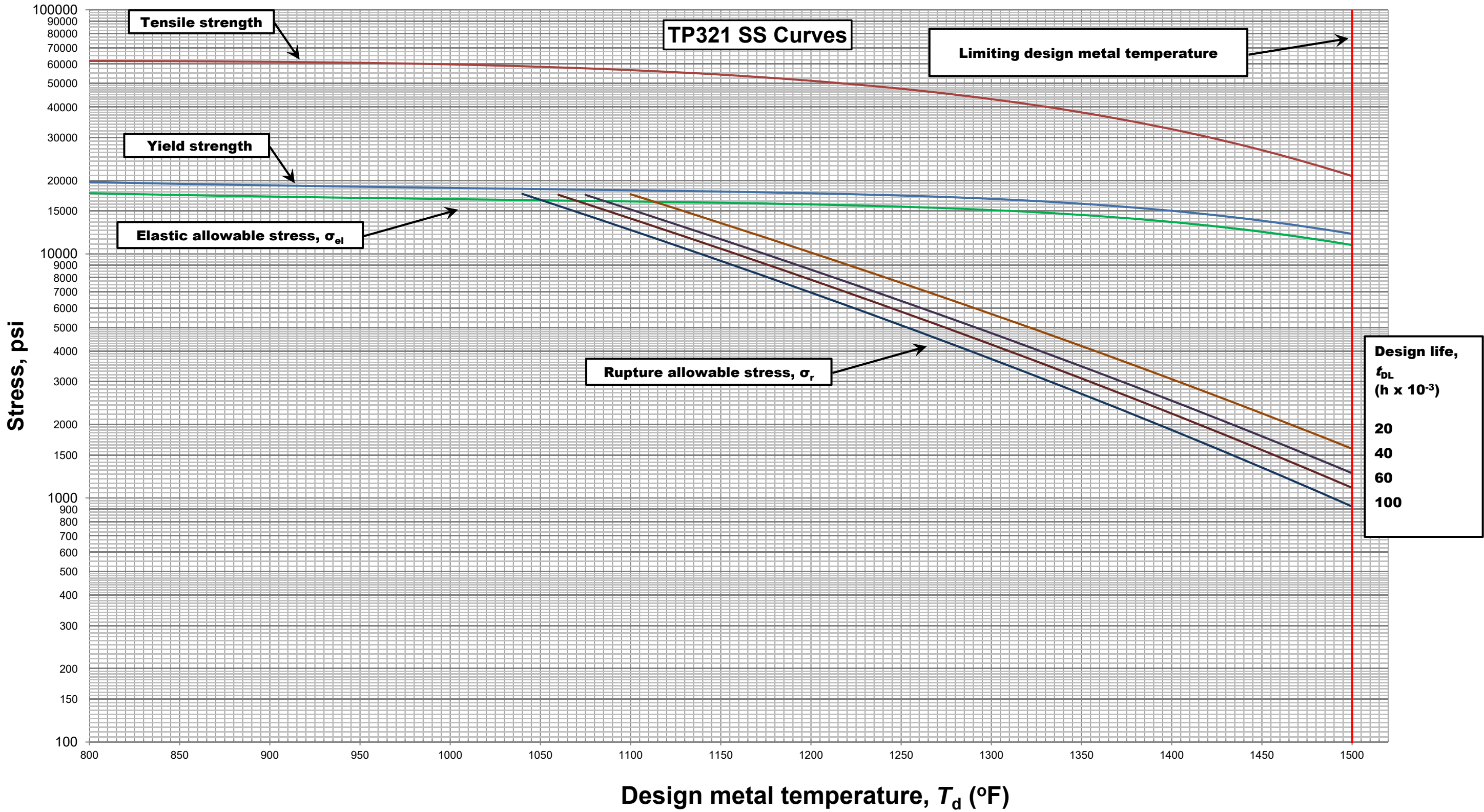


Figure F.43—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

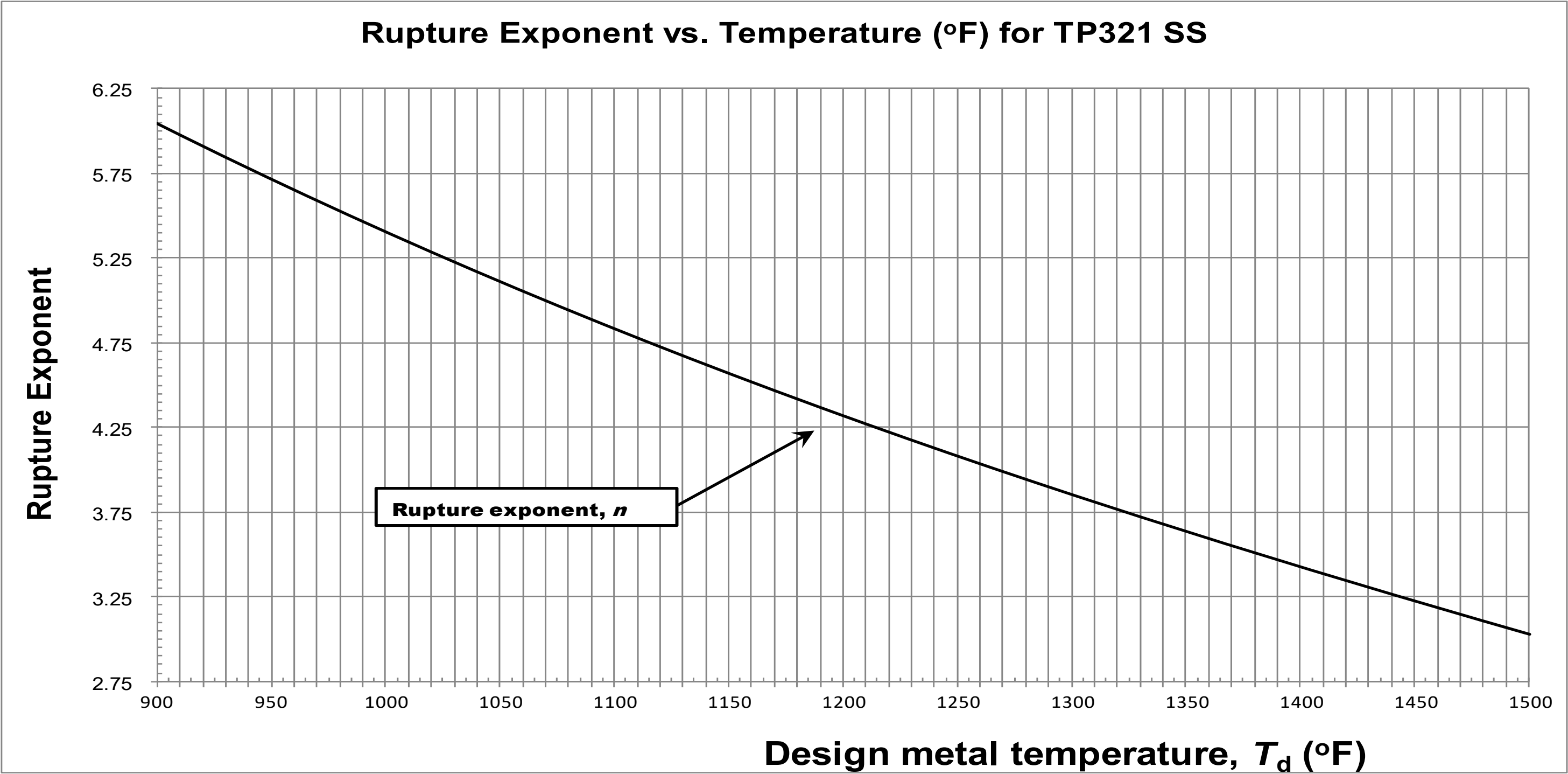


Figure F.44—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

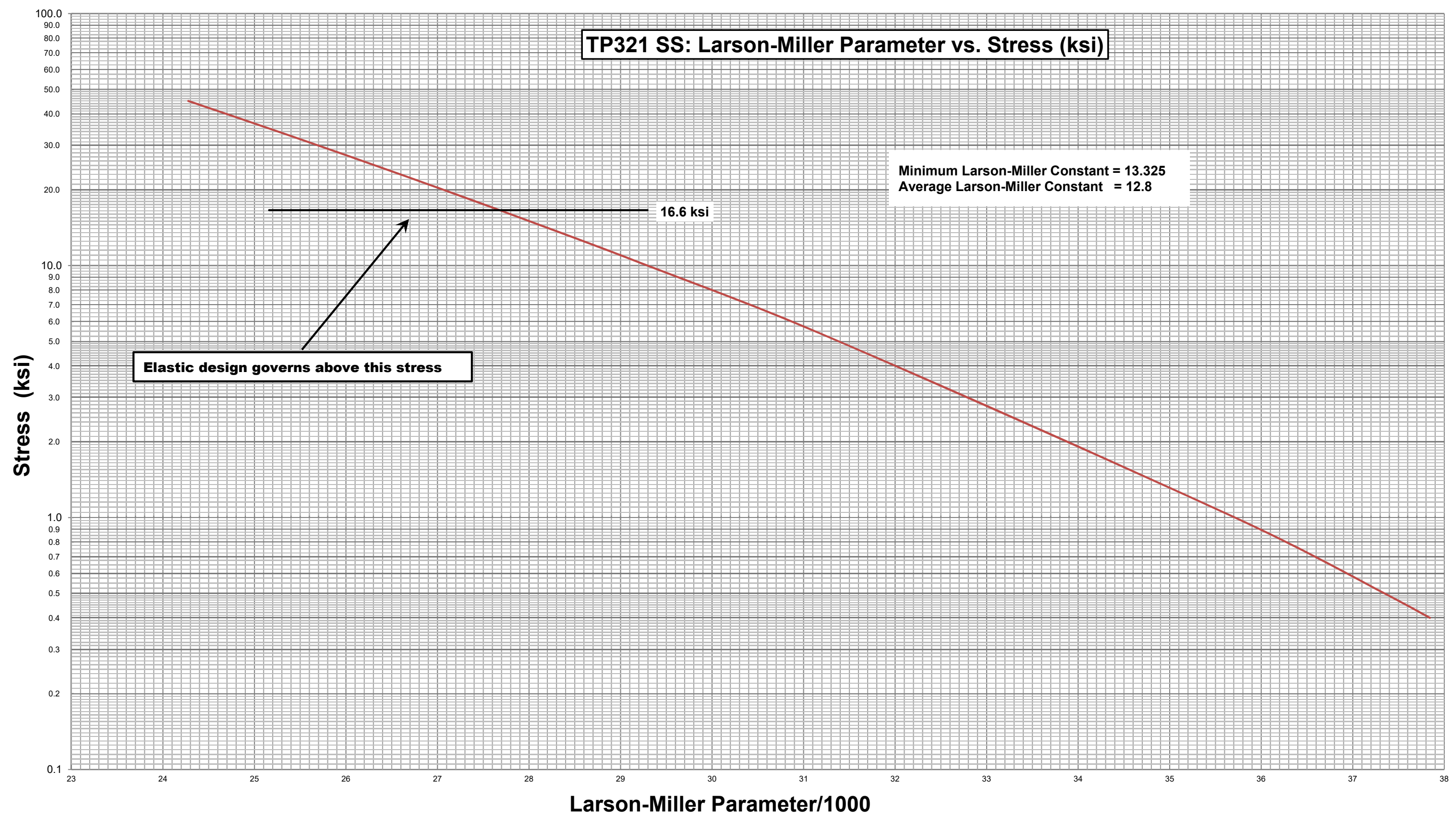


Figure F.45—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

Table F.15—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321 (18Cr-10Ni-Ti) Stainless Steels

TP321 SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	17.7					
820	17.6					
840	17.5					
860	17.4					
880	17.3					
900	17.2					6.0
920	17.1					5.9
940	17.0					5.8
960	16.9					5.7
980	16.8					5.5
1000	16.8					5.4
1020	16.7	19.7	21.7	23.5	26.8	5.3
1040	16.6	17.6	19.5	21.1	24.1	5.2
1060	16.6	15.7	17.5	18.9	21.7	5.1
1080	16.5	14.1	15.6	17.0	19.6	4.9
1100	16.4	12.5	14.0	15.2	17.6	4.8
1120	16.3	11.2	12.5	13.6	15.8	4.7
1140	16.3	9.9	11.1	12.2	14.1	4.6
1160	16.2	8.8	9.9	10.9	12.7	4.5
1180	16.1	7.8	8.8	9.7	11.3	4.4
1200	16.0	6.9	7.8	8.6	10.1	4.3
1220	15.8	6.1	7.0	7.7	9.0	4.2
1240	15.7	5.4	6.2	6.8	8.1	4.1
1260	15.5	4.8	5.5	6.0	7.2	4.0
1280	15.3	4.2	4.8	5.4	6.4	3.9
1300	15.1	3.7	4.3	4.7	5.7	3.9
1320	14.9	3.3	3.7	4.2	5.0	3.8
1340	14.6	2.9	3.3	3.7	4.5	3.7
1360	14.3	2.5	2.9	3.2	3.9	3.6
1380	13.9	2.2	2.5	2.9	3.5	3.5
1400	13.5	1.9	2.2	2.5	3.1	3.4
1420	13.1	1.7	1.9	2.2	2.7	3.3
1440	12.6	1.4	1.7	1.9	2.4	3.3
1460	12.1	1.2	1.5	1.7	2.1	3.2
1480	11.5	1.1	1.3	1.5	1.8	3.1
1500	10.9	0.9	1.1	1.3	1.6	3.0

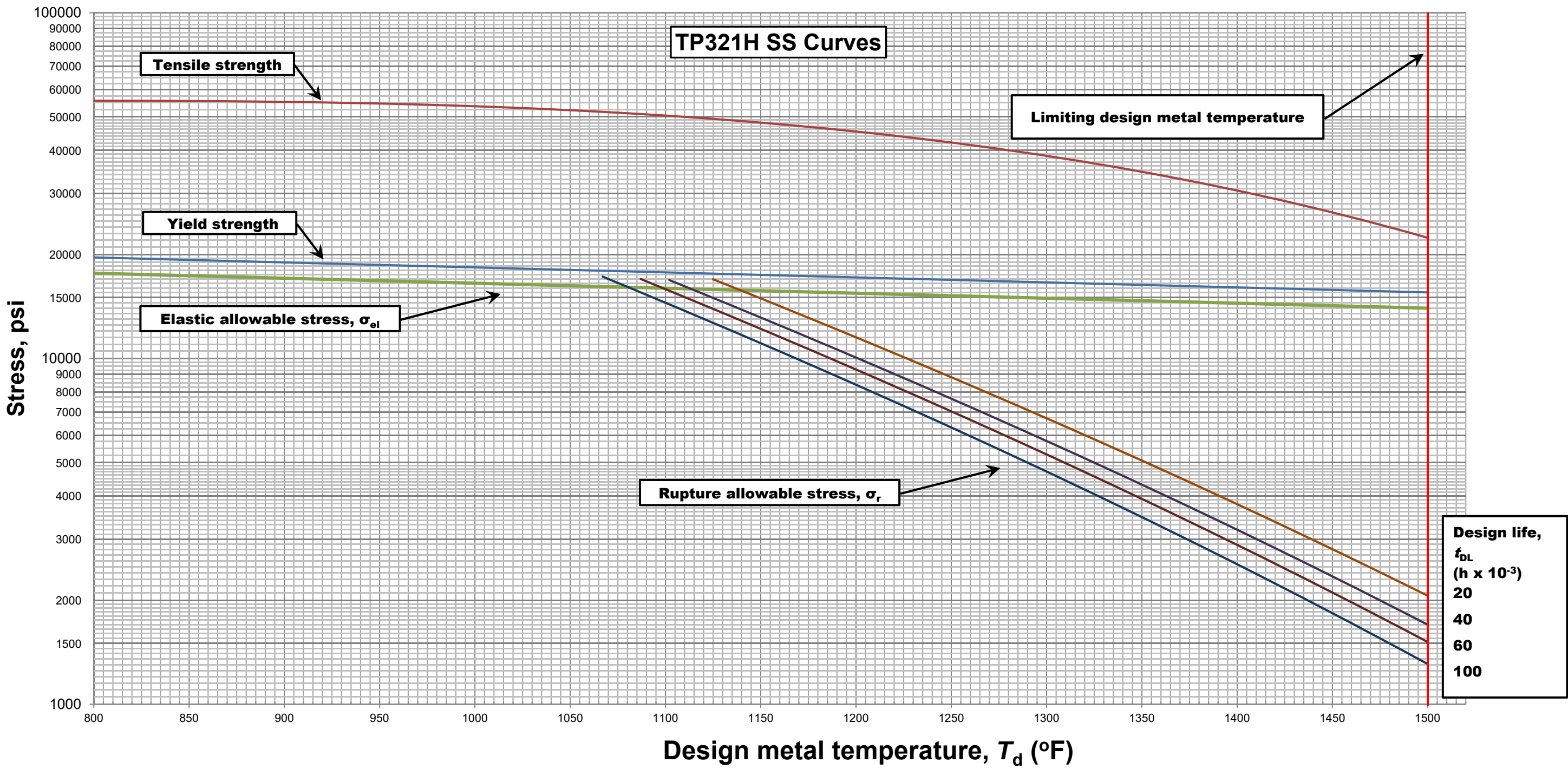


Figure F.46—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

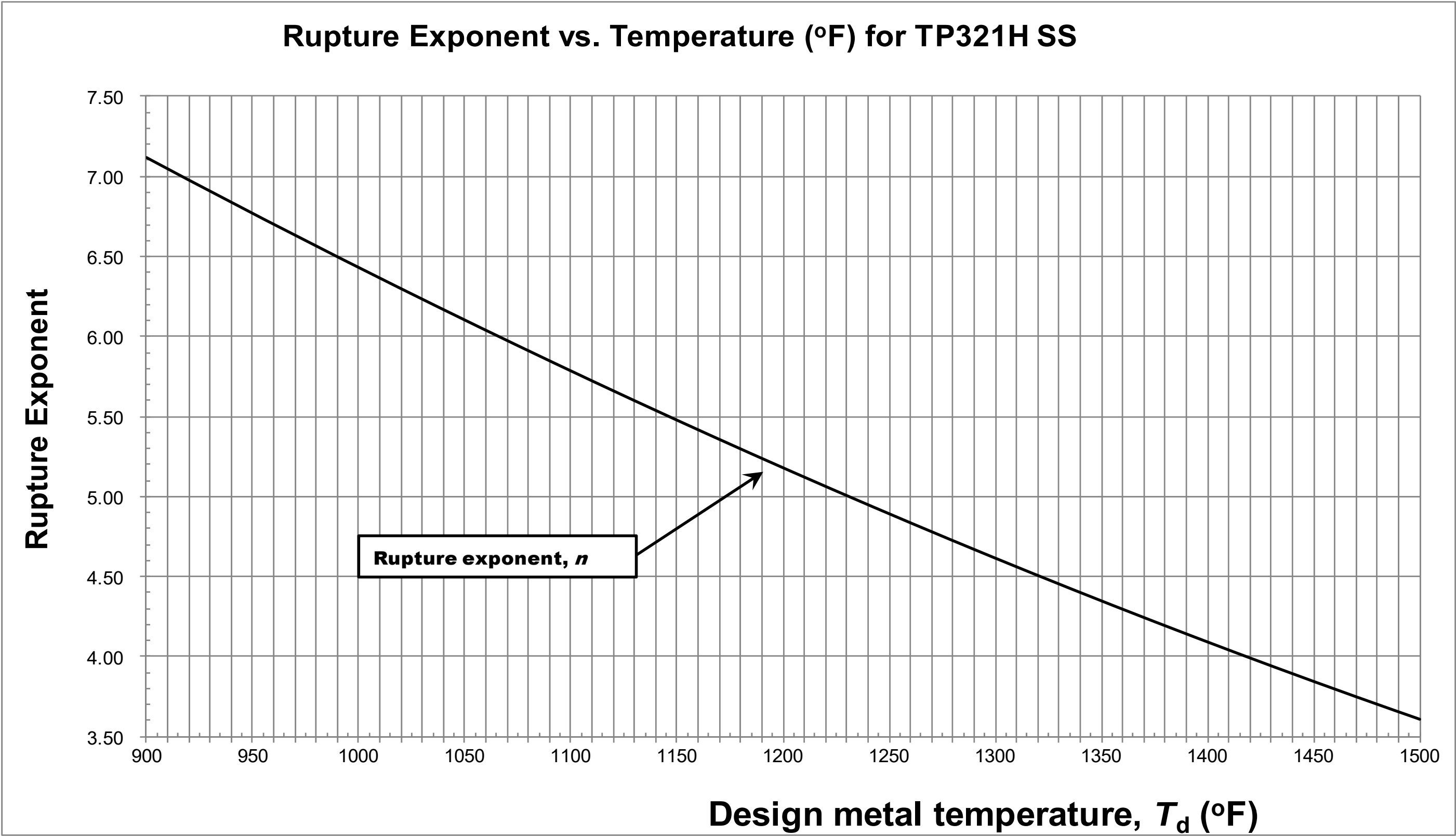


Figure F.47—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

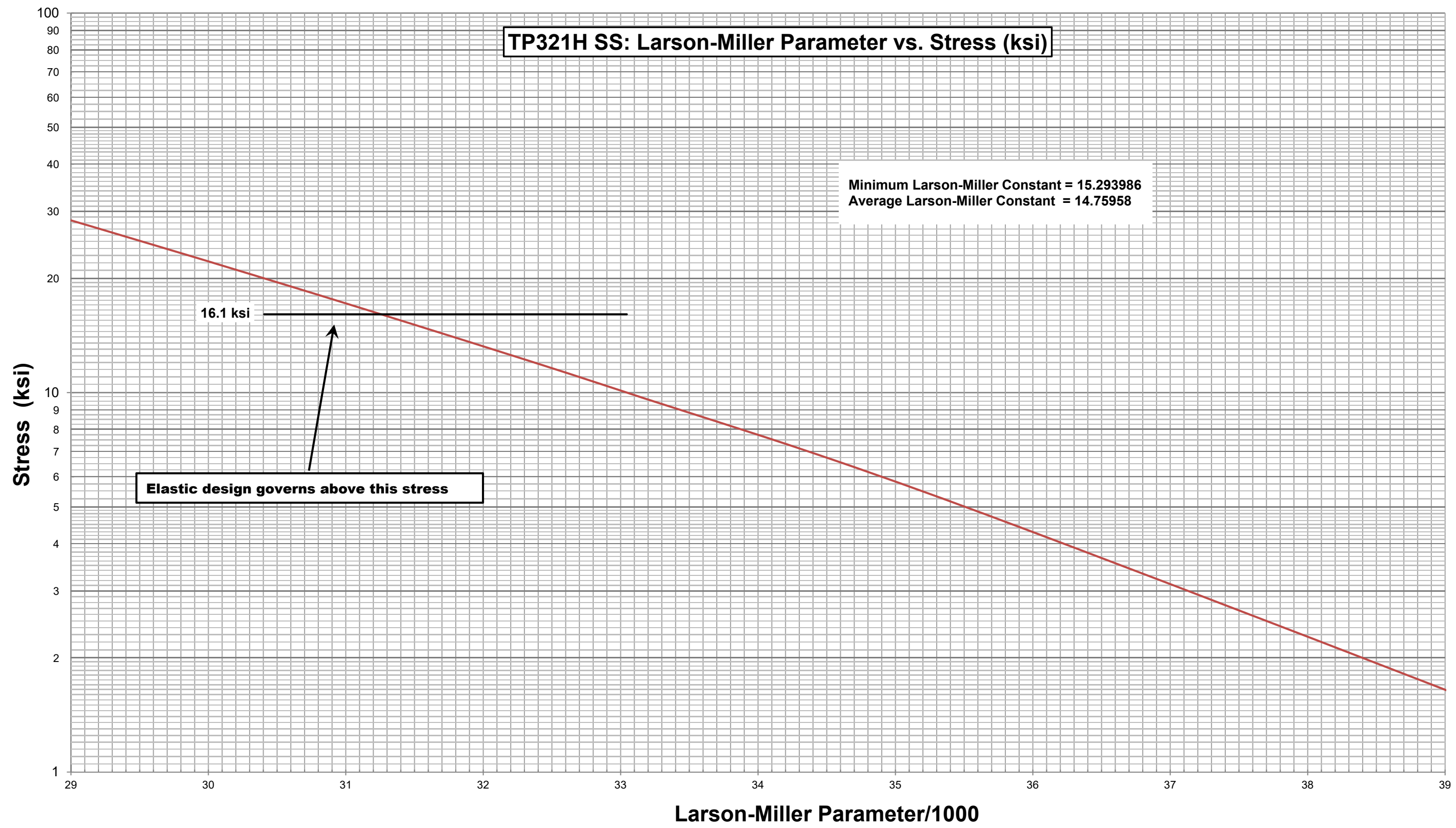


Figure F.48—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

Table F.16—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 321H (18Cr-10Ni-Ti) Stainless Steels

TP321H SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	17.6					
820	17.5					
840	17.4					
860	17.3					
880	17.2					
900	17.1					7.1
920	17.0					7.0
940	16.8					6.8
960	16.7					6.7
980	16.6					6.6
1000	16.5					6.4
1020	16.4					6.3
1040	16.3					6.2
1060	16.2	17.9	19.5	20.9	23.4	6.0
1080	16.1	16.1	17.6	18.9	21.2	5.9
1100	16.0	14.5	15.9	17.0	19.2	5.8
1120	15.9	13.0	14.3	15.4	17.4	5.7
1140	15.8	11.7	12.9	13.8	15.7	5.5
1160	15.7	10.5	11.6	12.5	14.2	5.4
1180	15.6	9.4	10.4	11.2	12.8	5.3
1200	15.5	8.4	9.3	10.1	11.5	5.2
1220	15.3	7.5	8.3	9.0	10.4	5.1
1240	15.2	6.7	7.4	8.1	9.3	4.9
1260	15.1	6.0	6.6	7.2	8.4	4.8
1280	15.0	5.3	5.9	6.5	7.5	4.7
1300	14.9	4.7	5.3	5.8	6.7	4.6
1320	14.8	4.2	4.7	5.1	6.0	4.5
1340	14.7	3.7	4.2	4.6	5.4	4.4
1360	14.6	3.3	3.7	4.1	4.8	4.3
1380	14.6	2.9	3.3	3.6	4.3	4.2
1400	14.5	2.5	2.9	3.2	3.8	4.1
1420	14.4	2.2	2.6	2.8	3.4	4.0
1440	14.3	2.0	2.2	2.5	3.0	3.9
1460	14.2	1.7	2.0	2.2	2.6	3.8
1480	14.1	1.5	1.7	1.9	2.3	3.7
1500	14.0	1.3	1.5	1.7	2.1	3.6

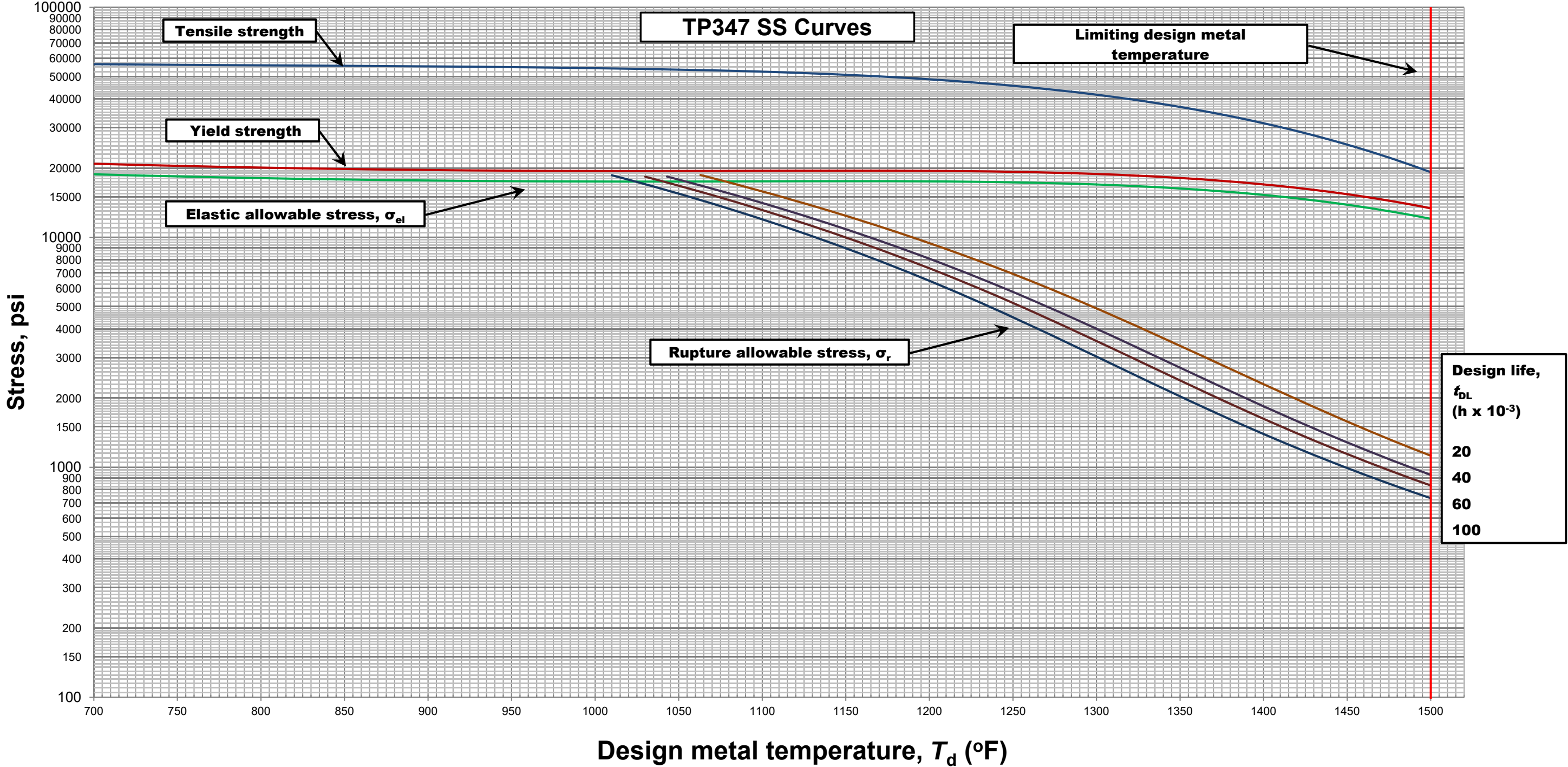


Figure F.49—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

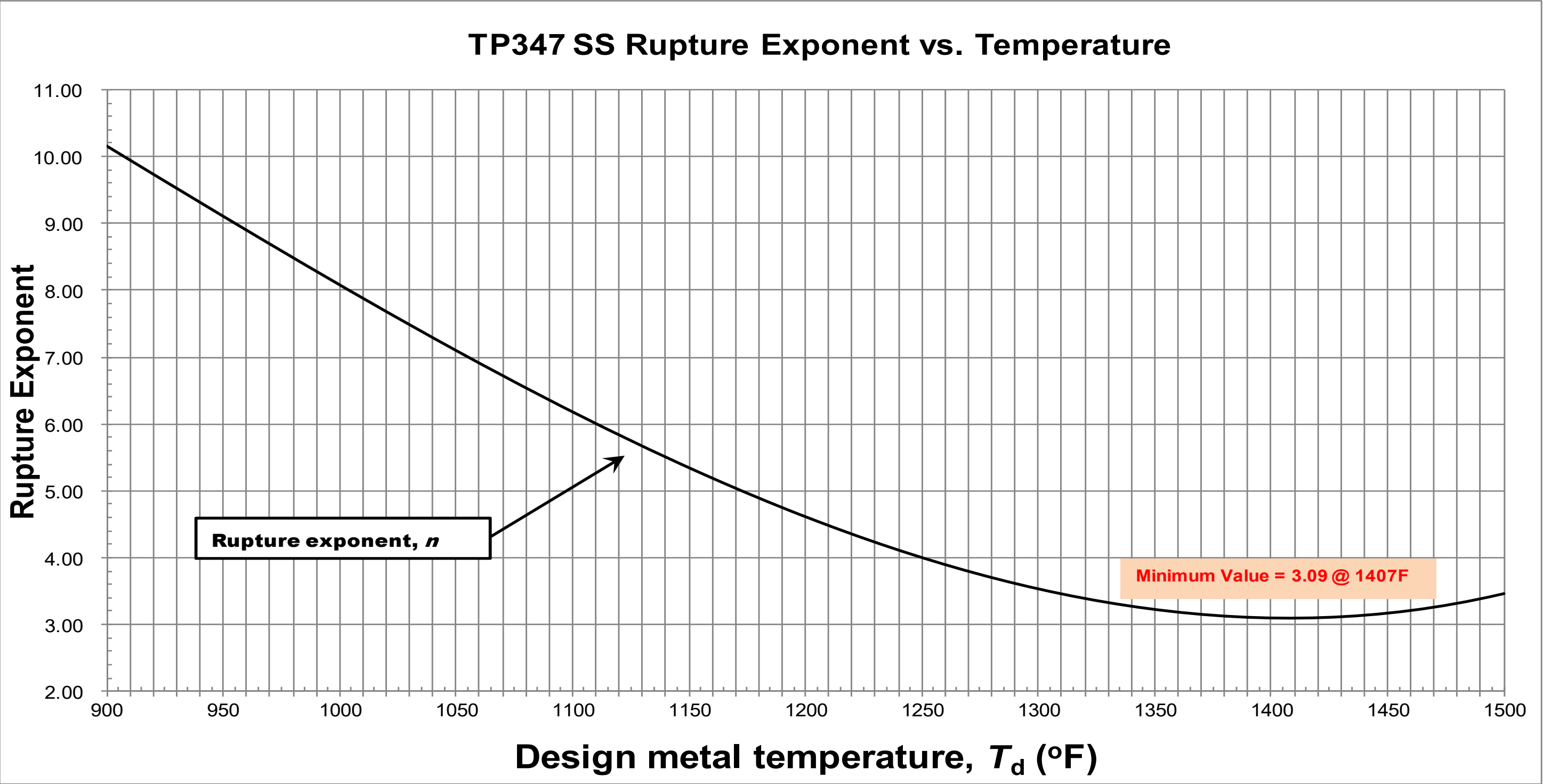


Figure F.50—Rupture Exponent vs. Temperature Surve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

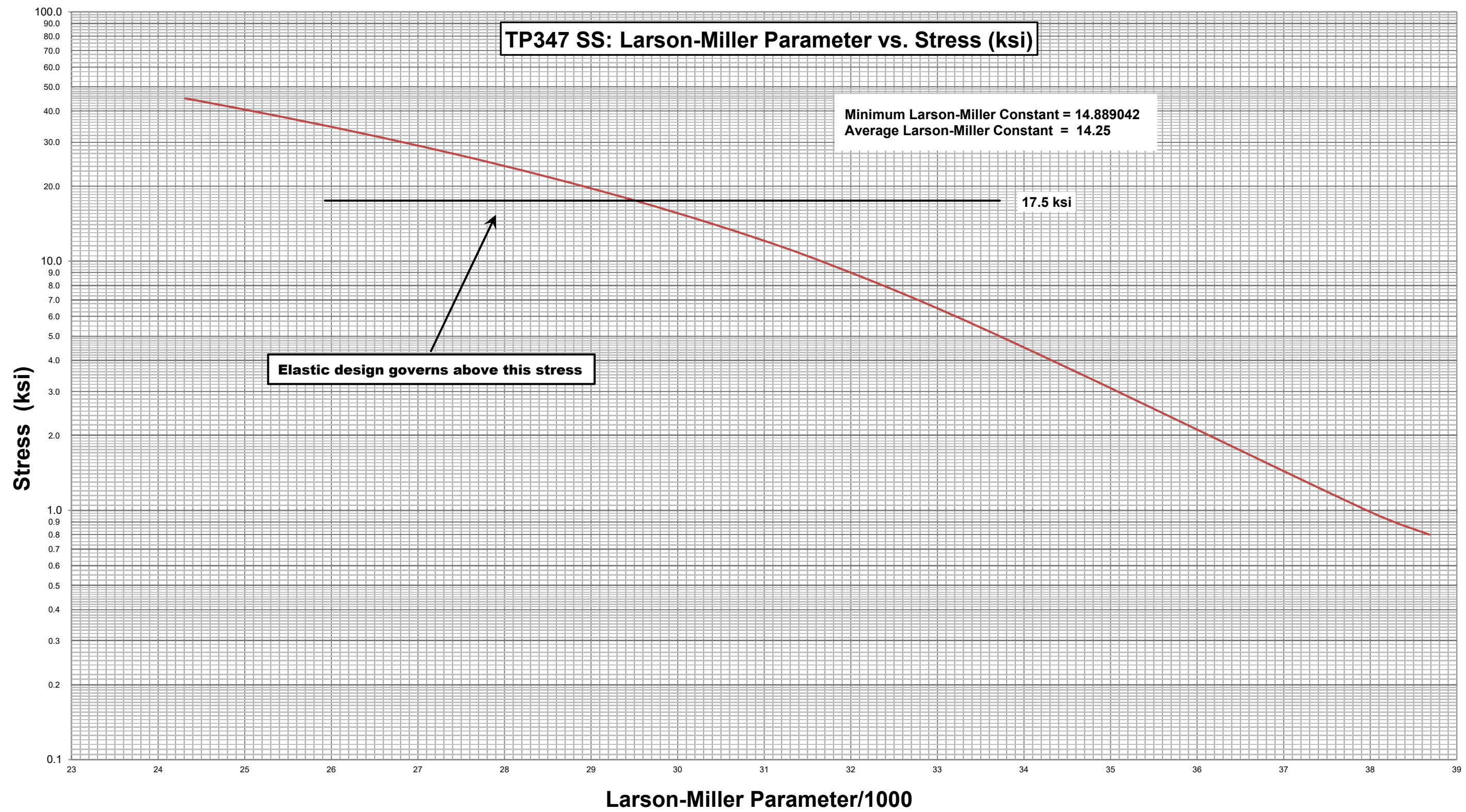


Figure F.51—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

Table F.17—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347 (18Cr-10Ni-Nb) Stainless Steels

TP347 SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	18.8					
720	18.7					
740	18.5					
760	18.4					
780	18.2					
800	18.1					
820	18.0					
840	17.9					
860	17.8					
880	17.7					
900	17.7					10.2
920	17.6					9.7
940	17.6					9.3
960	17.5					8.9
980	17.5					8.5
1000	17.5	19.5	20.9	22.0	24.0	8.1
1020	17.5	17.8	19.2	20.3	22.3	7.7
1040	17.5	16.2	17.5	18.6	20.5	7.3
1060	17.5	14.7	16.0	17.0	18.9	6.9
1080	17.5	13.3	14.5	15.5	17.3	6.5
1100	17.5	12.0	13.1	14.1	15.8	6.2
1120	17.5	10.7	11.8	12.7	14.4	5.8
1140	17.6	9.5	10.6	11.5	13.1	5.5
1160	17.6	8.4	9.4	10.3	11.8	5.2
1180	17.5	7.4	8.3	9.1	10.6	4.9
1200	17.5	6.5	7.3	8.1	9.4	4.6
1220	17.5	5.6	6.4	7.1	8.4	4.3
1240	17.4	4.8	5.6	6.2	7.4	4.1
1260	17.3	4.2	4.8	5.4	6.5	3.9
1280	17.2	3.6	4.1	4.7	5.7	3.7
1300	17.0	3.0	3.5	4.0	4.9	3.5
1320	16.8	2.6	3.0	3.4	4.2	3.4
1340	16.5	2.2	2.6	2.9	3.6	3.3
1360	16.1	1.9	2.2	2.5	3.1	3.2
1380	15.8	1.6	1.9	2.1	2.7	3.1
1400	15.3	1.4	1.6	1.8	2.3	3.1
1420	14.8	1.2	1.4	1.6	2.0	3.1
1440	14.2	1.1	1.2	1.4	1.7	3.1
1460	13.5	0.9	1.1	1.2	1.5	3.2
1480	12.8	0.8	0.9	1.1	1.3	3.3
1500	12.0	0.7	0.8	0.9	1.1	3.5

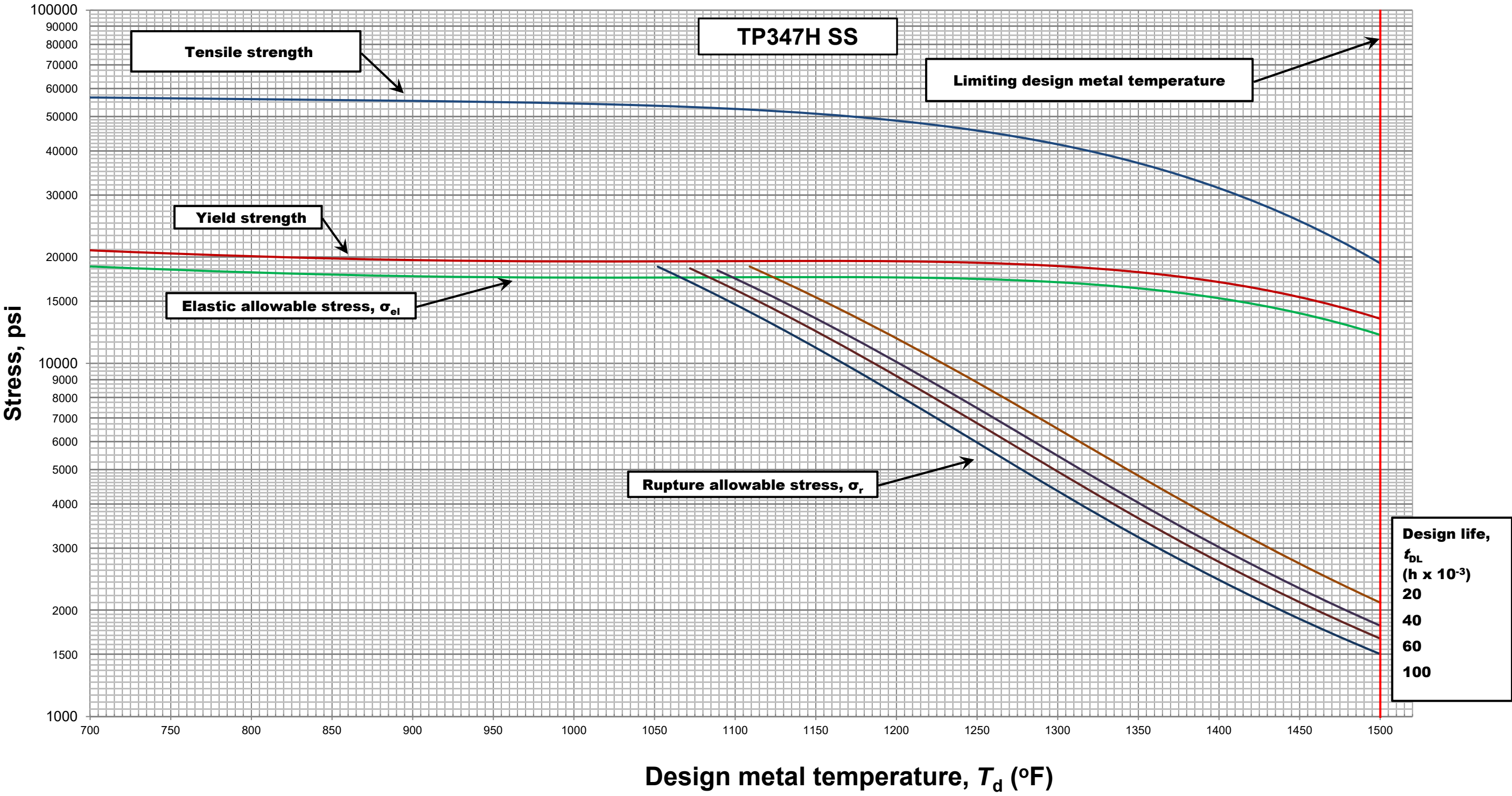


Figure F.52—Stress Curves (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

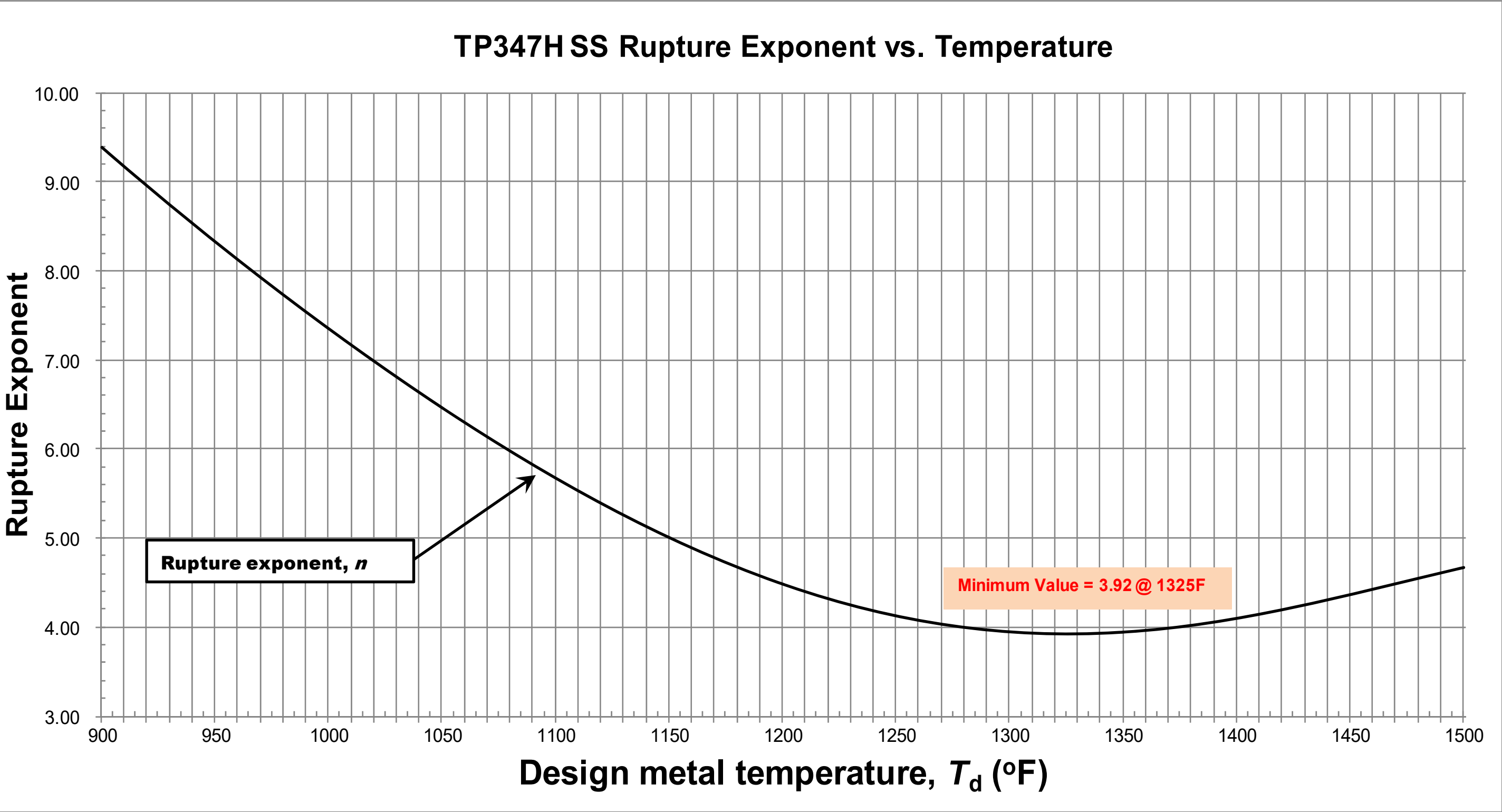


Figure F.53—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

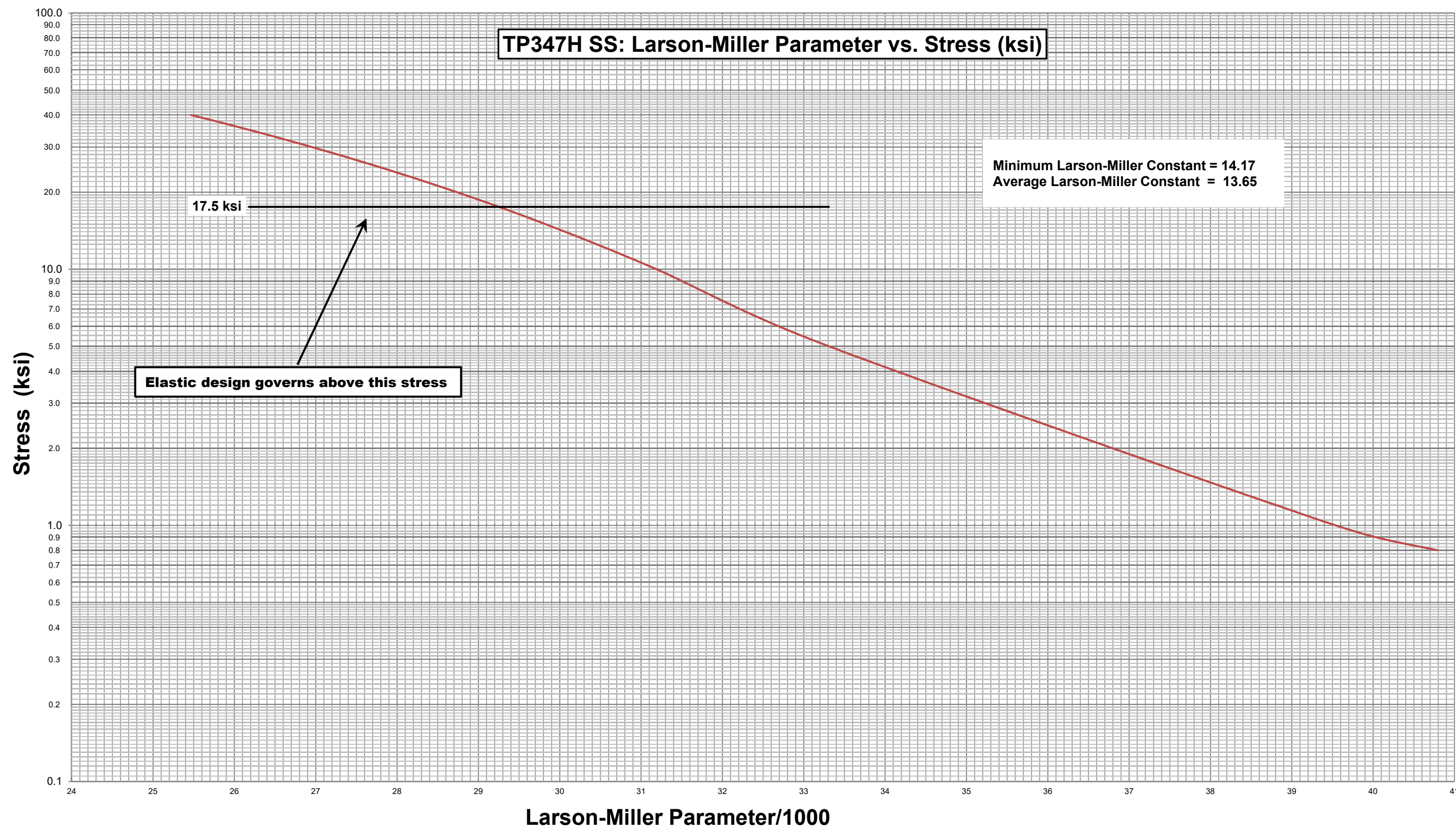


Figure F.54—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

Table F.18—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A271, ASTM A312, and ASTM 376 TP 347H (18Cr-10Ni-Nb) Stainless Steels

TP347H SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	18.8					
720	18.7					
740	18.5					
760	18.4					
780	18.2					
800	18.1					
820	18.0					
840	17.9					
860	17.8					
880	17.7					
900	17.7					9.4
920	17.6					9.0
940	17.6					8.5
960	17.5					8.1
980	17.5					7.7
1000	17.5					7.4
1020	17.5					7.0
1040	17.5	19.9	21.6	23.0	25.5	6.6
1060	17.5	18.1	19.7	21.0	23.5	6.3
1080	17.5	16.3	17.9	19.2	21.5	6.0
1100	17.5	14.7	16.2	17.4	19.6	5.7
1120	17.5	13.2	14.5	15.7	17.8	5.4
1140	17.6	11.7	13.0	14.2	16.2	5.1
1160	17.6	10.4	11.7	12.7	14.6	4.9
1180	17.5	9.3	10.4	11.3	13.1	4.7
1200	17.5	8.2	9.2	10.1	11.8	4.5
1220	17.5	7.2	8.2	9.0	10.5	4.3
1240	17.4	6.4	7.2	7.9	9.4	4.2
1260	17.3	5.6	6.4	7.0	8.3	4.1
1280	17.2	4.9	5.6	6.2	7.4	4.0
1300	17.0	4.4	4.9	5.5	6.5	3.9
1320	16.8	3.8	4.4	4.8	5.8	3.9
1340	16.5	3.4	3.9	4.3	5.1	3.9
1360	16.1	3.0	3.4	3.8	4.5	4.0
1380	15.8	2.7	3.1	3.4	4.0	4.0
1400	15.3	2.4	2.7	3.0	3.6	4.1
1420	14.8	2.2	2.5	2.7	3.2	4.2
1440	14.2	2.0	2.2	2.4	2.9	4.3
1460	13.5	1.8	2.0	2.2	2.6	4.4
1480	12.8	1.6	1.8	2.0	2.3	4.5
1500	12.0	1.5	1.7	1.8	2.1	4.7

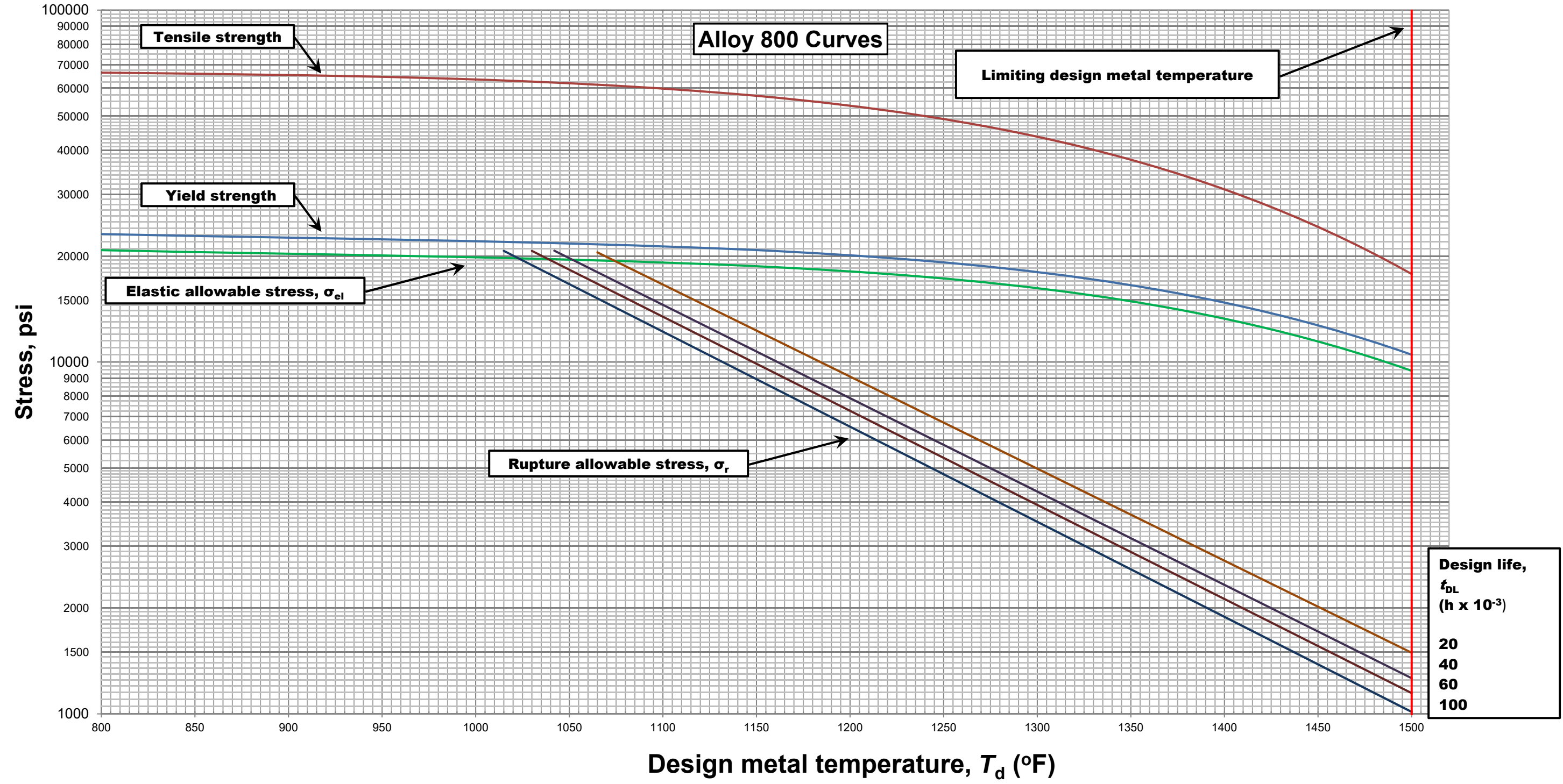


Figure F.55—Stress Curves (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

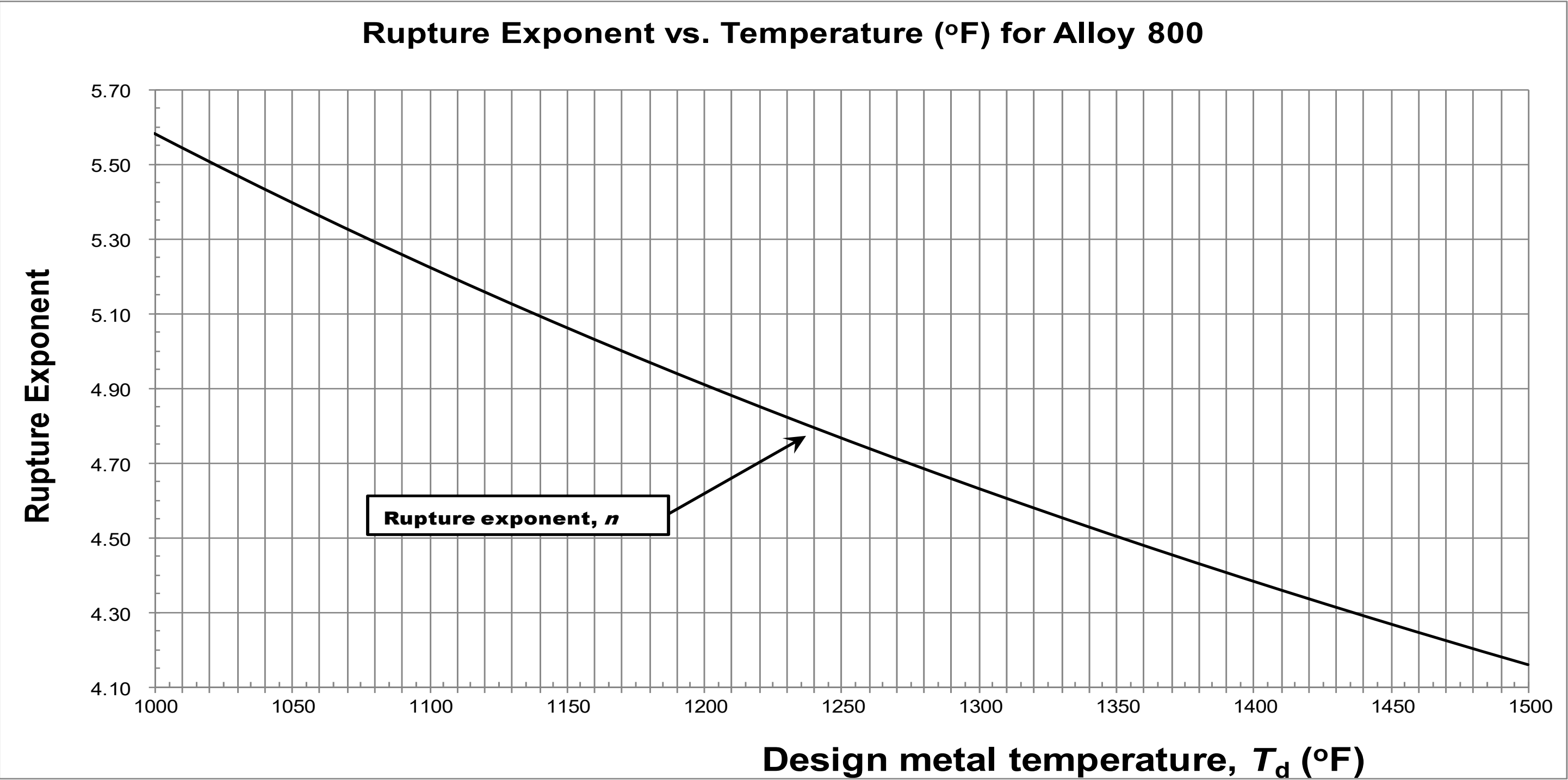


Figure F.56—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

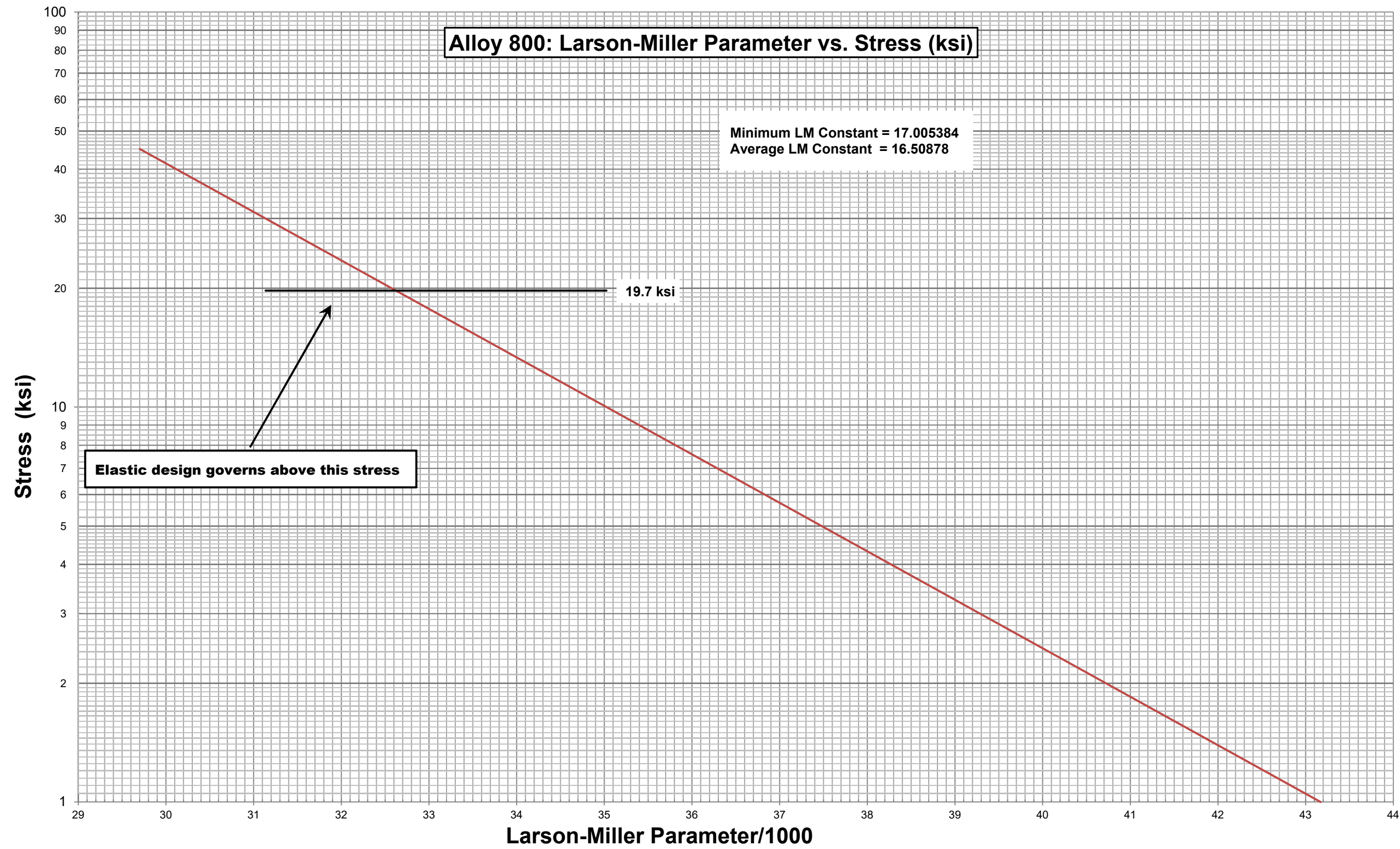


Figure F.57—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Table F.19—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08800 Alloy 800 Steels

Alloy 800						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	20.8					
820	20.7					
840	20.6					
860	20.5					
880	20.4					
900	20.3					6.0
920	20.2					5.9
940	20.1					5.8
960	20.0					5.7
980	19.9					5.7
1000	19.8	22.7	24.9	26.8	30.3	5.6
1020	19.7	20.1	22.0	23.7	26.9	5.5
1040	19.6	17.7	19.5	21.0	23.8	5.4
1060	19.5	15.6	17.2	18.6	21.1	5.4
1080	19.3	13.8	15.2	16.4	18.7	5.3
1100	19.2	12.2	13.5	14.5	16.6	5.2
1120	19.0	10.8	11.9	12.9	14.7	5.2
1140	18.8	9.5	10.5	11.4	13.0	5.1
1160	18.6	8.4	9.3	10.1	11.6	5.0
1180	18.4	7.4	8.2	8.9	10.3	5.0
1200	18.1	6.5	7.3	7.9	9.1	4.9
1220	17.8	5.8	6.4	7.0	8.1	4.8
1240	17.5	5.1	5.7	6.2	7.1	4.8
1260	17.1	4.5	5.0	5.5	6.3	4.7
1280	16.7	4.0	4.4	4.8	5.6	4.7
1300	16.2	3.5	3.9	4.3	5.0	4.6
1320	15.7	3.1	3.5	3.8	4.4	4.6
1340	15.2	2.7	3.1	3.4	3.9	4.5
1360	14.6	2.4	2.7	3.0	3.5	4.5
1380	14.0	2.1	2.4	2.6	3.1	4.4
1400	13.3	1.9	2.1	2.3	2.7	4.4
1420	12.6	1.7	1.9	2.1	2.4	4.3
1440	11.8	1.5	1.7	1.8	2.1	4.3
1460	11.1	1.3	1.5	1.6	1.9	4.2
1480	10.3	1.1	1.3	1.4	1.7	4.2
1500	9.4	1.0	1.1	1.3	1.5	4.2

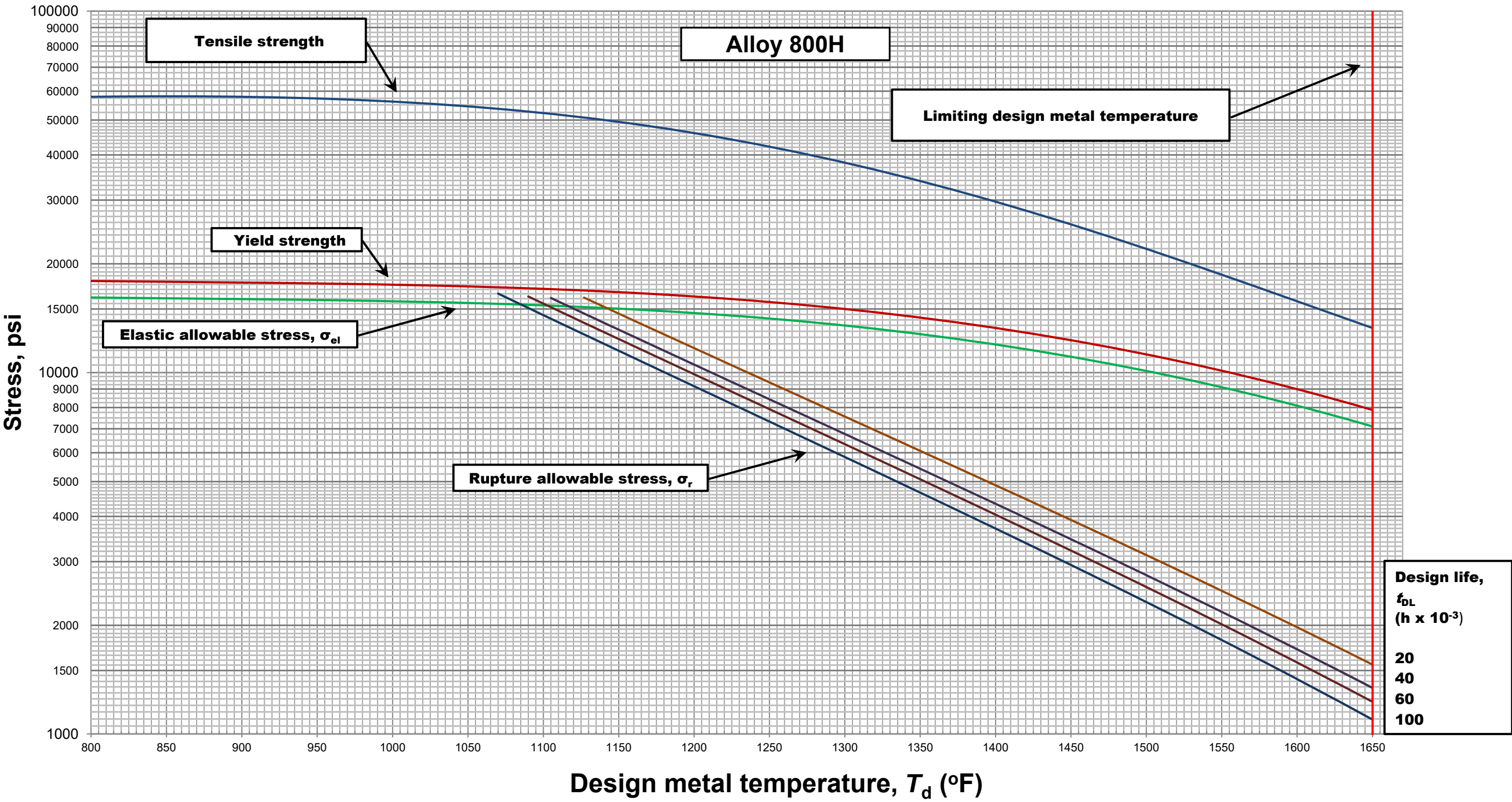


Figure F.58—Stress Curves (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

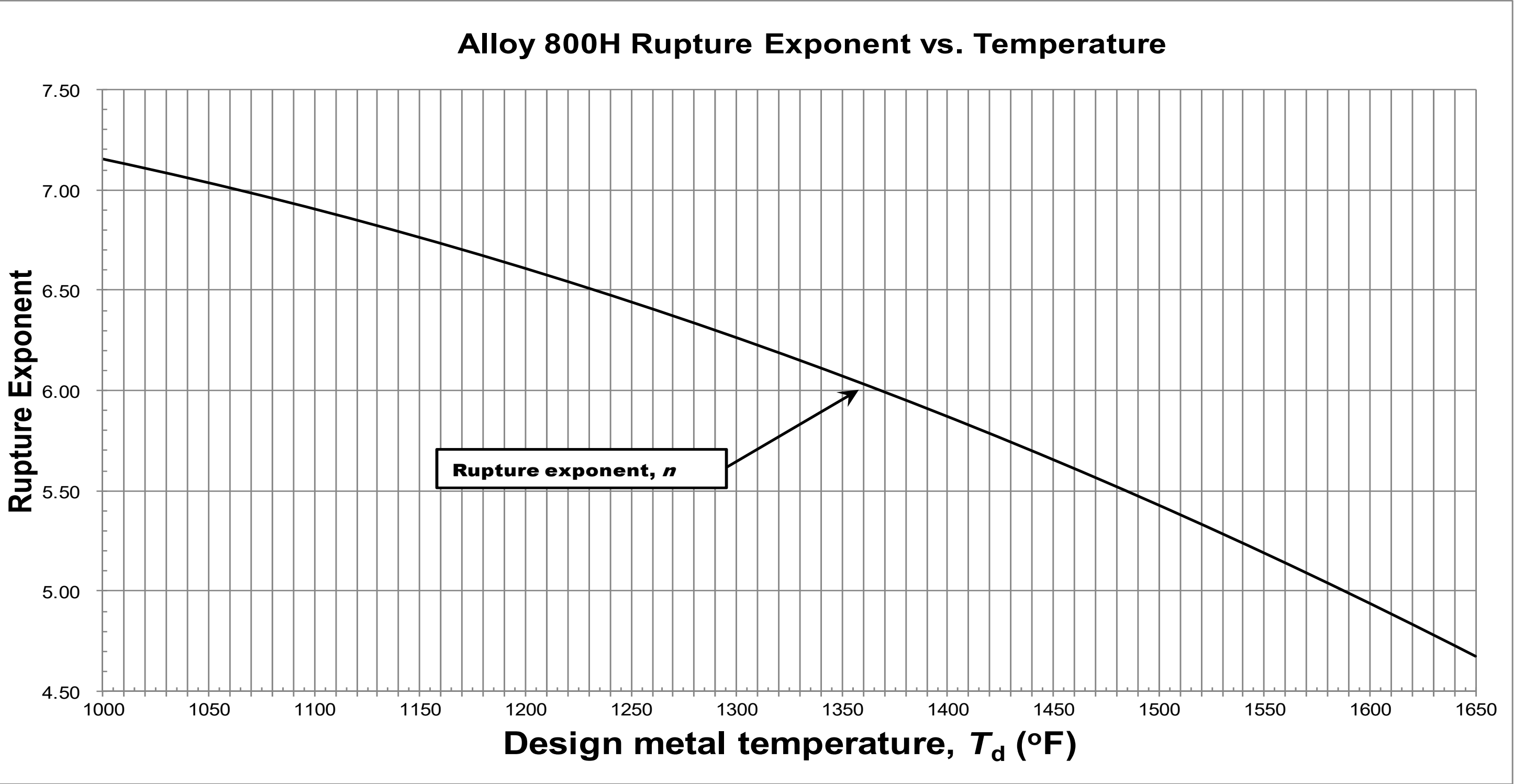


Figure F.59—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

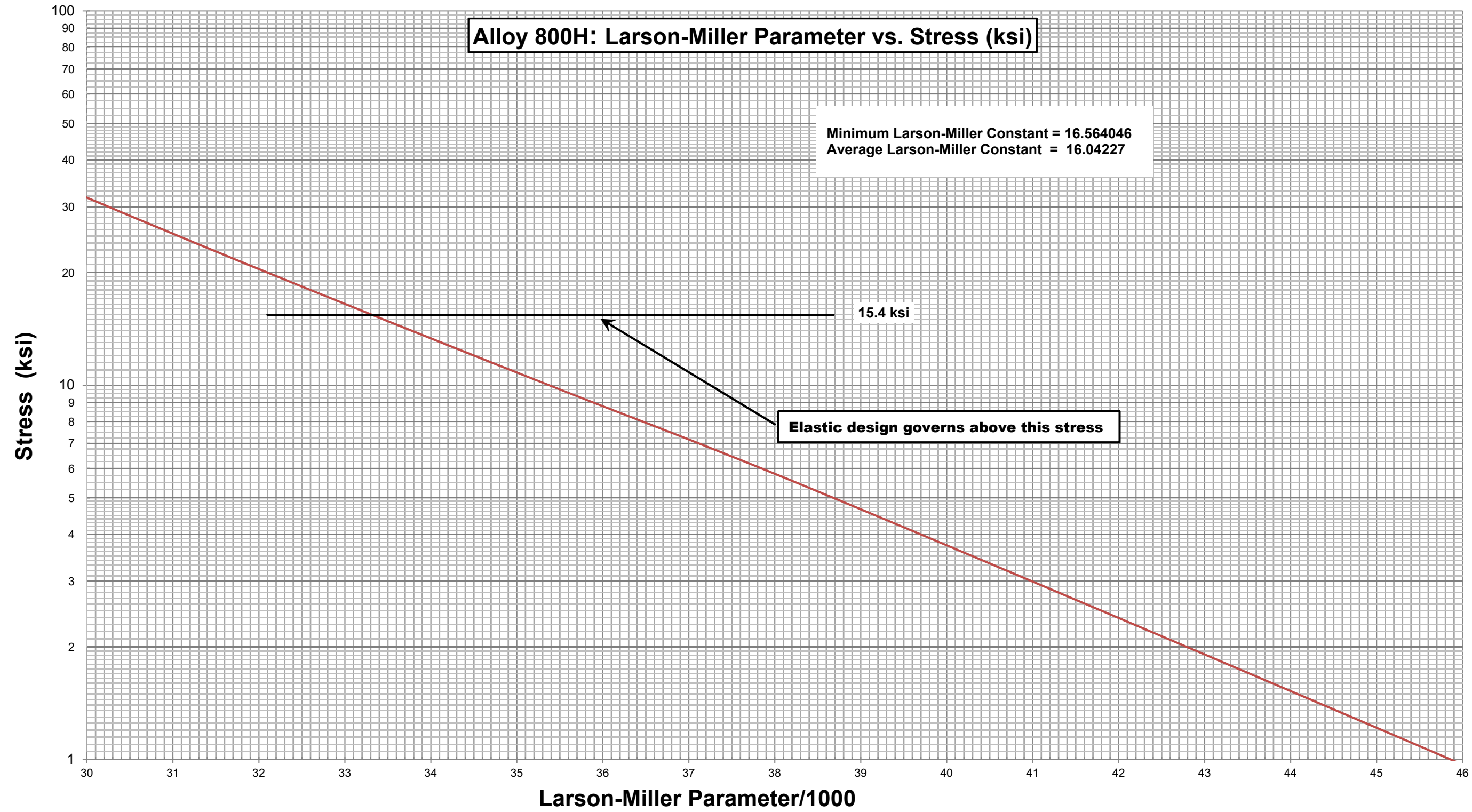


Figure F.60—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Table F.20—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08810 Alloy 800H Steels

Alloy 800H						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	16.1					
820	16.1					
840	16.1					
860	16.0					
880	16.0					
900	16.0					
920	15.9					
940	15.9					
960	15.9					
980	15.8					
1000	15.8					7.2
1020	15.7					7.1
1040	15.6					7.1
1060	15.5	17.3	18.6	19.7	21.8	7.0
1080	15.5	15.8	17.0	18.0	19.9	7.0
1100	15.3	14.4	15.5	16.4	18.2	6.9
1120	15.2	13.2	14.2	15.0	16.6	6.8
1140	15.1	12.0	13.0	13.7	15.2	6.8
1160	15.0	11.0	11.8	12.6	13.9	6.7
1180	14.8	10.0	10.8	11.5	12.8	6.7
1200	14.6	9.2	9.9	10.5	11.7	6.6
1220	14.4	8.4	9.1	9.6	10.7	6.5
1240	14.2	7.7	8.3	8.8	9.8	6.5
1260	14.0	7.0	7.6	8.1	9.0	6.4
1280	13.8	6.4	6.9	7.4	8.2	6.3
1300	13.5	5.8	6.3	6.8	7.6	6.3
1320	13.2	5.3	5.8	6.2	6.9	6.2
1340	12.9	4.9	5.3	5.7	6.3	6.1
1360	12.6	4.4	4.8	5.2	5.8	6.0
1380	12.3	4.1	4.4	4.7	5.3	6.0
1400	12.0	3.7	4.0	4.3	4.9	5.9
1420	11.6	3.4	3.7	4.0	4.5	5.8
1440	11.3	3.1	3.4	3.6	4.1	5.7
1460	10.9	2.8	3.1	3.3	3.7	5.6
1480	10.5	2.5	2.8	3.0	3.4	5.5
1500	10.1	2.3	2.6	2.8	3.1	5.4
1520	9.7	2.1	2.3	2.5	2.9	5.3
1540	9.3	1.9	2.1	2.3	2.6	5.2
1560	8.9	1.7	1.9	2.1	2.4	5.1
1580	8.5	1.6	1.7	1.9	2.2	5.0
1600	8.1	1.4	1.6	1.7	2.0	4.9
1620	7.7	1.3	1.4	1.6	1.8	4.8
1640	7.3	1.2	1.3	1.4	1.6	4.7
1650	7.1	1.1	1.2	1.3	1.6	4.7

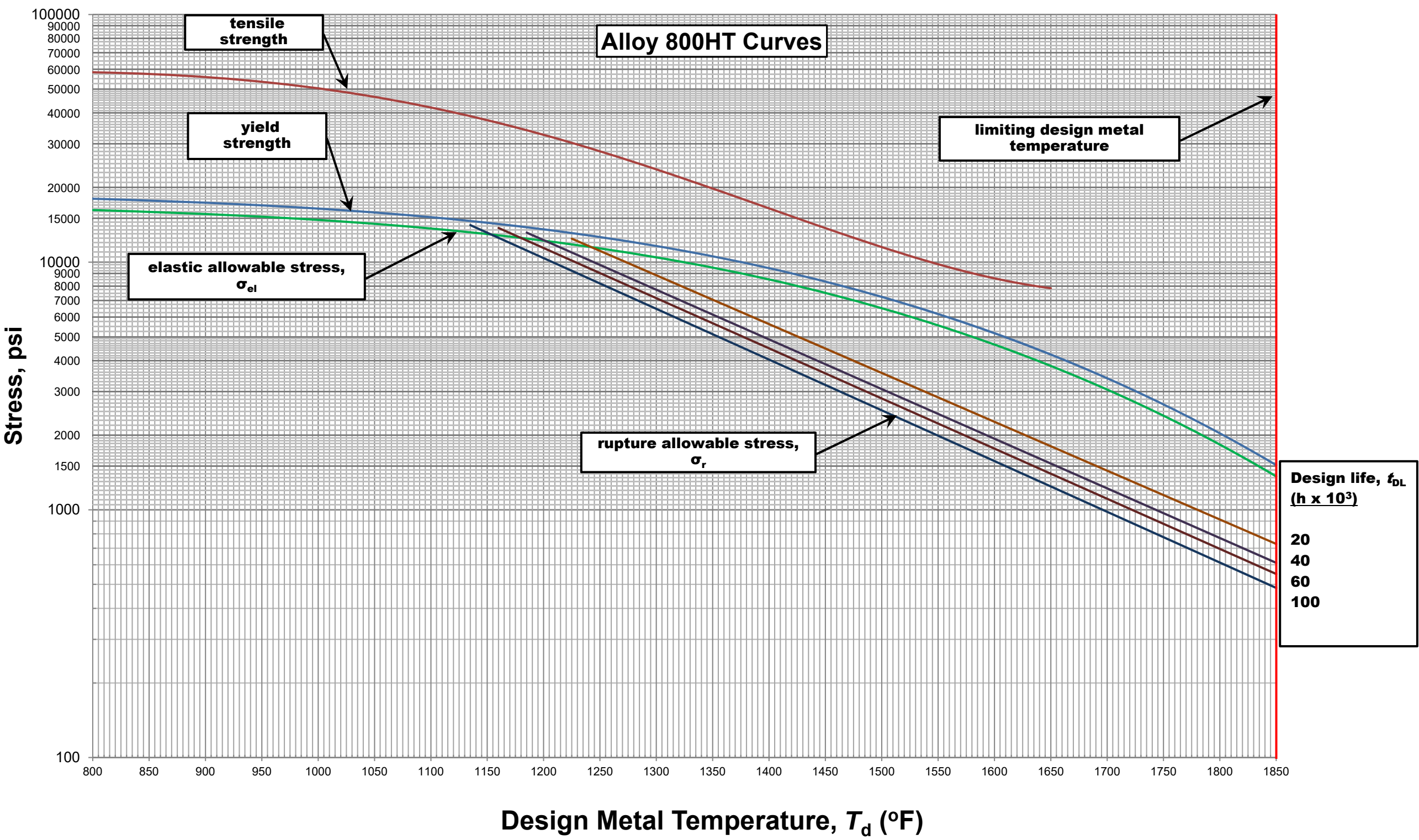


Figure F.61—Stress Curves (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

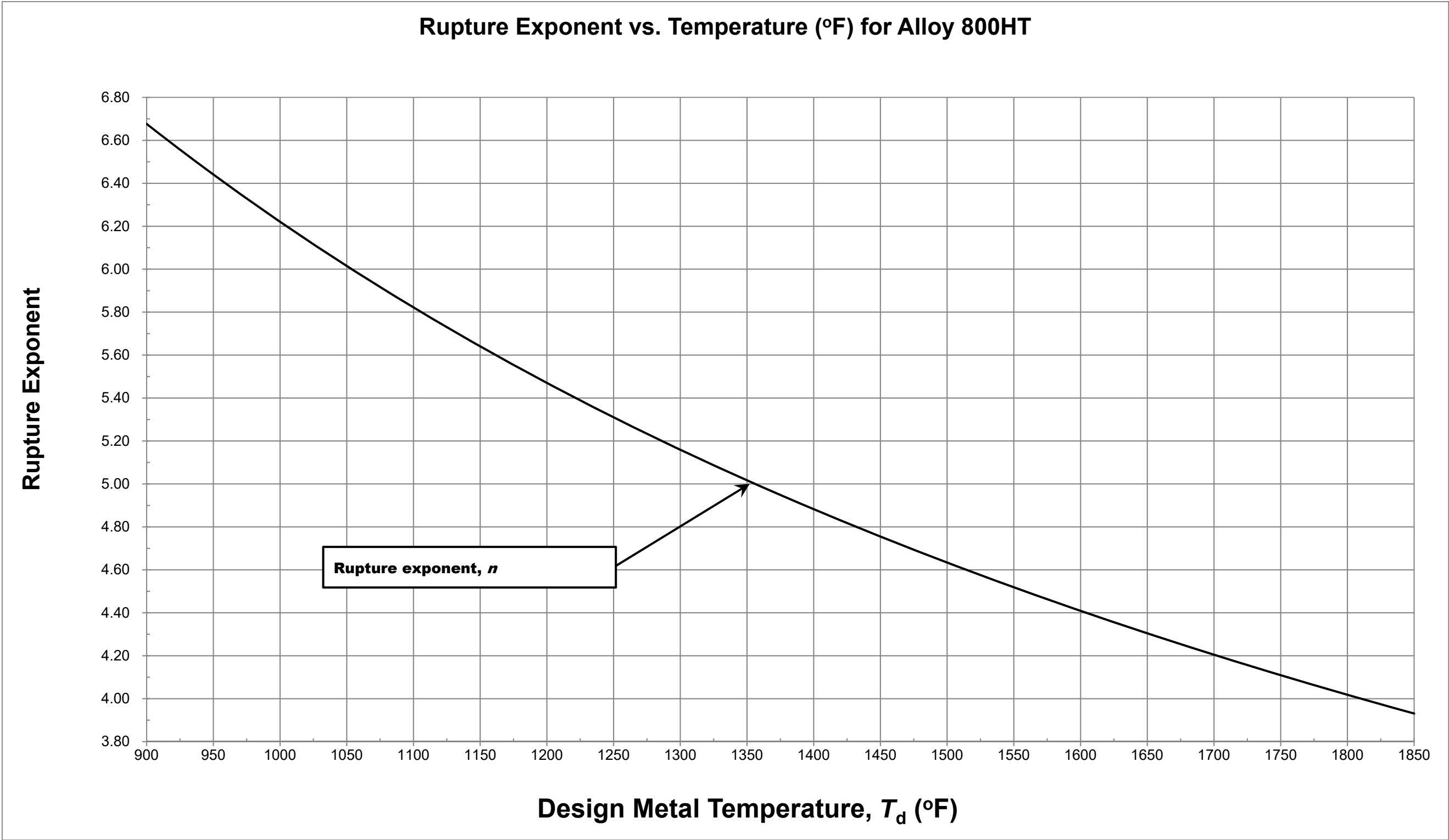


Figure F.62—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

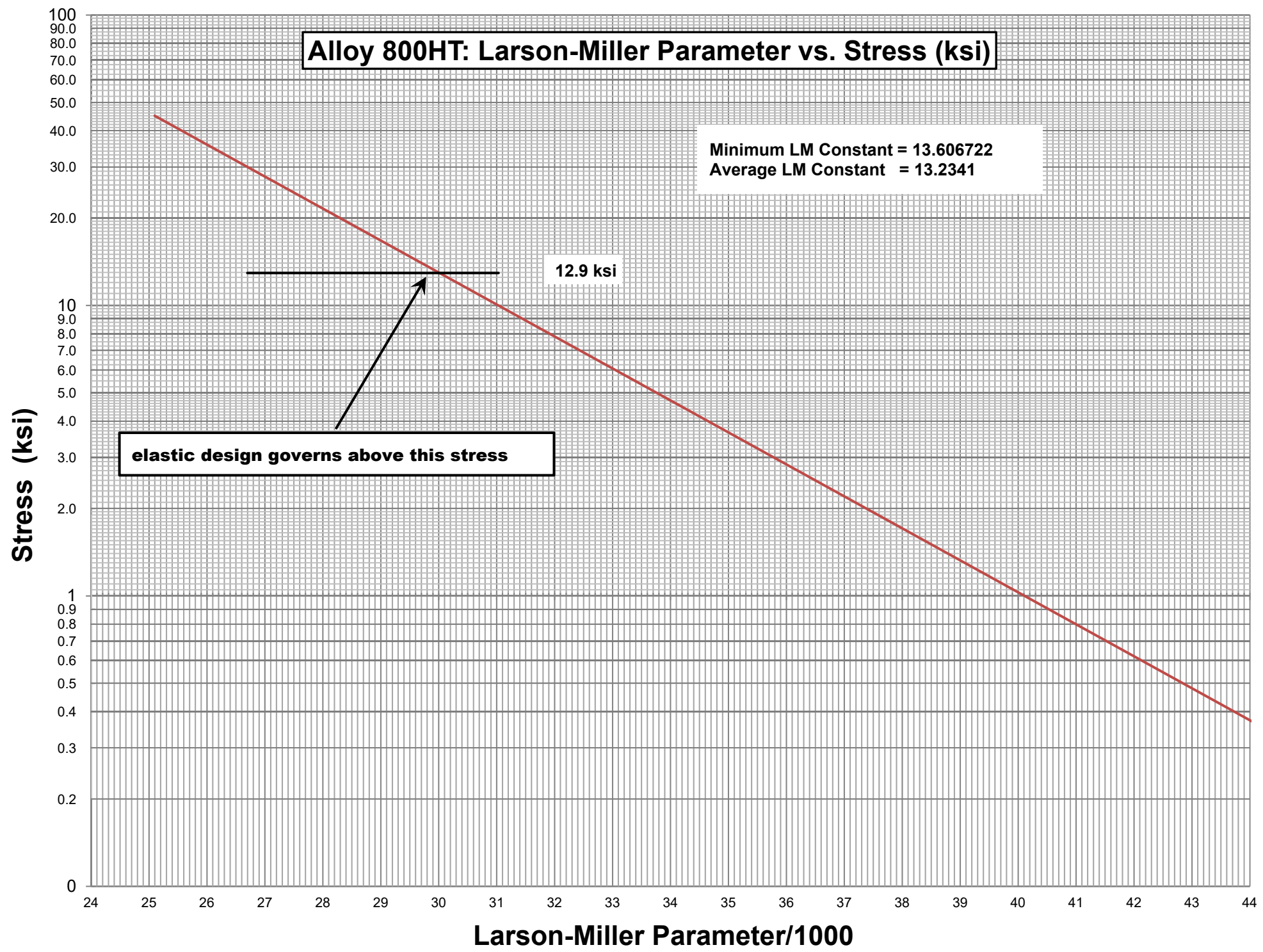


Figure F.63—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Table F.21—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM B407 UNS N08811 Alloy 800HT Steels

Alloy 800HT						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	16.2					
820	16.1					
840	16.0					
860	15.9					
880	15.8					
900	15.6					6.7
920	15.5					6.6
940	15.3					6.5
960	15.2					6.4
980	15.0					6.3
1000	14.8					6.2
1020	14.6	15.2	16.6	17.8	20.0	6.1
1040	14.4					6.1
1060	14.2					6.0
1080	13.9					5.9
1100	13.7					5.8
1120	13.4					5.7
1140	13.1					5.7
1160	12.8					5.6
1180	12.5					5.5
1200	12.2					5.5
1220	11.9	10.4	11.4	12.3	13.9	5.4
1240	11.5	9.5	10.4	11.2	12.7	5.3
1260	11.2	8.6	9.5	10.2	11.6	5.3
1280	10.8	7.8	8.6	9.3	10.6	5.2
1300	10.5	7.1	7.9	8.5	9.7	5.2
1320	10.1	6.5	7.2	7.7	8.9	5.1
1340	9.7	5.9	6.5	7.1	8.1	5.0
1360	9.3	5.4	5.9	6.4	7.4	5.0
1380	8.9	4.9	5.4	5.9	6.7	4.9
1400	8.5	4.4	4.9	5.3	6.2	4.9
1420	8.1	4.0	4.5	4.9	5.6	4.9
1440	7.7	3.7	4.1	4.4	5.1	4.8
1460	7.3	3.3	3.7	4.1	4.7	4.8
1480	6.9	3.0	3.4	3.7	4.3	4.7
1500	6.5	2.8	3.1	3.4	3.9	4.7
1520	6.1	2.5	2.8	3.1	3.6	4.6
1540	5.8	2.3	2.6	2.8	3.3	4.6
1560	5.4	2.1	2.3	2.6	3.0	4.5
1580	5.0	1.9	2.1	2.3	2.7	4.5
1600	4.7	1.7	1.9	2.1	2.5	4.5
1620	4.3	1.6	1.8	1.9	2.3	4.4
1640	4.0	1.4	1.6	1.8	2.1	4.4
1660	3.7	1.3	1.5	1.6	1.9	4.3
1680	3.4	1.2	1.3	1.5	1.7	4.3
1700	3.1	1.1	1.2	1.3	1.6	4.2
1720	2.8	1.0	1.1	1.2	1.4	4.2
1740	2.5	0.9	1.0	1.1	1.3	4.2
1760	2.3	0.8	0.9	1.0	1.2	4.1
1780	2.0	0.7	0.8	0.9	1.1	4.1
1800	1.8	0.7	0.8	0.8	1.0	4.1
1820	1.6	0.6	0.7	0.8	0.9	4.0
1840	1.5	0.6	0.6	0.7	0.8	4.0
1850	1.4	0.5	0.6	0.6	0.8	3.9
		0.5	0.6	0.6	0.7	3.9

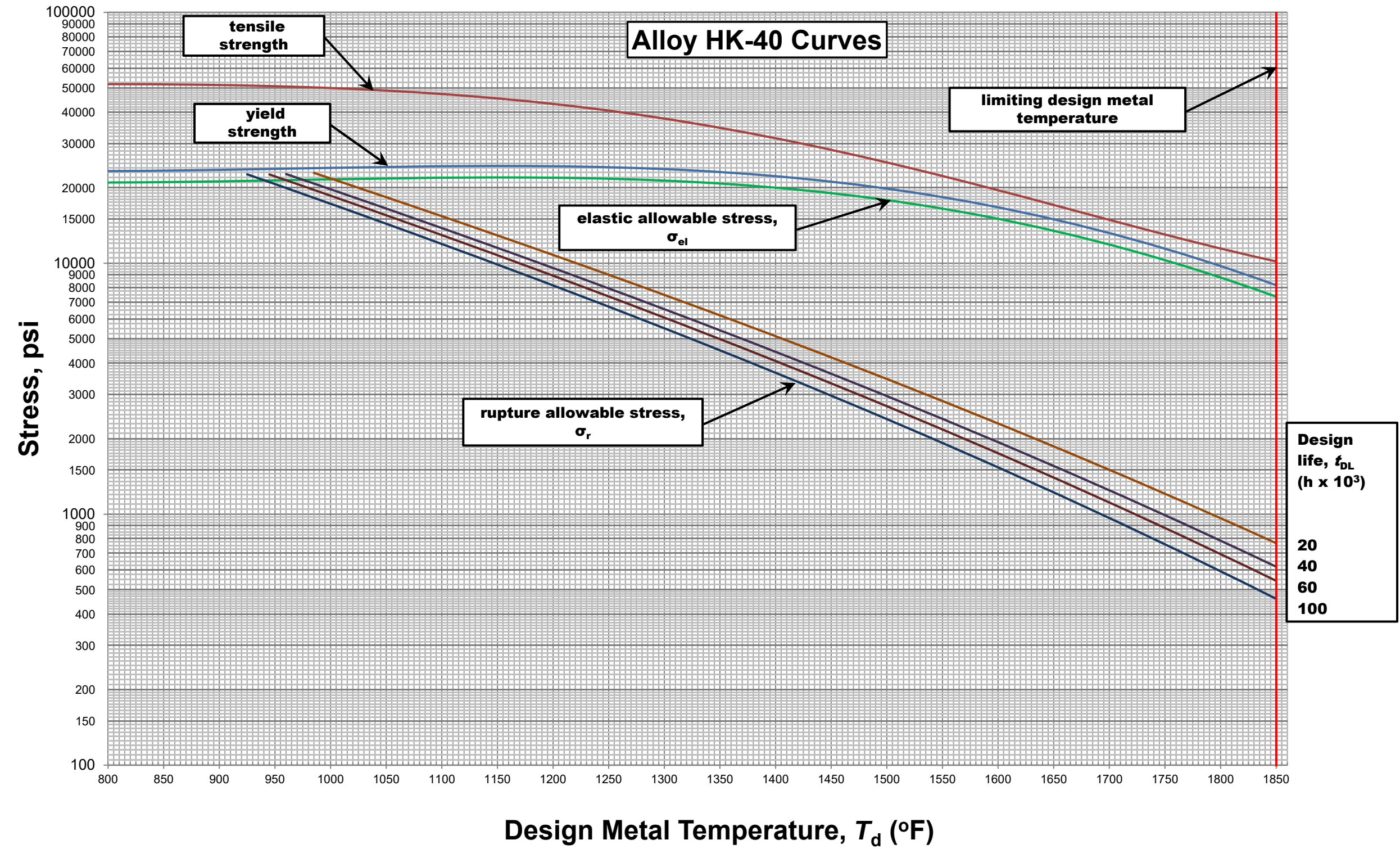


Figure F.64—Stress Curves (USC Units) for ASTM A608 Grade HK-40 Steels

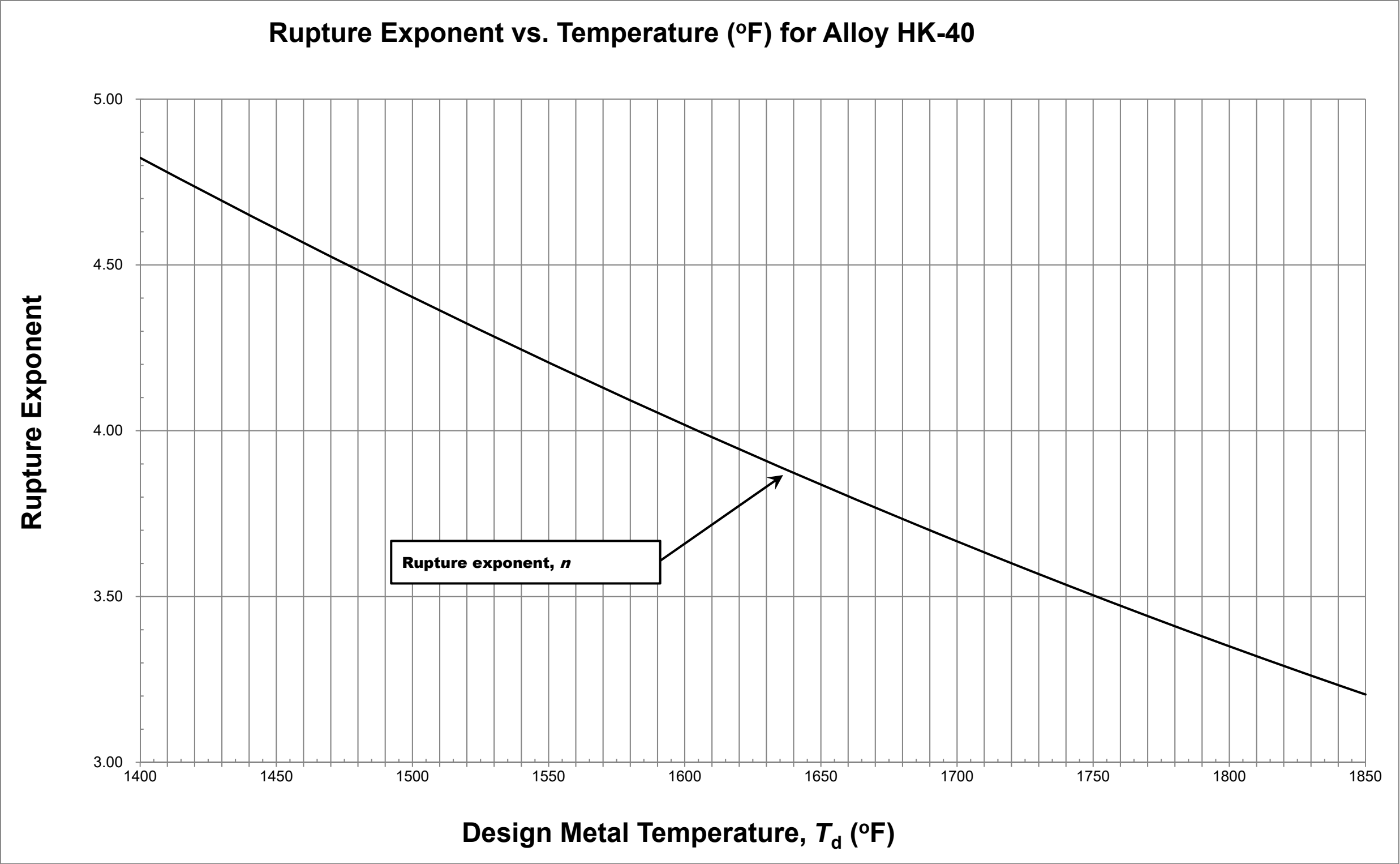


Figure F.65—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A608 Grade HK-40 Steels

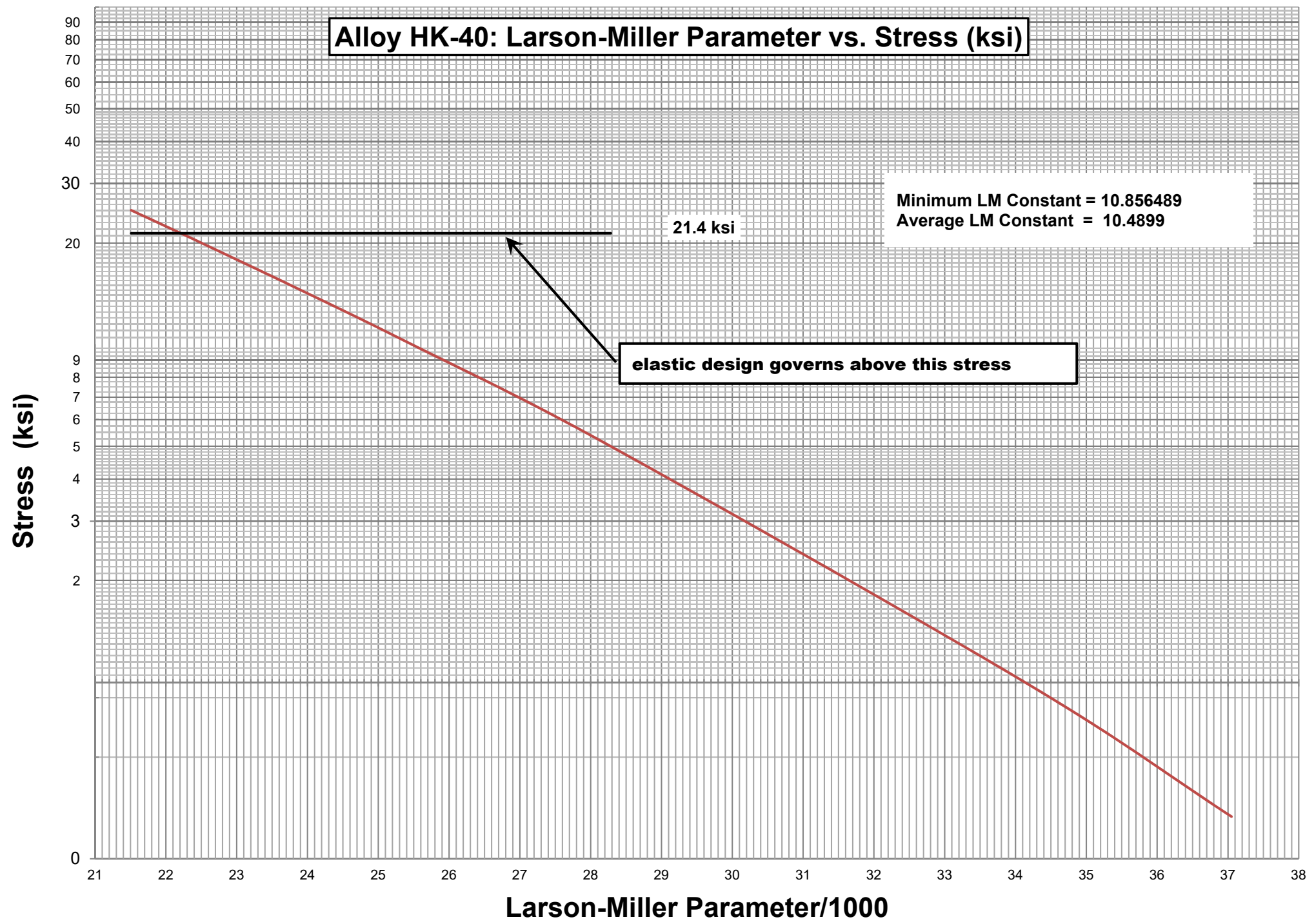


Figure F.66—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A608 Grade HK-40 Steels

Table F.22—Elastic, Rupture Allowable Stresses and Rupture Exponent (USC Units) for ASTM A608 Grade HK-40 Steels

Alloy HK-40						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
800	21.0					
820	21.0					
840	21.0					
860	21.1					
880	21.2					
900	21.2	24.7	26.4	27.9	30.5	
920	21.3	23.0	24.7	26.0	28.5	
940	21.4	21.5	23.0	24.3	26.7	
960	21.4	20.0	21.4	22.7	25.0	
980	21.5	18.6	20.0	21.2	23.3	
1000	21.6	17.3	18.6	19.7	21.8	
1020	21.7	16.1	17.3	18.4	20.3	
1040	21.8	14.9	16.1	17.1	19.0	
1060	21.8	13.9	15.0	16.0	17.7	
1080	21.9	12.9	13.9	14.9	16.5	
1100	21.9	12.0	13.0	13.8	15.4	
1120	22.0	11.1	12.0	12.9	14.4	
1140	22.0	10.3	11.2	12.0	13.4	
1160	22.0	9.5	10.4	11.1	12.5	
1180	22.0	8.8	9.6	10.3	11.6	
1200	21.9	8.2	8.9	9.6	10.8	
1220	21.9	7.6	8.3	8.9	10.0	
1240	21.8	7.0	7.7	8.2	9.3	
1260	21.7	6.5	7.1	7.6	8.7	
1280	21.5	6.0	6.6	7.1	8.1	
1300	21.4	5.5	6.1	6.6	7.5	
1320	21.2	5.1	5.6	6.1	6.9	
1340	20.9	4.7	5.2	5.6	6.4	
1360	20.7	4.3	4.8	5.2	6.0	
1380	20.4	4.0	4.4	4.8	5.5	
1400	20.0	3.7	4.1	4.4	5.1	4.8
1420	19.7	3.4	3.8	4.1	4.7	4.7
1440	19.3	3.1	3.5	3.8	4.4	4.7
1460	18.8	2.8	3.2	3.5	4.1	4.6
1480	18.4	2.6	2.9	3.2	3.7	4.5
1500	17.9	2.4	2.7	3.0	3.5	4.4
1520	17.3	2.2	2.5	2.7	3.2	4.3
1540	16.8	2.0	2.3	2.5	2.9	4.2
1560	16.2	1.8	2.1	2.3	2.7	4.2
1580	15.6	1.7	1.9	2.1	2.5	4.1
1600	15.0	1.5	1.8	1.9	2.3	4.0
1620	14.4	1.4	1.6	1.8	2.1	3.9
1640	13.8	1.3	1.5	1.6	1.9	3.9
1660	13.2	1.2	1.3	1.5	1.8	3.8
1680	12.5	1.1	1.2	1.4	1.6	3.7
1700	11.9	1.0	1.1	1.2	1.5	3.7
1720	11.2	0.9	1.0	1.1	1.4	3.6
1740	10.6	0.8	0.9	1.0	1.3	3.5
1760	10.0	0.7	0.8	0.9	1.2	3.5
1780	9.4	0.7	0.8	0.9	1.1	3.4
1800	8.8	0.6	0.7	0.8	1.0	3.3
1820	8.2	0.5	0.6	0.7	0.9	3.3
1840	7.6	0.5	0.6	0.6	0.8	3.2
1850	7.4	0.5	0.5	0.6	0.8	3.2

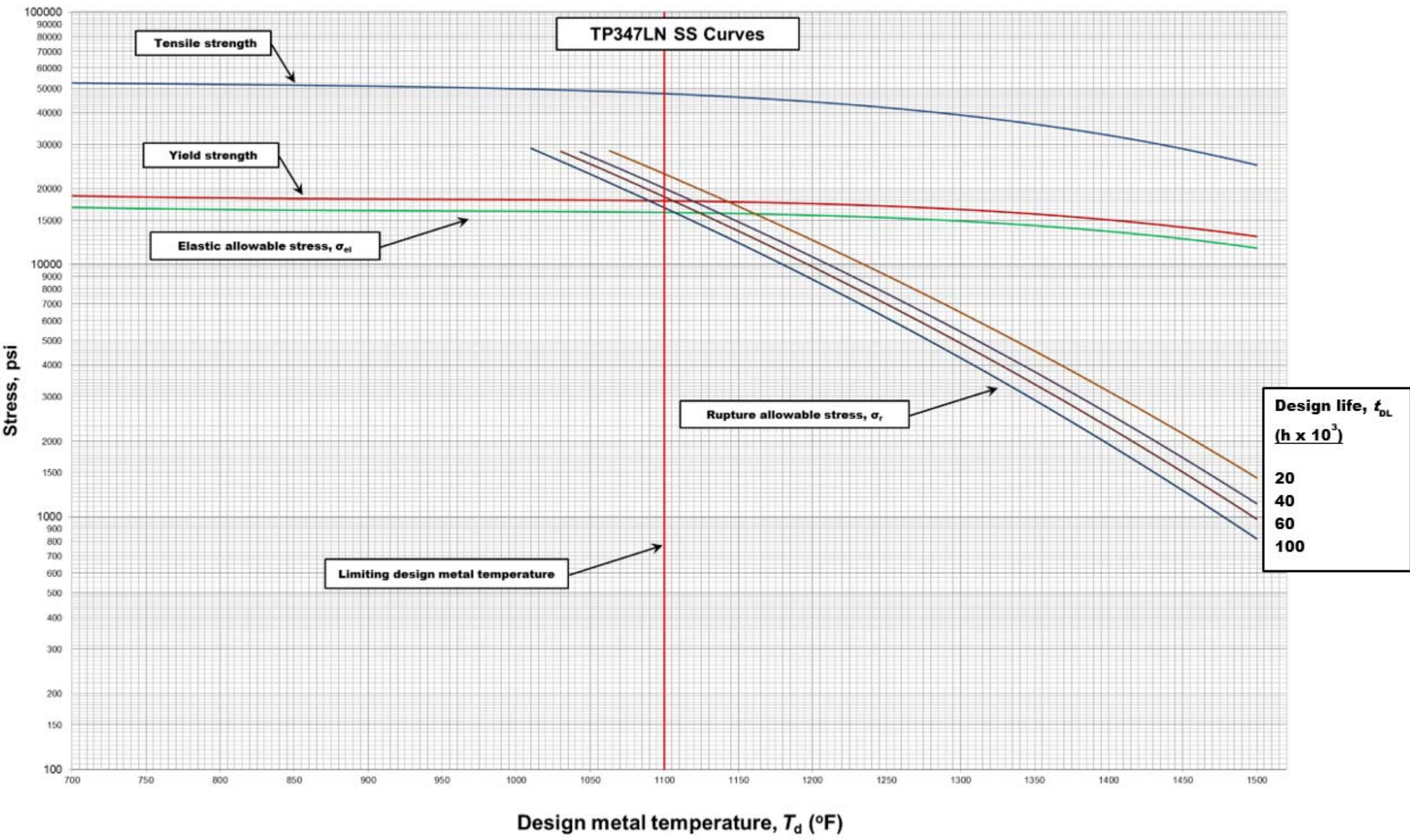


Figure F.67—Stress Curves (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

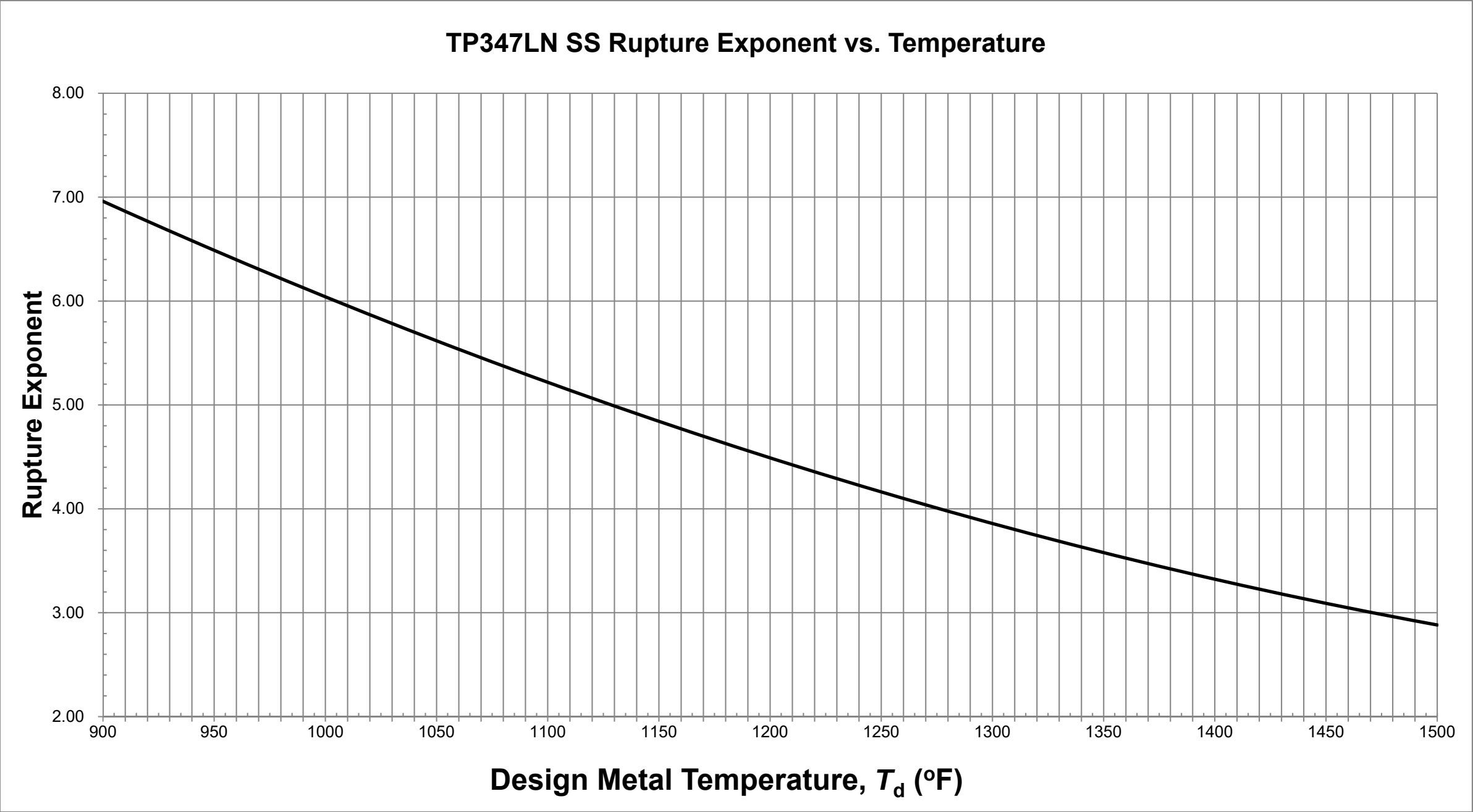


Figure F.68—Rupture Exponent vs. Temperature Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

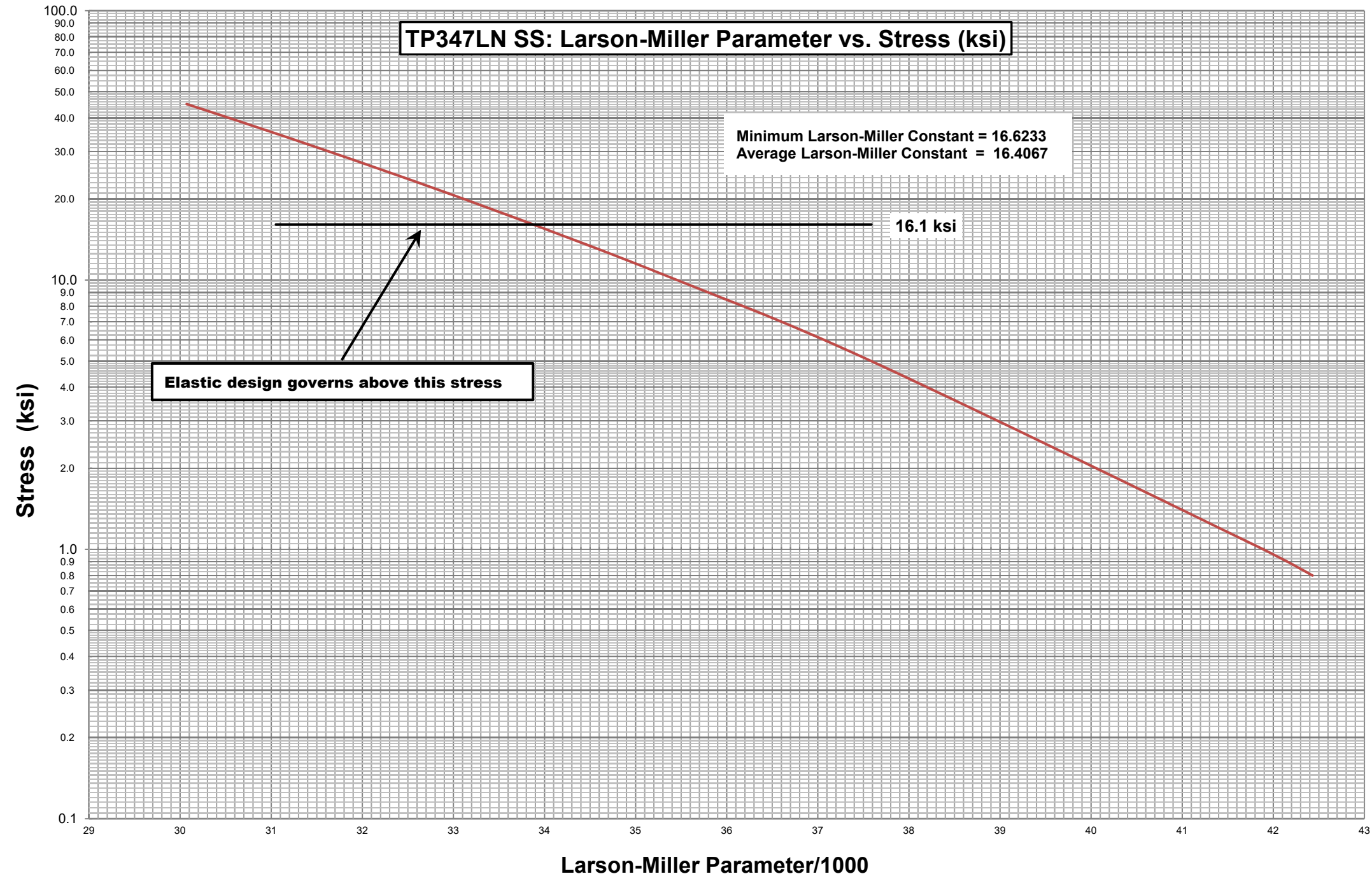


Figure F.69—Larson-Miller Parameter vs. Stress Curve (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

Table F.23—Elastic, Rupture and Allowable Stresses and Rupture Exponent (USC Units) for ASTM A213, ASTM A312, and ASTM A376 TP 347LN (18Cr-10Ni-Nb) Stainless Steels

TP347LN SS						
Temperature (Fahrenheit)	Elastic Allowable Stress, σ_{el} (ksi)	Rupture Allowable Stress, σ_r				Rupture Exponent, n
		$t_{DL} = 100,000\text{ h}$ (ksi)	$t_{DL} = 60,000\text{ h}$ (ksi)	$t_{DL} = 40,000\text{ h}$ (ksi)	$t_{DL} = 20,000\text{ h}$ (ksi)	
700	16.9					
720	16.8					
740	16.7					
760	16.6					
780	16.6					
800	16.5					
820	16.5					
840	16.4					
860	16.4					
880	16.4					
900	16.4					7.0
920	16.3					6.8
940	16.3					6.6
960	16.3					6.4
980	16.3					6.2
1000	16.3	30.6	33.3	35.6	39.9	6.0
1020	16.2	27.2	29.7	31.9	35.8	5.9
1040	16.2	24.2	26.5	28.5	32.1	5.7
1060	16.2	21.5	23.6	25.4	28.7	5.5
1080	16.1	19.0	20.9	22.6	25.6	5.4
1100	16.1	16.8	18.5	20.0	22.9	5.2
1120	16.0	14.8	16.4	17.8	20.3	5.1
1140	16.0	13.0	14.5	15.7	18.1	4.9
1160	15.9	11.4	12.7	13.9	16.0	4.8
1180	15.8	10.0	11.2	12.2	14.2	4.6
1200	15.7	8.7	9.8	10.7	12.5	4.5
1220	15.6	7.6	8.6	9.4	11.0	4.4
1240	15.4	6.6	7.5	8.2	9.7	4.2
1260	15.3	5.7	6.5	7.2	8.5	4.1
1280	15.1	4.9	5.6	6.2	7.4	4.0
1300	14.9	4.3	4.9	5.4	6.5	3.9
1320	14.7	3.7	4.2	4.7	5.6	3.7
1340	14.4	3.1	3.6	4.1	4.9	3.6
1360	14.1	2.7	3.1	3.5	4.2	3.5
1380	13.8	2.3	2.7	3.0	3.7	3.4
1400	13.5	1.9	2.3	2.6	3.1	3.3
1420	13.2	1.6	1.9	2.2	2.7	3.2
1440	12.8	1.4	1.6	1.9	2.3	3.1
1460	12.5	1.2	1.4	1.6	2.0	3.0
1480	12.0	1.0	1.2	1.3	1.7	3.0
1500	11.6	0.8	1.0	1.1	1.4	2.9

Annex G (informative)

Derivation of Corrosion Fraction and Temperature Fraction

G.1 General

The 1958 edition of API 530 [16] contained a method for designing tubes in the creep-rupture range. The method took into consideration the effects of stress reductions produced by the corrosion allowance. In developing this design method, the following ideas were used.

At temperatures in the creep-rupture range, the life of a tube is limited. The rate of using up the life depends on temperature and stress. Under the assumption of constant temperature, the rate of using up the life increases as the stress increases. In other words, the tube lasts longer if the stress is lower.

If the tube undergoes corrosion or oxidation, the tube thickness will decrease over time. Therefore, under the assumption of constant pressure, the stress in the tube increases over time. As a result, the rate of using up the rupture life also increases in time.

An integral of this effect over the life of the tube was solved graphically in the 1988 edition of API 530 [17] and developed using the linear-damage rule (see G.2). The result is a nonlinear equation that provides the initial tube thickness for various combinations of design temperature and design life.

The concept of corrosion fraction used in 5.4 and derived in this annex is developed from the same ideas and is a simplified method of achieving the same results.

Suppose a tube has an initial thickness, δ_σ , calculated using Equation (4). This is the minimum thickness required to achieve the design life without corrosion. If the tube does not undergo corrosion, the stress in the tube will always equal the minimum rupture strength for the design life, σ_r . This tube will probably fail after the end of the design life.

If this tube were designed for use in a corrosive environment and had a corrosion allowance of δ_{CA} , the minimum thickness, $\delta_{\min}$, can be set as given in Equation (G.1):

$$\delta_{\min} = \delta_\sigma + \delta_{CA} \quad (G.1)$$

The stress is initially less than σ_r . After operating for its design life, the corrosion allowance is used up, and the stress is only then equal to σ_r . Since the stress has always been lower than σ_r , the tube still has some time to operate before it fails.

Suppose, instead, that the initial thickness were set as given in Equation (G.2):

$$\delta_{\min} = \delta_\sigma + f_{\text{corr}}\delta_{CA} \quad (G.2)$$

In this equation, f_{corr} is a fraction less than unity. The stress is initially less than σ_r , and the rate of using up the rupture life is low. At the end of the design life, the tube thickness is as given in Equation (G.3):

$$\delta_{\min} - \delta_{CA} = \delta_\sigma - (1 - f_{\text{corr}})\delta_{CA} \quad (G.3)$$

This thickness is less than δ_σ ; therefore, at the end of the design life, the stress is greater than σ_r , and the rate of using up the rupture life is high. If the value of f_{corr} is selected properly, the integrated effect of this changing

rate of using up the rupture life yields a rupture life equal to the design life. The corrosion fraction, f_{corr} , given in Figure 1 is such a value.

The curves in Figure 1 were developed by solving the nonlinear equation that results from applying the linear-damage rule. Figure 1 can be applied to any design life, provided only that the corrosion allowance, δ_{CA} , and rupture allowable stress, σ_r , are based on the same design life.

G.2 Linear-damage Rule

Consider a tube that is operated at a constant stress, σ , and a constant temperature, T , for a period of time, Δt . Corresponding to this stress and temperature is the rupture life, t_r , as given in Equation (G.4):

$$t_r = t_r(\sigma, T) \quad (\text{G.4})$$

The fraction, $\Delta t/t_r$, is then the fraction of the rupture life used up during this operating period. After j operating periods, each with a corresponding fraction as given in Equation (G.5),

$$\left(\frac{\Delta t}{t_r} \right)_{i=1,2,3,\dots,j} \quad (\text{G.5})$$

the total fraction, F (also known as the life fraction), of the rupture life used up would be the sum of the fractions used in each period, as given in Equation (G.6):

$$F(j) = \sum_{i=1}^j \left(\frac{\Delta t}{t_r} \right)_i \quad (\text{G.6})$$

In developing this equation, no restrictions were placed on the stress and temperature from period to period. It was assumed only that during any one period the stress and temperature were constant. The life fraction, therefore, provides a way of estimating the rupture life used up after periods of varying stress and temperature.

The linear-damage rule asserts that creep rupture occurs when the life fraction totals unity, that is, when $F(j) = 1$.

The limitations of this rule are not well understood. Nevertheless, the engineering utility of this rule is widely accepted, and this rule is frequently used in both creep-rupture and fatigue analysis [18], [19], [20], and [21].

G.3 Derivation of Equation for Corrosion Fraction

With continually varying stress and temperature, the life fraction can be expressed as an integral as given in Equation (G.7):

$$F(t_{\text{op}}) = \int_0^{t_{\text{op}}} \frac{dt}{t_r} \quad (\text{G.7})$$

where

t_{op} is the operating life;

t_r is $t_r(\sigma, T)$, i.e. the rupture life at stress, σ , and temperature, T ;

t is the time.

In general, both the stress, σ , and the temperature, T , are functions of time.

The rupture life, t_r , can be related to the stress as given in Equation (G.8), at least over limited regions of stress or time (see H.4):

$$t_r = m \sigma^{-n} \quad (\text{G.8})$$

where

m is a material parameter which is a function of temperature;

n is the rupture exponent, which is a function of temperature and is related to the slope of the stress-rupture curve.

For a specified design life, t_{DL} , and corresponding rupture strength, σ_r , Equations (G.9) through (G.11) hold:

$$t_{DL} = m \sigma_r^{-n} \quad (\text{G.9})$$

So:

$$m = t_{DL} \sigma_r^n \quad (\text{G.10})$$

Hence:

$$t_r = t_{DL} \left(\frac{\sigma_r}{\sigma} \right)^n \quad (\text{G.11})$$

Substituting Equation (G.11) into Equation (G.7), the life fraction can be expressed as given in Equation (G.12):

$$F(t_{OP}) = \int_0^{t_{OP}} \left[\frac{\sigma(t)}{\sigma_r} \right]^n \frac{dy}{t_{DL}} \quad (\text{G.12})$$

where $\sigma(t)$ is the stress expressed as a function of time.

This integral can be calculated once the temperature and stress history are known, but in general this calculation is difficult to perform. For the purposes of this development for tube design, the temperature is assumed to be constant. (This assumption is not made in G.5.) The remaining variable is, therefore, the stress as a function of time, $\sigma(t)$, which is given by the mean-diameter equation for stress as in Equation (G.13):

$$\sigma(t) = \frac{p_r}{2} \left(\frac{D_o}{\delta(t)} - 1 \right) \quad (\text{G.13})$$

where

p_r is the rupture design pressure;

D_o is the outside diameter;

$\delta(t)$ is the thickness expressed as a function of time.

In general, the rupture design pressure (operating pressure) is also a function of time; however, like temperature, it is assumed to be constant for the purposes of tube design. The thickness is determined from Equation (G.14):

$$\delta(t) = \delta_0 - \phi_{\text{corr}} t \quad (\text{G.14})$$

where

δ_0 is the initial thickness;

ϕ_{corr} is the corrosion rate.

Calculating $F(t_{\text{op}})$ is then simply a matter of substituting Equations (G.13) and (G.14) into Equation (G.12) and integrating. This integration cannot be done in closed form; a simplifying assumption is needed.

Let δ_{σ} be the thickness calculated from σ_r as given in Equation (G.15):

$$\delta_{\sigma} = \frac{p_r D_o}{2\sigma_r + p_r} \quad (\text{G.15})$$

To a first approximation, Equation (G.16) holds:

$$\sigma(t) \cong \frac{\delta_{\sigma}}{\delta(t)} \quad (\text{G.16})$$

Substituting Equations (G.13), (G.14), and (G.16) into Equation (G.12) and integrating results in Equation (G.17):

$$F(t_{\text{op}}) = \frac{\delta_{\sigma}^n}{(n-1)\phi_{\text{corr}} t_{\text{DL}}} \left[\left(\frac{1}{\delta_0 - \phi_{\text{corr}} t_{\text{op}}} \right)^{n-1} - \left(\frac{1}{\delta_0} \right)^{n-1} \right] \quad (\text{G.17})$$

At $t = t_{\text{DL}}$, $F(t_{\text{DL}})$ should equal unity; that is, the accumulated damage fraction should equal unity at the end of the design life. Using $F(t) = 1$ and $t = t_{\text{DL}}$ in Equation (G.17) results in Equation (G.18):

$$1 = \frac{\delta_{\sigma}^n}{(n-1)\phi_{\text{corr}} t_{\text{DL}}} \left[\left(\frac{1}{\delta_0 - \phi_{\text{corr}} t_{\text{DL}}} \right)^{n-1} - \left(\frac{1}{\delta_0} \right)^{n-1} \right] \quad (\text{G.18})$$

Now let $\delta_0 = \delta_{\sigma} + f_{\text{corr}} \delta_{\text{CA}}$ and $B = \delta_{\text{CA}} / \delta_{\sigma}$, where $\delta_{\text{CA}} = \phi_{\text{corr}} t_{\text{DL}}$; that is, the corrosion allowance is defined as being equal to the corrosion rate times the design life. With these changes, Equation (G.18) reduces to an equation as a function of the corrosion fraction, f_{corr} , as given in Equation (G.19):

$$1 = \frac{1}{(n-1)B} \left[\left(\frac{1}{1 + f_{\text{corr}} B - B} \right)^{n-1} - \left(\frac{1}{1 + f_{\text{corr}} B} \right)^{n-1} \right] \quad (\text{G.19})$$

For given values of B and n , Equation (G.19) can be solved for the corrosion fraction, f_{corr} . The solutions are shown in Figure 1.

G.4 Limitations of the Corrosion Fraction

In addition to the limitations of the linear-damage rule mentioned in G.2, the corrosion fraction has other limitations. For the derivation, the temperature, pressure, and corrosion rate were assumed to be constant throughout the operating life. In an operating heater, these factors are usually not constant; nevertheless, the assumptions of constant pressure, temperature and corrosion rate are made for any tube design. The assumptions are, therefore, justified in this case, since the corrosion fraction is part of the rupture design procedure. (The assumption of constant temperature is not made in G.5.)

The derivation of the corrosion fraction also relies on the relationship between rupture life and stress expressed in Equation (G.11). For those materials that show a straight-line Larson-Miller Parameter curve in Figures E.3 to E.66 in Annex E [in metric (SI) units] and Figures F.3 to F.66 in Annex F [in U.S. customary (USC) units], this representation is exact. For those materials that show a curvilinear Larson-Miller Parameter curve, using Equation (G.11) is equivalent to making a straight-line approximation of the curve. To minimize the resulting error, the values of the rupture exponent shown in Figures E.3 to E.66 and in Figures F.3 to F.66 were developed from the minimum 60,000-hour and 100,000-hour rupture strengths (see H.4). In effect, this applies the straight-line approximation to a shorter segment of the curved line and minimizes the error over the usual range of application.

Finally, the mathematical approximation of Equation (G.16) was used. A more accurate approximation is available; however, when it is used, the resulting graphical solution for the corrosion fraction is more difficult to use. Furthermore, the resulting corrosion fraction differs from that given in Figure 1 by less than 0.5 %. This small error and the simplicity of using Figure 1 justify the approximation of Equation (G.16).

G.5 Derivation of Equation for Temperature Fraction

Since tube design in the creep-rupture range is very sensitive to temperature, special consideration should be given to cases in which a large difference exists between start-of-run and end-of-run temperatures. In the derivation of the corrosion fraction in G.3, the temperature was assumed to remain constant. The corrosion fraction can be applied to cases in which the temperature varies if an equivalent temperature can be calculated. The equivalent temperature should be such that a tube operating at this constant equivalent temperature sustains the same creep damage as a tube operating at the changing temperature. Equation (G.6) can be used to calculate an equivalent temperature for a case in which the temperature changes linearly from start of run to end of run.

Equation (G.11) was developed to relate the rupture life, t_r , to the applied stress, σ . A comparable equation is needed to relate the rupture life to both stress and temperature. This equation can be derived by means of the Larson-Miller Parameter plot. When this plot is a straight line (or when the curve can be approximated by a straight line), the stress, σ , can be related to the Larson-Miller Parameter, Γ , as given in Equation (G.20):

$$\sigma = a \times 10^{-b\Gamma} \quad (\text{G.20})$$

where

a, b are curve-fit constants;

$$\Gamma = T^* (C_{LM} + \lg t_r) \times 10^{-3};$$

T^* is the absolute temperature, expressed in Kelvin;

C_{LM} is the Larson-Miller constant;

t_r is the rupture time, expressed in hours.

Solving Equation (G.20) for t_r yields Equation (G.21):

$$t_r = \frac{1}{10^{C_{LM}}} \left(\frac{a}{\sigma} \right)^{1000/(bT^*)} \quad (G.21)$$

Using Equation (G.21), the life fraction, $F(t_{op})$ given by Equation (G.7) becomes Equation (G.22):

$$F(t_{op}) = \int_0^{t_{op}} 10^{C_{LM}} \left(\frac{\sigma}{a} \right)^{1000/(bT^*)} dt \quad (G.22)$$

where

σ is stress as a function of time;

T^* is the absolute temperature as a function of time.

The thickness, $\delta(t)$, which is also a function of time, can be expressed as given in Equation (G.23):

$$\delta(t) = \delta_0 - \left(\frac{\Delta\delta}{t_{op}} \right) t = \delta_0 \left[1 - \left(\frac{\Delta\delta}{\delta_0} \right) \left(\frac{t}{t_{op}} \right) \right] \quad (G.23)$$

where

δ_0 is the initial thickness;

$\Delta\delta$ is the thickness change in time t_{op} ;

t_{op} is the duration of the operating period.

For this derivation, let

$$B = \frac{\Delta\delta}{\delta_0} \quad (G.24)$$

$$\rho = \frac{t}{t_{op}} \quad (G.25)$$

Therefore,

$$\delta(t) = \delta_0 (1 - B\rho) \quad (G.26)$$

Using Equations (G.13) and (G.26) and the approximation given by Equation (G.16), the stress can be expressed as given in Equation (G.27):

$$\sigma(t) \cong \sigma_0 \left[\frac{\delta_0}{\delta(t)} \right] = \frac{\sigma_0}{1 - B\rho} \quad (G.27)$$

where

$$\sigma_0 = \frac{p_r}{2} \left(\frac{D_o}{\delta_0} - 1 \right) \quad (\text{G.28})$$

If a linear change in temperature occurs during the time t_{op} , then the temperature, T^* , can be expressed as a function of time, t , as given in Equation (G.29):

$$T^*(t) = T_0^* + \left(\frac{\Delta T}{t_{op}} \right) t = T_0^* \left[1 + \left(\frac{\Delta T}{T_0^*} \right) \left(\frac{t}{t_{op}} \right) \right] \quad (\text{G.29})$$

where

T_0^* is the initial absolute temperature, expressed in Kelvin;

ΔT is the temperature change in operating time period, t_{op} , expressed in Kelvin.

Let

$$\gamma = \frac{\Delta T}{T_0^*} \quad (\text{G.30})$$

Using Equations (G.25) and (G.30), the equation for temperature becomes as given in Equation (G.31):

$$T(t) = T_0^* (1 + \gamma \rho) \quad (\text{G.31})$$

Using Equations (G.27) and (G.31), Equation (G.22) can be written as given in Equation (G.32):

$$F(t_{op}) = \int_0^1 10^{C_{LM}} \left[\left(\frac{\sigma_0}{a} \right) \left(\frac{1}{1 - B\rho} \right) \right]^{n_0/(1+\gamma\rho)} t_{op} d\rho \quad (\text{G.32})$$

where

$$n_0 = \frac{1000}{bT_0^*}$$

n_0 is the rupture exponent at the initial temperature, T_0^* .

The aim of this analysis is to find a constant equivalent temperature, T_{eq}^* , between T_0^* and $(T_0^* + \Delta T)$ such that the life fraction at the end of the period t_{op} with the linearly changing temperature is equal to the life fraction with the equivalent temperature. This equivalent temperature can be expressed as given in Equation (G.33):

$$T_{eq}^* = T_0^* (1 + \gamma \varpi), \quad 0 < \varpi < 1 \quad (\text{G.33})$$

From Equation (G.32), the resulting life fraction is as given in Equation (G.34):

$$F(t_{op}) = \int_0^1 10^{C_{LM}} \left[\left(\frac{\sigma_0}{a} \right) \left(\frac{1}{1 - B\rho} \right) \right]^{n_0/(1+\gamma\varpi)} t_{op} d\rho \quad (\text{G.34})$$

Equating Equations (G.32) and (G.34) and dividing out common terms yields an integral equation for the parameter ϖ :

$$\int_0^1 \left[\left(\frac{\sigma_0}{a} \right) \left(\frac{1}{1-B\rho} \right) \right]^{n_0/(1+\gamma\rho)} d\rho = \int_0^1 \left[\left(\frac{\sigma_0}{a} \right) \left(\frac{1}{1-B\rho} \right) \right]^{n_0/(1+\gamma\varpi)} d\rho \quad (\text{G.35})$$

For given values of σ_0 , a , n_0 , b , and γ , Equation (G.35) can be solved numerically for ϖ . Using ϖ and Equations (G.30) and (G.33), the equivalent temperature is calculated as given in Equation (G.36):

$$T_{\text{eq}}^* = T_0^* \left(1 + \frac{\Delta T}{T_0^*} \varpi \right) = T_0^* + \varpi \Delta T \quad (\text{G.36})$$

The parameter ϖ is the temperature fraction, f_T , in 4.8.

The solutions to Equation (G.35) can be approximated by a graph if the given values are combined into two parameters as given in Equations (G.37) and (G.38):

$$V = n_0 \gamma \ln \left(\frac{a}{\sigma_0} \right) = n_0 \left(\frac{\Delta T}{T_0^*} \right) \ln \left(\frac{a}{\sigma_0} \right) \quad (\text{G.37})$$

$$N = n_0 B = n_0 \left(\frac{\Delta \sigma}{\sigma_0} \right) \quad (\text{G.38})$$

Using these two parameters, the solutions to Equation (G.35) are shown in Figure 2.

The constant A in Table 3 is one of the least-squares curve-fit constants, a and b , in the equation $\sigma = a \times 10^{-b\Gamma}$, where Γ is the Larson-Miller Parameter and σ is the minimum rupture strength. For materials that have a linear Larson-Miller Parameter curve, A can be calculated directly from any two points on the curve. For all other materials, a least-squares approximation of the minimum rupture strength is calculated in the stress region below the intersection of the rupture and elastic allowable stresses, since this is the region of most applications. For the purpose of calculating the temperature fraction, this accuracy is sufficient.

Annex H (informative)

Data Sources

H.1 General

The American Petroleum Institute [through the API Committee on Refining Equipment (CRE) Subcommittee on Heat Transfer Equipment (SCHTE) Standard 530 Task Group] contracted the Materials Property Council (MPC) to gather new mechanical property data for heater tube alloys and analyze this data using modern parametric data analysis methods to derive equations suitable for incorporation into API 530. The alloys analyzed by the MPC are used for petroleum refinery heater applications and reflect modern steel making practices.

The data collections for prior editions of API 530 were limited to alloys produced in the United States. The new data gathered and analyzed by the MPC included materials test results produced and tested at facilities outside of the United States. For heater tube design calculations per this standard, the material data required include the yield strength, ultimate tensile strength, stress-rupture exponent, and minimum and average stress rupture properties (as described using Larson-Miller Parameter equations). The aforementioned material data is used to calculate the (time-independent) elastic allowable stress and the (time-dependent) rupture allowable stress for the specified design service life and design temperature.

WRC Bull 541 details and outlines the results of the material data review performed by MPC. The scope of this work is summarized in a paper titled *Development of a Material Databook for API Std 530* ^[22].

The yield-, tensile-, and rupture-strength data displayed in Figures E.1 to E.64 and Figures F.1 to F.64 originated in WRC Bull 541.

WRC Bull 541 provides mechanical property data for alloys that have been gathered and analyzed using systematic computerized statistical data fitting methods. Detailed descriptions of the data are not repeated in this annex. The material that follows is limited to a discussion of the deviations from published data and of data that have been used, but are not generally available.

H.2 Yield Strength

Equation (1) in WRC Bull 541 is used to calculate the yield strength as a function of temperature for all materials listed in Table 4. Additionally, the material coefficients for use with this equation are listed in Table 1 (in USC units) and Table 1M (in SI units) of WRC Bull 541. Figures E.1 to E.64 and Figures F.1 to F.64 graphically depict the material yield strength for a range of temperatures in both SI and USC units, respectively.

H.3 Ultimate Tensile Strength

Equation (2) in WRC Bull 541 is used to calculate the ultimate tensile strength as a function of temperature for all materials listed in Table 4. Additionally, the material coefficients for use with this equation are listed in Table 1 (in USC units) and Table 1M (in SI units) of WRC Bull 541. Figures E.1 to E.64 and Figures F.1 to F.64 graphically depict the materials' ultimate tensile strength for a range of temperatures, in both SI and USC units, respectively.

The use of Figures E.1 to E.64 and Figures F.1 to F.64 or Tables E.1 to E.22 and Tables F.1 to F.22 is equally acceptable. When using the tables, semi-log interpolation can be used to determine rupture allowable stresses at intermediate temperatures.

H.4 Elastic Allowable Stress

The elastic allowable stress (time-independent stress) for all materials listed in Table 4 is directly proportional to the materials yield strength over the specific range of temperatures as calculated using the following:

$$S_e = F_{ed} * \sigma_{ys} \quad (H.1)$$

where

S_e is the Elastic Allowable Stress (time-independent);

F_{ed} is the Elastic Allowable Stress Factor; for ferritic steels, $F_{ed} = 0.66$; for austenitic steels, $F_{ed} = 0.90$ (refer to Table 2 of WRC Bull 541);

σ_{ys} is the material yield strength at temperature.

Figures E.1 to E.64 and Figures F.1 to F.64 graphically depict the materials' elastic allowable stresses for a range of temperatures, in both SI and USC units, respectively. Additionally, Tables E.1 to E.22 and Tables F.1 to F.22 list the materials' elastic allowable stresses for a range of temperatures, in both SI and USC units.

The use of Figures E.1 to E.64 and Figures F.1 to F.64 or Tables E.1 to E.22 and Tables F.1 to F.22 is equally acceptable. When using the tables, semi-log interpolation can be used to determine rupture allowable stresses at intermediate temperatures.

H.5 Larson-Miller Parameter

The relationship between temperature, T , design life, L_d , expressed in hours, and stress is provided by the Larson-Miller Parameter (LMP). Equations (H.2) and (H.3), below, give the basic expression for the Larson-Miller Parameter. The term $LMP(\sigma)$ is evaluated using Equation (H.4).

$$LMP(\sigma) = (T + 460)(C_{LM} + \log_{10}[L_d]) \quad (\text{hours, ksi, } ^\circ\text{F}) \quad (H.2)$$

$$LMP(\sigma) = (T + 273)(C_{LM} + \log_{10}[L_d]) \quad (\text{hours, MPa, } ^\circ\text{C}) \quad (H.3)$$

The coefficient C_{LM} in Equations (H.2) and (H.3) is the Larson-Miller Constant. As explained in Section 5 of WRC Bull 541, the Larson-Miller Constant for each heater tube alloy has been optimized by the parametric analysis (Lot-Centered Analysis) of test results from various sources or lots. The log stress and the reciprocal of the absolute temperature were used as the independent variables, while the log time was used as the dependent variable. As a result of the analysis, a value of C_{LM} is obtained for each lot of material studied in the data set, and minimum and average values computed.

The LMP for each heater tube alloy is presented as a polynomial in $\log_{10}$ of stress in the form given by Equation (H.3). Refer to Table 3 of WRC Bull 541 for the list of coefficients (i.e. A_0, A_1 , etc.), the applicable Larson-Miller Constant, C_{LM} , (for the average and minimum properties for each material) and the applicable temperature range. Additionally, it is important to note that the equations for the Larson-Miller Parameter should not be used for temperatures outside of the limiting metal design temperatures shown in Table 3 of WRC Bull 541. The minimum constant entries shown in the aforementioned Table 3 are appropriate to represent the variance expected at a 95 % confidence interval.

$$LMP(\sigma) = A_0 + A_1 * \log_{10}[\sigma] + A_2 * (\log_{10}[\sigma])^2 + A_3 * (\log_{10}[\sigma])^3 \quad (H.4)$$

Figures E.3 to E.66 and Figures F.3 to F.66 graphically depict the materials' Larson-Miller Parameters for a range of stresses, in both SI and USC units, respectively. Additionally, the Larson-Miller Constants for the minimums and averages of the materials' properties are listed as well.

H.6 Rupture Allowable Stress

The rupture allowable stress, σ , (time-dependent stress) and rupture strength for all materials listed in Table 4, may be determined from the Larson-Miller Parameter calculated from Equation (H.4). The solution is given by the following equation:

$$S_t = \sigma = 10^X$$

where

S_t is rupture Allowable Stress (time-dependent);

σ is rupture strength at temperature;

X is exponent computed based on the values of the coefficients in Equation (H.4). A thorough explanation of the calculation for X is detailed in Section 6 of WRC Bull 541.

Figures E.1 to E.64 and Figures F.1 to F.64 graphically depict the materials' rupture allowable stresses for a range of temperatures, in both SI and USC units, respectively, for 20,000-hour, 40,000-hour, 60,000-hour, and 100,000-hour design lives. Additionally, Tables E.1 to E.22 and Tables F.1 to F.22 list the material rupture allowable stress for a range of temperatures in both SI and USC units for each of the design life values listed above in tabular form.

The use of Figures E.1 to E.64 and Figures F.1 to F.64 or Tables E.1 to E.22 and Tables F.1 to F.22 is equally acceptable. When using the tables, semi-log interpolation can be used to determine rupture allowable stresses at intermediate temperatures.

H.7 Rupture Exponent

The rupture exponent can be obtained from the first derivative of log time with respect to stress at any temperature. The rupture exponents used in this document were determined between 60,000 hours and 100,000 hours for the minimum rupture strengths determined from the Larson-Miller Parameter curves.

$$n = \text{abs} \frac{\log_{10} [100,000] - \log_{10} [60,000]}{\log_{10} [S_{100,000}] - \log_{10} [S_{60,000}]} \quad (\text{H.5})$$

where

n is the rupture exponent, at the desired temperature;

$S_{100,000}$ is the rupture allowable stress at 100,000 hours at the desired temperature;

$S_{60,000}$ is the rupture allowable stress at 60,000 hours at the desired temperature.

The values of the rupture exponents obtained were fitted with up to a fifth order polynomial as shown in Equation (H.6). The resulting coefficients are presented in Table 4 of WRC Bull 541.

$$n = C_0 + C_1T + C_2T^2 + C_3T^3 + C_4T^4 + C_5T^5 \quad (\text{H.6})$$

Figures E.2 to E.65 and Figures F.2 to F.65 graphically depict the materials' rupture exponents for a range of temperatures, in both SI and USC units, respectively. Additionally, Tables E.1 to E.22 and Tables F.1 to F.22 list the materials' rupture exponents for a range of temperatures, in both SI and USC units.

H.8 Modification of, and Additions to, Published Data

The data and equations used to generate the curves exhibited and Annex F were obtained from WRC Bull 541. The Tables listing all of the coefficients used to calculate the Annex E and F curves are provided in Section 14 of WRC Bull 541; additionally, notes addressing the data group studied for each material is explained in Section 15 of WRC Bull 541. A summary of several material notes are provided in H.9.

H.9 Steels

H.9.1 5Cr-0.5Mo-Si Steel

Since there are no new data sources for this material, the material parameters developed for the 5Cr-0.5Mo steels were used.

H.9.2 9Cr-1Mo-V Steel

For this material, new data was obtained primarily from Japan.

H.9.3 Type 304L Stainless Steel

Very little rupture testing of Type 304L materials is intentionally conducted; therefore, the performance of this alloy was estimated from data for Type 304 stainless steel with a carbon content in the range of 0.04 %. Note that the limiting design metal temperature for this low-carbon stainless alloy was established at 677 °C (1250 °F).

H.9.4 Type 304/304H Stainless Steel

Only data from tube materials from overseas sources was utilized in this study; more than 450 heats were included in the final database. The high carbon grade and the normal grade materials were grouped together. The minimum was about the same, but the resulting scatter band was less than the current curves.

H.9.5 Type 316L/317L Stainless Steel

The data analysis indicates that the differences in the yield and ultimate tensile strength trend curves for Type 316L and Type 317L materials are indistinguishable; therefore, the material parameters for these two alloys are identical. Note that the limiting design metal temperature for these low-carbon stainless alloys was established at 704 °C (1300 °F).

H.9.6 Type 347 Stainless Steel

New data analyzed for this material was obtained primarily from Japan. Microstructural changes at higher temperatures associated with carbide precipitation or dissolution/formation of sigma phase cause the rupture exponent plot to increase slightly with increasing temperatures (see curve deflection in Figures E.50 and F.50). Thus, for this alloy, the minimum value is noted on the rupture exponent curves.

The owner/user should specify whether their Type 347 stainless steel heater tubes should be optimized for corrosion resistance (fine grained practice) or for creep resistance (coarse grained practice).

H.9.7 Type 347H Stainless Steel

New data analyzed for this material was obtained primarily from Japan. Microstructural changes at higher temperatures associated with carbide precipitation or dissolution/formation of sigma phase cause the rupture exponent plot to increase slightly with increasing temperatures (see curve deflection in Figures E.53 and F.53). Thus, for this alloy, the minimum value is noted on the rupture exponent curves.

H.9.8 Alloy 800

Material results from heats that do not take advantage of the heat treating and compositional controls imposed to obtain the Alloy 800H and Alloy 800HT grades were excluded from the analysis. Thus, this unrestricted material is not usually used for creep service and the database is relatively small.

H.9.9 Alloy 800H

Tubular product data for yield and ultimate tensile strength was obtained for this alloy. A broad international material database is represented in the stress rupture data shown and is generally in conformance with prior estimates. Some test results lasted in excess of 100,000 hours.

H.9.10 Alloy 800HT

More recent material data from tubular products from overseas sources was combined with the original database. Due to the strengthening nickel-aluminum-titanium compounds and redissolving of carbides, the improvement of Alloy 800HT, over Alloy 800H, is not expected to be very large at intermediate temperatures, and it disappears at very high temperatures.

H.9.11 Alloy HK-40

Material properties (elevated temperature yield and ultimate tensile strength) from high carbon content Alloy HK-40 castings were evaluated. The analysis showed an increase in yield strength in the 1200 °F to 1300 °F range due to precipitation. Lower minimums are shown, as compared to the existing ANSI/API 530 curves, from this large database collected.

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