Calculation of Heater-tube Thickness in Petroleum Refineries

API STANDARD 530
Proposed EIGHTH EDITION
COMMENTS ONLY BALLOT DRAFT

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Introduction

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In API Standards, the SI system of units is used. In this standard, where practical, US Customary (USC) units are included in parenthesis for information.

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Calculation of Heater-tube Thickness in Petroleum Refineries

1 Scope

This standard specifies the requirements and provides guidance 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. The requirements are appropriate for designing tubes for service in both corrosive and noncorrosive applications.

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.

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/A106M [2], *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*

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

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

WRC Bulletin 541 [3], *Evaluation of Material Strength Data for Use in API Std 530*, M. Prager, D.A. Osage, and C.H. Panzarella, 2013

3 Terms, Definitions, and Symbols

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, e.g., 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 corrosion fraction
f_corr

A factor applied to the corrosion allowance in determining the minimum rupture thickness of a tube.

NOTE See Annex G for derivation of this factor.

3.5
creep rupture design factor
F_{cr}
A factor applied to determine the rupture allowable stress.

3.6
design life
t_DL
Operating time used as a basis for tube design.

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

3.7
design metal temperature

T_d

Tube-metal or skin temperature used for design.

3.8
elastic allowable stress
time-independent allowable stress

σ_el

Allowable stress for the elastic range. See 6.2.

3.9
elastic design pressure

p_el

Maximum instantaneous pressure that the heater coil can sustain.

3.10
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.

3.11
inside diameter

D_i^*

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

3.12
minimum thickness

δ_min

The minimum required thickness of a new tube, considering all appropriate allowances.

3.13
outside diameter

D_o

Outside diameter of a new tube.

3.14
pressure design code

Recognized pressure design code or standard specified or agreed by the user.

EXAMPLES ASME BPVC, Section VIII or EN 13445 (all parts) for pressure vessels and ASME B31.3 or EN 13480 (all parts) for piping.

3.15
rupture allowable stress
time-dependent allowable stress

σ_r

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

3.16
rupture design pressure
p_r
Maximum operating pressure that the coil section can sustain during normal operation.

3.17
rupture exponent
n
Parameter used for design in the creep-rupture range.

3.18
rupture stress (minimum)
σ_{r*}
The minimum rupture strength based on minimum LM-parameter with F_{cr} = 1.0 for a specified design life within the limiting design metal temperatures.

3.19
stress thickness
δ_σ
Thickness, excluding all thickness allowances, calculated from an equation that uses an allowable stress.

3.20
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.

3.21
user
The party that undertakes the calculations in the design, specification, and evaluation (where applicable) of tubes and associated components for fired heaters.

3.22
vendor
The party that provides new tubes and associated component fittings for fired heaters.

NOTE The vendor has the responsibility for the quality of the product in accordance with the standard.

4 General Design Information

4.1 Information Required

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

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 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.

4.1.2 If any of items in 4.1.1 a) to e) are not provided, the following applicable parameters shall be used:

a) design life equal to 100,000 hours;

b) design metal temperature based on the maximum metal temperature (the equivalent-temperature concept shall not apply);

c) temperature allowance equal to 15 °C (25 °F);

d) corrosion fraction given in Figure 1;

e) elastic-range thermal-stress limits.

4.1.3 If the heater is required to operate in turndown or operating conditions other than design mode, the user shall identify all the required operating cases on the datasheet, with the designer identifying the controlling or limiting case used for design.

NOTE: A review of these operations is required with the purpose of identifying the most conservative case.

4.2 Limitations for Design Procedures

4.2.1 The design procedures in this standard shall only be used for seamless tubes; they are not applicable to tubes that have a longitudinal weld.

4.2.2 The design procedures in this standard shall only be used for tubes with a thickness-to-outside diameter ratio $\delta_{\mathrm{min}}/D_{\mathrm{o}}$ of less than 0.15.

NOTE This standard applies specifically to the design of refinery fired heater tubes (direct-fired, heat-absorbing tubes within enclosures), which are subject to an internal pressure that exceeds the external pressure. These procedures are not intended for the design of external piping.

5 Design

5.1 General

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.

NOTE A sample calculation that uses these methods herein described is included in Annex A. Calculation sheets (see Annex D) are available for summarizing the calculations of minimum thickness and equivalent tube metal temperature.

5.2 Equation for Stress

5.2.1 The design equation for stress in a tube in both the elastic range and the creep-rupture range shall be based on the mean-diameter equation for stress in a tube. The mean-diameter equation for stress is as given in Equation (1):

$$\sigma = \frac{p}{2}\left(\frac{D_{\mathrm{o}}}{\delta} - 1\right) = \frac{p}{2}\left(\frac{D_{\mathrm{i}}}{\delta} + 1\right) \tag{1}$$

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).

5.2.2 In the elastic range, the elastic design pressure, (p_el,) and the elastic allowable stress, (σ_el,) shall be used in Equation (1).

5.2.3 In the creep-rupture range, the rupture design pressure, (p_r,) and the rupture allowable stress, (σ_r,) shall be used.

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

5.3 Elastic Design

5.3.1 With the elastic design, the stress thickness (δ_σ) and the minimum thickness (δ_min) shall be calculated as given in Equations (2) and (3):

$$\delta_\sigma = \frac{p_\mathrm{el} D_\mathrm{o}}{2\sigma_\mathrm{el} + p_\mathrm{el}} \text{ or } \delta_\sigma = \frac{p_\mathrm{el} D_\mathrm{i}^*}{2\sigma_\mathrm{el} - p_\mathrm{el}} \tag{2}$$

$$\delta_\mathrm{min} = \delta_\sigma + \delta_\mathrm{CA} \tag{3}$$

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;

δ_CA is the corrosion allowance, expressed in millimeters (inches).

NOTE Also refer to 5.6 for minimum allowable wall thickness.

5.3.2 When use of the elastic range thermal limits is specified [4.1.2 e)], the thermal stress design requirements in Annex C shall be followed.

5.4 Rupture Design

With the rupture design, δ_σ and δ_min shall be calculated from Equations (4) and (5):

$$\delta_\sigma = \frac{p_\mathrm{r} D_\mathrm{o}}{2\sigma_\mathrm{r} + p_\mathrm{r}} \text{ or } \delta_\sigma = \frac{p_\mathrm{r} D_\mathrm{i}^*}{2\sigma_\mathrm{r} - p_\mathrm{r}} \tag{4}$$

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

where

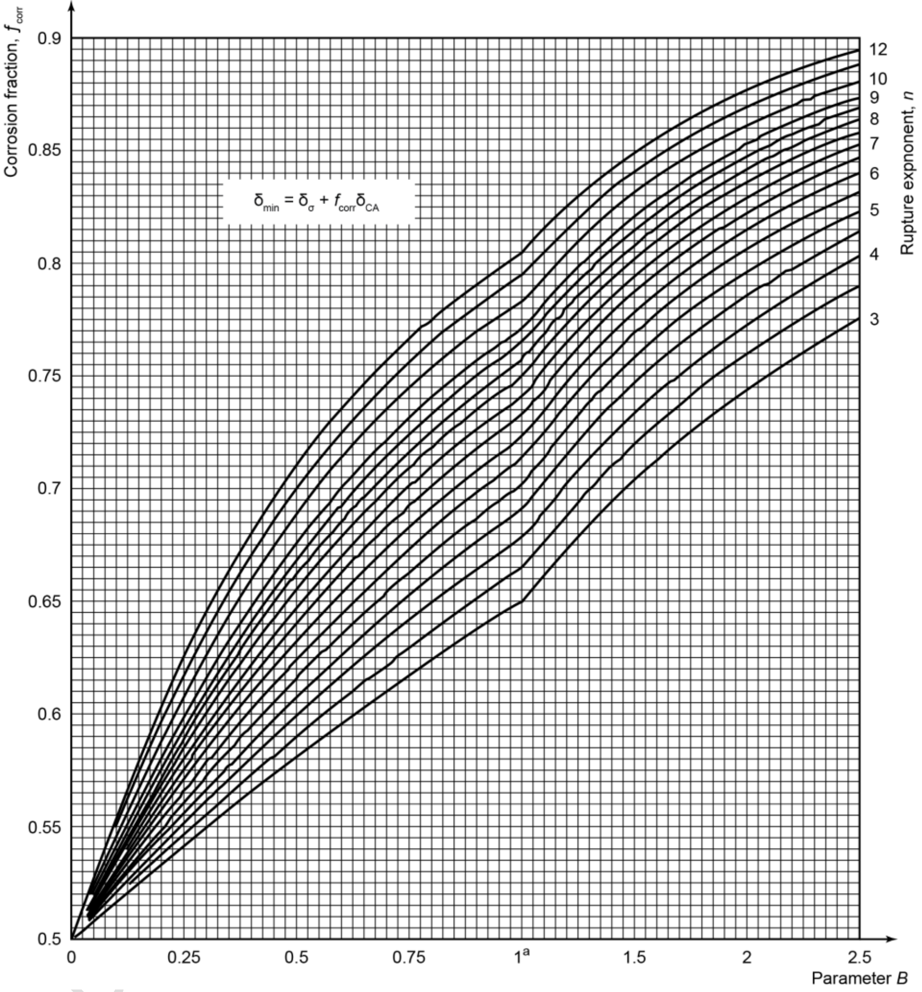
σ_{r} is the rupture allowable stress, expressed in megapascals (pounds per square inch), at the design metal temperature and the design life;

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 Annex E and Annex F).

NOTE 1 Also refer to 5.6 for minimum allowable wall thickness.



Key

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

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

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

[a] Note change of scale at X = 1.

Figure 1—Corrosion Fraction

5.5 Selection of Stress Thickness

The stress thickness (δ_σ) for both elastic design and rupture design conditions shall be calculated to determine which of the two conditions govern the tube design case, i.e. the larger calculated value of δ_σ.

5.6 Minimum Allowable Thickness

The minimum thickness, (δ_{min}) of a new tube, including the corrosion allowance, shall not be less than that shown in Table 1.

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)

NOTE 1 For ferritic steels, the values shown are the minimum allowable thicknesses of schedule 40 average wall pipe.
NOTE 2 For austenitic steels, the values are the minimum allowable thicknesses of schedule 10S average wall pipe.
NOTE 3 Table 6 shows which alloys are ferritic and which are austenitic.

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 for the material in accordance with the recognized material specification, e.g. ASTM specification, to which the tubes or pipes are purchased.

5.8 Equivalent Tube Metal Temperature

5.8.1 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}) shall be calculated as given in Equation (6):

$$T_{\text{eq}} = T_{\text{sor}} + f_{\text{T}}\,(T_{\text{eor}} - T_{\text{sor}}) \tag{6}$$

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.

5.8.2 The temperature fraction is a function of two parameters, V and N, which shall be calculated as given in Equations (7) and (8):

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

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

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^*_{sor} $= T_{\text{sor}} + 273$ °K (or $T_{\text{sor}} + 460$ °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).

NOTE The material constant A is given in Table 2. The significance of the material constant is explained in G.5.

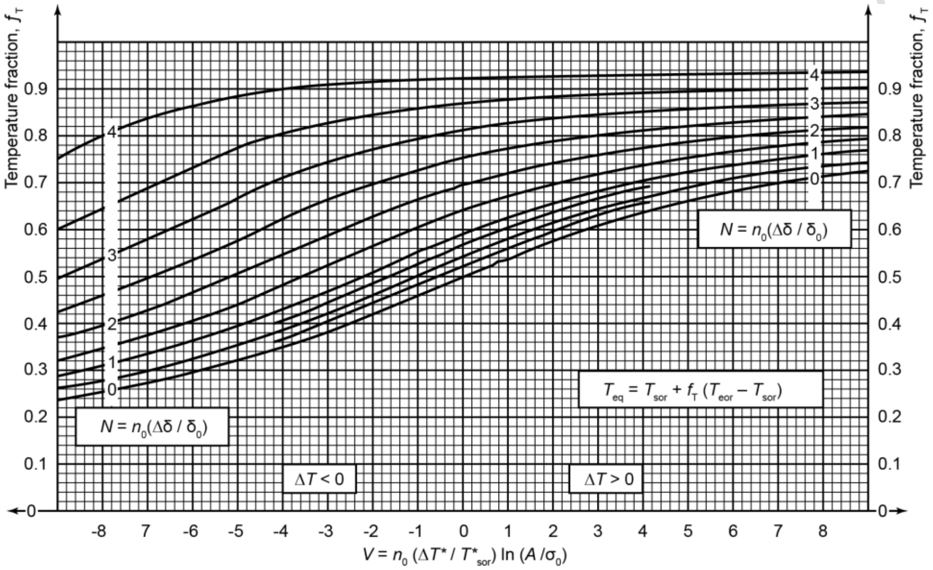


Figure 2—Temperature Fraction

Table 2—Material Constant for Temperature Fraction

Material	Type or Grade	Constant A	
		MPa	(psi)
Low-carbon Steel	—	1.14×10^6	(2.72×10^7)
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	1.31×10^7	(1.29×10^9)
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)

Material	**Type or Grade**	**Constant** *A*	
		MPa	(psi)
9Cr-1Mo Steel	T9 or P9	8.15×10^5	(8.64×10^7)
9Cr-1Mo V Steel	T91 or P91	9.65×10^5	(3.41×10^8)
9Cr-2Si-1Cu Steel	T921 or P921	2.02×10^6	(8.64×10^7)
10.5Cr-V (Alloy 115)	T115 or P115	8.65×10^6	(4.02×10^8)
18Cr-8Ni Steel	304 or 304H	2.05×10^5	(2.98×10^7)
18Cr-8Ni Steel	304L	1.09×10^5	(1.68×10^7)
16Cr-12Ni-2Mo Steel	316 or 316H	4.02×10^5	(5.83×10^7)
16Cr-12Ni-2Mo Steel	316L	2.15×10^5	(3.47×10^7)
16Cr-12Ni-3Mo Steel	317L	2.15×10^5	(3.47×10^7)
18Cr-10Ni-Ti Steel	321	1.07×10^6	(1.31×10^8)
18Cr-10Ni-Ti Steel	321H	7.10×10^5	(8.68×10^7)
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)
18Cr-10Ni-Nb Steel	347LN	4.43×10^6	(6.21×10^8)
18Cr-10Ni-3Cu-Nb Steel	Advanced 347AP	3.26×10^6	(3.72×10^8)
Ni-Fe-Cr	Alloy 800	1.37×10^6	(1.99×10^8)
Ni-Fe-Cr	Alloy 800H	1.35×10^5	(1.87×10^7)
Ni-Fe-Cr	Alloy 800HT	1.80×10^5	(2.61×10^7)
25Cr-20Ni	HK-40	2.04×10^4	(4.65×10^6)

[a] Formerly called columbium (Cb)

5.8.3 The temperature fraction and the equivalent temperature shall be calculated for the first operating cycle.

5.8.4 In applications that involve very high corrosion rates, the calculation of the temperature fraction and the equivalent temperature shall be based on the last cycle since the temperature fraction for the last cycle is greater than that for the first.

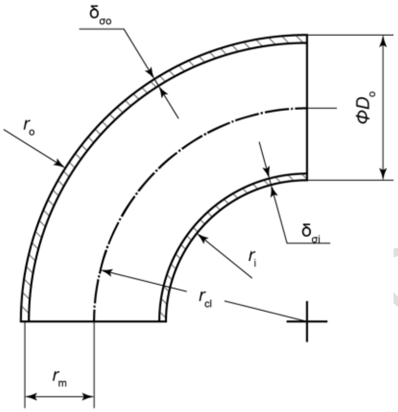
5.8.5 Placeholder – new paragraph for non-linear change in metal temperature change from SOR to EOR (Tim to provide verbiage).

5.9 Component Fittings

5.9.1 Unless otherwise specified, factory-made wrought buttweld fittings shall be manufactured in accordance with the pressure design code, e.g., ASME B16.9.

5.9.2 The pressure-temperature ratings shall be determined in accordance with API 530 calculations for tube thickness of seamless straight tubes.

5.9.3 Other wrought (non-ASME B16.9) component fittings and cast components shall be specifically designed in accordance with the pressure design code, e.g., ASME B31.3.



Key

r_o is the outer radius;

r_i is the inner radius.

For other symbols, see text below Equation (9).

Figure 3—Return Bend and Elbow Geometry

5.9.4 The hoop stress (σ_i) along the inner radius of the bend shall be calculated as given in Equation (9):

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

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).

NOTE 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.

5.9.5 The hoop stress (σ_o) along the outer radius shall be calculated as given by Equation (10):

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

NOTE Using the approximation for r_m given in 5.9.3, Equation (10) can be solved for the stress thickness at the outer radius.

5.9.6 For design, the inner radius stress thickness shall be calculated as given by Equation (11):

$$\delta_{\sigma \mathrm{i}} = \frac{D_\mathrm{o} p}{2N_\mathrm{i}\sigma + p} \tag{11}$$

where

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

$$N_\mathrm{i} = \frac{4\dfrac{r_\mathrm{cl}}{D_\mathrm{o}} - 2}{4\dfrac{r_\mathrm{cl}}{D_\mathrm{o}} - 1} \tag{12}$$

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

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

5.9.7 For elastic design, the outer radius stress thickness shall be calculated as given in Equation (13):

$$\delta_{\sigma \mathrm{o}} = \frac{D_\mathrm{o} p}{2N_\mathrm{o}\sigma + p} \tag{13}$$

where

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

$$N_\mathrm{o} = \frac{4\dfrac{r_\mathrm{cl}}{D_\mathrm{o}} + 2}{4\dfrac{r_\mathrm{cl}}{D_\mathrm{o}} + 1} \tag{14}$$

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

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

5.9.8 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.

5.9.9 In addition to determining the governing thickness for the inside and outside radius of the return bend using the calculations given in Equations (11) and (13), and the evaluations in 5.9.6, the corrosion allowance (δ_CA) shall be added to the minimum calculated thickness for the return bend.

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

6 Allowable Stresses

6.1 General

The allowable stress values used for calculating the required wall thickness of new tubes and associated component fittings for fired heaters shall be in accordance with this standard *unless otherwise agreed between user and vendor*.

NOTE 1 The allowable stress values for various heater-tube alloys are plotted against design metal temperature in Figures E.1 to E.79 (SI Units) and Figures F.1 to F.79 (USC Units). The data is also provided in tabular format in Tables E.1 to E.27 (SI Units) and Tables F.1 to F.27 (USC Units).

NOTE 2 Two different allowable stress values are provided in the figures and tables; the elastic allowable stress and the rupture allowable stress. The basis for these stress values are given in 6.2 and 6.3. Also see 4.2.1.

6.2 Elastic Allowable Stress

6.2.1 The elastic allowable stress, σ_{el}, given in this standard or originating from 6.2.2 used for design shall be two-thirds of the yield strength at temperature for ferritic steels and 90 % of the yield strength at temperature for austenitic steels.

6.2.2 When 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}, shall be calculated as given in Equation (15):

$$\sigma_r = F_{cr} \times \sigma_{r*} \tag{15}$$

where:

F_{cr} is the creep-rupture design factor for the specific material as shown in Table 4.

F_{cr} equals 1.0 for most materials, except for L-grade austenitic stainless steels where F_{cr} equals 0.8; for Advanced SS 347AP, F_{cr} equals 1.0 below a temperature of 704 °C (1300 °F), and F_{cr} equals 0.8 for temperatures above 704 °C (1300 °F).

σ_{r*} is the minimum rupture strength for a specific design life within the limiting design metal temperature shown in Table 5.

NOTE 1 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. All rupture allowable stress curves and data tables shown in API 530 already include the appropriate F_{cr}.

NOTE 2 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) and the appropriate F_{cr}.

6.4 Rupture Exponent

The rupture exponent, n, shall be used for design in the creep-rupture range (see 5.4).

NOTE 1 The rupture exponent values for various heater-tube materials are plotted against design metal temperature in Figures E.2 to E.80 (SI units) and Figures F.2 to F.80 (USC units). The data is also provided in tabular format in Tables E.1 to E.27 (SI units) and Tables F.1 to F.27 (USC units).

6.5 DELETED

6.6 Larson-Miller Parameter Curves

6.6.1 The Larson-Miller Parameter as a function of stress shall be calculated as given in Equations (16) and (17).

In SI units:

$$\mathrm{LMP}(\sigma) = (T_\mathrm{d} + 273)\,(C_\mathrm{LM} + \log_{10} t_\mathrm{DL}) \tag{16}$$

In USC units:

$$\mathrm{LMP}(\sigma) = (T_\mathrm{d} + 460)\,(C_\mathrm{LM} + \log_{10} t_\mathrm{DL}) \tag{17}$$

where:

LMP(σ) is the Larson-Miller Parameter as a function of stress, dimensionless,

T_d is design metal temperature, expressed in Celsius (Fahrenheit)

C_LM is the Larson-Miller Constant, dimensionless;

t_DL is the design life of the tube, expressed in hours;

The Larson-Miller Parameter versus rupture strength curve as calculated in Equations (16) and (17) are shown as Figures E.3 through E.81 and Figures F.3 through F.81 for each individual material with the Larson-Miller Constants for minimum and average properties for each material provided in Table 4.

6.6.2 The curves shall not be used to determine rupture allowable stresses for temperatures higher than the limiting design metal temperatures shown in Table 5.

6.6.3 The curves shall not be used for rupture allowable stresses for a tube life of less than 20,000 hours or greater than 200,000 hours (refer to H.5).

>>> Insert Table 4

6.7 Limiting Design Metal Temperature

6.7.1 The limiting design metal temperature for each heater-tube material shall be as given in Table 5.

6.7.2 Lower critical temperatures for ferritic steels shall be as given in Table 5.

NOTE Austenitic steels do not have lower critical temperatures.

6.7.3 Users shall consider operating, process environmental or other possible factors and their affect in determining the limiting design tube-metal temperature.

EXAMPLE Factors such as oxidation, graphitization, carburization, and hydrogen attack may require lower long-term operating temperature limits than those specified in Table 5.

>>> Insert Table 5

6.8 Allowable Stress Curves

The figure number for set of curves for each alloy is shown in Table 6 and Table 7 below.

Table 4—Larson-Miller Constants[4]

Material	Type or Grade	Larson-Miller Constants C_{LM}		Creep-Rupture Design Factor
		minimum properties	average properties	F_{cr}
Low-carbon Steel	—	18.15	17.70	1.0
Medium-carbon Steel	B	15.6	15.15	1.0
C-½Mo Steel	T1 or P1	19.007756	18.72537	1.0
1-¼Cr-½Mo Steel	T11 or P11	22.05480	21.55	1.0
2-¼Cr-1Mo Steel	T22 or P22	19.565607	18.9181	1.0
3Cr-1Mo Steel	T21 or P21	15.785226	15.38106	1.0
5Cr-½Mo Steel	T5 or P5	16.025829	15.58928	1.0
5Cr-½Mo-Si Steel	T5b or P5b	16.025829	15.58928	1.0
9Cr-1Mo Steel	T9 or P9	20.946	20.5	1.0
9Cr-1Mo V Steel	T91 or P91	23.45	23.11	1.0
9Cr-2Si-1Cu Steel	T921 or P921	20.946	20.5	1.0
10.5Cr-V (Alloy 115)	T115 or P115	25.95	25.66	1.0
18Cr-8Ni Steel	304 or 304H	16.145903	15.52195	1.0
18Cr-8Ni Steel	304L	18.287902	17.55	0.8
16Cr-12Ni-2Mo Steel	316 or 316H	16.764145	16.30987	1.0
16Cr-12Ni-2Mo Steel	316L	15.740107	15.2	0.8
16Cr-12Ni-3Mo Steel	317L	15.740107	15.2	0.8
18Cr-10Ni-Ti Steel	321	13.325	12.8	1.0
18Cr-10Ni-Ti Steel	321H	15.293986	14.75958	1.0
18Cr-10Ni-Nb[a] Steel	347	14.889042	14.25	1.0
18Cr-10Ni-Nb[a] Steel	347H	14.17	13.65	1.0
18Cr-10Ni-Nb[a] Steel	347LN	16.6233	16.4067	1.0
18Cr-10Ni-3Cu-Nb[a] Steel	Advanced 347AP	17.99	16.67	[b]
Ni-Fe-Cr	Alloy 800	17.005384	16.50878	1.0
Ni-Fe-Cr	Alloy 800H	16.564046	16.04227	1.0
Ni-Fe-Cr	Alloy 800HT	13.606722	13.2341	1.0
25Cr-20Ni	HK-40	10.856489	10.4899	1.0

[a] Formerly called columbium, Cb

[b] 1.0 up to and below 704 °C (1300 °F), 0.8 above 704 °C (1300 °F)

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[4] WRC Bulletin 541, 3rd Edition.

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

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	(1427)
2¼Cr-1Mo Steel	T22 or P22	650	(1200)	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)
9Cr-2Si-1Cu Steel	T921 or P921	705	(1300)	785	(1445)
10.5Cr-V (Alloy 115)	T115 or P115	677	(1250)	830	(1525)
18Cr-8Ni Steel	304 or 304H	815	(1500)	—	—
18Cr-8Ni Steel	304L	815	(1500)	—	—
16Cr-12Ni-2Mo Steel	316 or 316H	815	(1500)	—	—
16Cr-12Ni-2Mo Steel	316L	815	(1500)	—	—
18Cr-12Ni-3Mo Steel	317L	815	(1500)	—	—
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	694	(1282)	—	—
18Cr-10Ni-3Cu-Nb[a]	Advanced 347AP	815	(1500)	—	—
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)	—	—

[a] Formerly called columbium (Cb).

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[5] WRC Bulletin 541, 3rd Edition.

Table 6—Index to Allowable Stress Curves (SI Units)

Steel Type	Figures & Table Number, Addendum 1	Figures & Table Number, Addendum 2	Alloy
Ferritic	E.1, 2, 3 (Table E.1)	E.1, 2, 3 (Table E.1)	Low-carbon steel (A 192)
	E.4, 5, 6 (Table E.2)	E.4, 5, 6 (Table E.2)	Medium-carbon steel (A 106B, A 210A1)
	E.7, 8, 9 (Table E.3)	E.7, 8, 9 (Table E.3)	C-½ Mo Steel
	E.10, 11, 12 (Table E.4)	E.10, 11, 12 (Table E.4)	1¼ Cr-½ Mo Steel
	E.13, 14, 15 (Table E.5)	E.13, 14, 15 (Table E.5)	2¼ Cr-1 Mo Steel
	E.16, 17, 18 (Table E.6)	E.16, 17, 18 (Table E.6)	3Cr-1 Mo Steel
	E.19, 20, 21 (Table E.7)	E.19, 20, 21 (Table E.7)	5Cr-½ Mo Steel
	E.22, 23, 24 (Table E.8)	E.22, 23, 24 (Table E.8)	5Cr-½ Mo-Si Steel
	E.25, 26, 27 (Table E.9)	E.25, 26, 27 (Table E.9)	9Cr-1Mo Steel
	E.28, 29, 30 (Table E.10)	E.28, 29, 30 (Table E.10	9Cr-1Mo-V Steel
	N/A	E.31, 32, 33 (Table E.11)	9Cr-2Si-1Cu Steel
	N/A	E.34, 35, 36 (Table E.12)	10.5Cr-V (Alloy 115)
Austenitic	E.31, 32, 33 (Table E.11)	E.37, 38, 39 (Table E.13)	18Cr-8Ni (304 and 304H) Stainless Steel
	E.34, 36, 37 (Table E.12)	E.40, 41, 42 (Table E.14)	18Cr-8Ni (304L) Stainless Steel
	E.37, 38, 39 (Table E.13)	E.43, 44, 45 (Table E.15)	16Cr-12Ni-2Mo (316 and 316H) Stainless Steel
	E.40, 41, 42 (Table E.14)	E.46, 47, 48 (Table E.16)	16Cr-12Ni-2Mo (316L) Stainless Steel
	E.40, 41, 42 (Table E.14)	E.49, 50, 51 (Table E.17)	16Cr-12Ni-3Mo (317L) Stainless Steel
	E.43, 43, 44 (Table E.15)	E.52, 53, 54 (Table E.18)	18Cr-10Ni-Ti (321) Stainless Steel
	E.46, 47, 48 (Table E.16)	E.55, 56, 57 (Table E.19)	18Cr-10Ni-Ti (321H) Stainless Steel
	E.49, 50, 51 (Table E.17)	E.58, 59, 60 (Table E.20)	18Cr-10Ni-Nb (347) Stainless Steel
	E.52, 53, 54 (Table E.18)	E.61, 62, 63 (Table E.21)	18Cr-10Ni-Nb (347H) Stainless Steel
	E.67, 68, 69 (Table E.23)	E.64, 64, 65 (Table E.22)	18Cr-10Ni-Nb (347LN) Stainless Steel
	N/A	E.67, 68, 69 (Table E.23)	18Cr-10Ni-3Cu-Nb (Adv. 347AP) Stainless Steel
	E.55, 56, 57 (F.19)	E.70, 71, 72 (Table E.24)	Ni-Fe-Cr (Alloy 800)
	E.58, 59, 60 (F.20)	E.73, 74, 75 (Table E.25)	Ni-Fe-Cr (Alloy 800H)
	E.61, 62, 63 (F.21)	E.76, 77, 78 (Table E.26)	Ni-Fe-Cr (Alloy 800HT)
	E.64, 65, 66 (F.22)	E.79, 80, 81 (Table E.27)	25Cr-20Ni (HK-40)

Table 7— Index to Allowable Stress Curves (USC Units)

Steel Type	Figures & Table Number, Addendum 1	Figures & Table Number, Addendum 2	Alloy
Ferritic	F.1, 2, 3 (Table F.1)	F.1, 2, 3 (Table E.1)	Low-carbon steel (A192)
	F.4, 5, 6 (Table F.2)	F.4, 5, 6 (Table E.2)	Medium-carbon steel (A106B, A210A1)
	F.7, 8, 9 (Table F.3)	F.7, 8, 9 (Table E.3)	C-½ Mo Steel
	F.10, 11, 12 (Table F.4)	F.10, 11, 12 (Table E.4)	1¼ Cr-½ Mo Steel
	F.13, 14, 15 (Table F.5)	F.13, 14, 15 (Table E.5)	2¼ Cr-1 Mo Steel
	F.16, 17, 18 (Table F.6)	F.16, 17, 18 (Table E.6)	3Cr-1 Mo Steel
	F.19, 20, 21 (Table F.7)	F.19, 20, 21 (Table E.7)	5Cr-½ Mo Steel
	F.22, 23, 24 (Table F.8)	F.22, 23, 24 (Table E.8)	5Cr-½ Mo-Si Steel
	F.25, 26, 27 (Table F.9)	F.25, 26, 27 (Table E.9)	9Cr-1Mo Steel
	F.28, 29, 30 (Table F.10)	F.28, 29, 30 (Table E.9)	9Cr-1Mo-V Steel
	N/A	F.31, 32, 33 (Table E.11)	9Cr-2Si-1Cu Steel
	N/A	F.34, 35, 36 (Table E.12)	10.5Cr-V (Alloy 115)
Austenitic	F.31, 32, 33 (Table F.11)	F.37, 38, 39 (Table E.13)	18Cr-8Ni (304 and 304H) Stainless Steel
	F.34, 36, 37 (Table F.12)	F.40, 41, 42 (Table E.14)	18Cr-8Ni (304L) Stainless Steel
	F.37, 38, 39 (Table F.13)	F.43, 44, 45 (Table E.15)	16Cr-12Ni-2Mo (316 and 316H) Stainless Steel
	F.40, 41, 42 (Table F.14)	F.46, 47, 48 (Table E.16)	16Cr-12Ni-2Mo (316L) Stainless Steel
	F.40, 41, 42 (Table F.14)	F.49, 50, 51 (Table E.17)	16Cr-12Ni-3Mo (317L) Stainless Steel
	F.43, 43, 44 (Table F.15)	F.52, 53, 54 (Table E.18)	18Cr-10Ni-Ti (321) Stainless Steel
	F.46, 47, 48 (Table F.16)	F.55, 56, 57 (Table E.19)	18Cr-10Ni-Ti (321H) Stainless Steel
	F.49, 50, 51 (Table F.17)	F.58, 59, 60 (Table E.20)	18Cr-10Ni-Nb (347) Stainless Steel
	F.52, 53, 54 (Table F.18)	F.61, 62, 63 (Table E.21)	18Cr-10Ni-Nb (347H) Stainless Steel
	F.67, 68, 69 (Table F.23)	F.64, 65, 66 (Table E.22)	18Cr-10Ni-Nb (347LN) Stainless Steel
	N/A	F.67, 68, 69 (Table E.23)	18Cr-10Ni-3Cu-Nb (Adv. 347AP) Stainless Steel
	F.55, 56, 57 (F.19)	F.70, 71, 72 (Table E.24)	Ni-Fe-Cr (Alloy 800)
	F.58, 59, 60 (F.20)	F.73, 74, 75 (Table E.25)	Ni-Fe-Cr (Alloy 800H)
	F.61, 62, 63 (F.21)	F.76, 77, 78 (Table E.26)	Ni-Fe-Cr (Alloy 800HT)
	F.64, 65, 66 (F.22)	F.79, 80, 81 (Table E.27)	25Cr-20Ni (HK-40)

Annex A requires additional content. Intended modifications are denoted by comments.

Annex A

Design, including coil replacement, Tube Metal Temperature Limits, and In-service Threshold Wall Thickness Considerations

1. General

Commented [DA1]: Will need to follow annex numbering convention (A.#, A.#.#, etc.) once this section is completed.

1.1. Describe what is provided in AxA -

The first part of this annex addresses the design of new tubes for petroleum refinery fired heater services. The informative design considerations are provided to supplement the normative text provided in the main body of this standard. The end-user/operator is responsible for identifying the applicable considerations applied in the design thickness of new tubes. The applied considerations should be documented in the documentation provided to the end-user/operator, allowing recreation and validation of the design basis.

1.2. Fitness for Service and Remaining Life Assessment

The second part of this annex addresses in-service tube integrity management and its relationship to the tube design. In accordance with API 584, a methodology for the establishment of in-service tube metal temperature (TMT) limits is provided. In accordance with API 579-1/ASME FFS-1 the in-service tube minimum required thickness and Maximum Allowable Working Pressure (MAWP) may be computed based on the original construction code. Capturing the unique operating characteristics of fired heater tubes that may have metal loss and creep damage, a methodology for the establishment of in-service tube threshold thickness is provided that manages future metal loss and creep damage rates within end-user/operator defined operating period and condition. These methodologies do not replace the requirements of API 584 and 579 and should be used in conjunction with these documents to manage in-service tube integrity. Ultimately, it is the end-user/operator's responsibility to determine if the tubes will be acceptable for future operation with an appropriate margin of safety based on these methodologies, operational controls, inspection methodology, and their overall integrity management strategy.

2. Design Considerations

2.1. General

This Annex provides design information and methods for determining the minimum tube wall thickness for new tubes/tube coils for direct fired heaters typical of those designed in accordance with API 560. These methods are only applicable to seamless tubes with a thickness-to-outside-diameter ratio (δ_{min}/D_o) of less than or equal to 0.15. No considerations are given to the effects of cyclic pressure or cyclic thermal loading or for supplemental loads on the tubes such as stresses imposed by the tube or fluid weight, tube supports, end connections, etc.

For tubes with a δ_{min}/D_o ratio of greater than 0.15, additional considerations such as thermal stress, multi-axial stress, etc., can apply to the design of these thicker tubes. In the absence of an applicable local or national code, a boiler pressure design code, such as ASME BPVC, Section 1, may be used to address thick wall tube designs.

2.2. Design Parameters

2.2.1. General

2.2.1.1. 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 a higher temperature may creep, or permanently deform, even at stress levels 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, even though no metal loss mechanism, e.g. corrosion, oxidation, etc. may be active. For the steel operating at the lower temperature, the effects of creep are nonexistent or negligible with experience indicating that, tube life is indefinite, unless a metal loss mechanism is active.

2.2.1.2. 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 (rupture) design.

Elastic design is design in the elastic range, in which the allowable stress of the material is based on the yield strength (see 5.3) and is independent of service time. Rupture design is the design for the creep-rupture range, at higher temperatures, in which allowable stress is dependent on the rupture strength of the material (see 5.4) and service time.

The metal temperature that separates the elastic and creep-rupture ranges of a heater tube is referred to as the threshold temperature. The threshold temperature is not a single value; it is a range of temperatures that depends on the alloy being considered.

For the purposes of this design document, the threshold temperature (or onset of rupture design) has been defined as the intersection of elastic allowable stress with the 100,000 hour min creep property stress. Below the threshold temperature for any material, elastic design (left pointing arrow) would typically govern design whereas above the threshold temperature, rupture design (right pointing arrow) would typically govern design.

Figure X – Example Threshold Temperature.

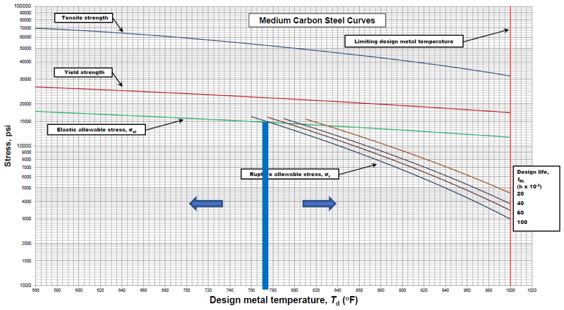

Figure F.4—Stress Curves (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Left pointing arrow: Elastic Design; Right pointing arrow: Rupture Design

>>> RW – Develop a figure with the threshold temperature and left / right pointing arrows in the figure (Action RW)

2.2.1.3. The elastic design is based on preventing failure by bursting at the end of design life. The rupture design is based on preventing failure by creep rupture during the design life.

2.2.1.4. Other considerations that govern the design tube wall thickness include:
- design pressure,
- tube metal temperature,
- diameter,
- material properties,
-design life, and
- corrosion allowance.

2.2.1.5. All the design equations described in Section 5 are summarized in Table A.1.

Commented [HT2]: API 579 Creep threshold doesn't apply because using a different definition of onset of creep range. 579 reference Section 4.11 Tables
Table 4.1 – Temperature Limit Used to Define the Creep Range

Commented [HT3]: Remove Carbon steel reference. Show a generic material.

2.2.1.6. A sample calculation that uses these methods is included in A.2.2.10. Calculation sheets (see Annex D) are available for summarizing the calculations of minimum thickness and equivalent tube metal temperature.

Table A.1—Summary of Working Equations

Elastic design:

$$\delta_\sigma = \frac{p_{\mathrm{el}} D_{\mathrm{o}}}{2\sigma_{\mathrm{el}} + p_{\mathrm{el}}} \text{ or } \delta_\sigma = \frac{p_{\mathrm{el}} D_{\mathrm{i}}^*}{2\sigma_{\mathrm{el}} - p_{\mathrm{el}}} \tag{2}$$

$$\delta_{\min} = \delta_\sigma + \delta_{\mathrm{CA}} \tag{3}$$

Rupture design:

$$\delta_\sigma = \frac{p_{\mathrm{r}} D_{\mathrm{o}}}{2\sigma_{\mathrm{r}} + p_{\mathrm{r}}} \text{ or } \delta_\sigma = \frac{p_{\mathrm{r}} D_{\mathrm{i}}^*}{2\sigma_{\mathrm{r}} - p_{\mathrm{r}}} \tag{4}$$

$$\delta_{\min} = \delta_\sigma + f_{\mathrm{corr}}\delta_{\mathrm{CA}} \tag{5}$$

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;

$\delta_{\min}$ 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 as a function of *B* and *n* in Figure 1;

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

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

Equivalent tube metal temperature:

$$T_{\mathrm{eq}} = T_{\mathrm{sor}} + f_{\mathrm{T}}\left(T_{\mathrm{eor}} - T_{\mathrm{sor}}\right) \tag{6}$$

where

ΔT^* $(= T_{\mathrm{eor}} - T_{\mathrm{sor}})$ 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}^* $= T_{\mathrm{sor}} + 273$ °K (or $T_{\mathrm{sor}} + 460$ °R);

f_{T} is the temperature fraction given in Figure 2.

2.2.2. Design Pressure

Commented [HT4]: Formula available for this in later Annex. Add reference later in this document.

Commented [RW5R4]: This table would be best located in the section on examples

Commented [HT6R4]: Move and incorporate in section with examples.

2.2.2.1. The elastic design pressure is based on preventing failure by bursting when a pressure excursion has occurred near the end of the design life and the corrosion allowance has been consumed. Elastic design pressure is usually related to relief-valve settings, pump shut-in pressure, system hydraulic analysis, etc. The elastic design should consider the maximum possible pressure that may occur in the lifetime of the coil, e.g., flow blockage at the outlet-end of the coil.

2.2.2.2. Rupture design pressure is usually related to normal (not upset, transient) operation and should consider the maximum possible pressure that may occur in the lifetime of the coil under normal conditions, e.g., normal end-of-run coil pressure at the inlet end of the coil.

2.2.2.3. Rupture design is commonly used for heater tubes that will operate in the creep range during the tube's design life, e.g., Coker heater service. To further reduce the conservatism of the design thickness, multiple pressure zones may be used to represent the normal operating pressure of each tube more closely. For example, the radiant section of a Coker heater may be divided into pressure zones that gradually reduce the pressure from inlet to outlet end, aligning with an increasing temperature.

2.2.2.4. 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 may last only hours or days. The rupture design pressure is used in the rupture design equation since creep damage accumulates due to the action of the operating, or long-term, stress. The elastic design pressure is used in the elastic design equation to prevent excessive, i.e., above allowable, stress in the tube during periods of operation at the maximum pressure.

2.2.2.5. Vacuum design is not covered in this standard. In the absence of an applicable local or national codes, one should use a pressure design code, e.g., ASME BPVC, Section VIII, Division 1, to address external pressure designs.

Commented [HT7]: 579 Committee has recommended removing this reference. Suggest Creep Buckling that is going to be added to 579, but not in current edition. We need to find another reference or keep this one to bridge the gap. Leave in for now, to be addressed later.

2.2.3. Design Tube Metal Temperature

2.2.3.1. Design tube metal temperature (TMT) is determined by calculating the maximum tube metal temperature (T_{max}) or the equivalent tube metal temperature (T_{eq}) and adding an appropriate temperature allowance (T_A). In some designs, a different design value for elastic and rupture cases may be appropriate, especially if an equivalent tube metal temperature design case is specified.

2.2.3.2. A procedure for calculating the maximum tube metal temperature from the heat-flux, and other heater configuration parameters, is included in Annex B. Commercial software models that consider the heater service, configuration, operating plan, etc., are commonly used to perform the calculation of T_{max}.

Commented [HT8]: Add information to Annex B that discusses limitations of commercial software.

2.2.3.3. The elastic design metal temperature is the maximum calculated TMT in consideration of all the specified operating cases plus the appropriate temperature allowance. The elastic case should consider the effect of internal fouling on the maximum operating temperature.

2.2.3.4. For the rupture design metal temperature, the accumulation of creep damage is a function of the actual operating TMTs. The rupture design metal temperature is also the maximum calculated TMT in consideration of all the specified operating cases plus the appropriate temperature allowance. However, for applications in which there are significant differences between start-of-run and end-of-run TMTs, a design based only on the maximum temperature can be conservative, since for most of the operating time, the

TMT is usually less than the maximum. In these cases, an equivalent tube metal temperature should be used for the rupture design metal temperature.

2.2.3.4.1. The calculation of T_{eq} is described in 5.8. The practice provides a procedure to calculate the T_{eq} that would cause the same amount of creep damage as a range of operating TMTs. The practice is based on a linear change of TMT from start-of-run to end-of-run. For a non-linear change, a more rigorous calculation of the T_{eq} may be calculated by dividing the temperature range into operating periods and utilizing the Linear-damage Rule to calculate the one T_{eq} that would produce the same creep damage as does the sum of the operating periods. An example calculation of the Linear-damage Rule is provided in Annex A…….

The meaning of the rupture exponent is discussed in H.7.

Commented [HT9]: New example to be provided for the group to review and approve.

Commented [HT10]: The meaning is not explained in H.7. H.7 just provides equations for determining the rupture component. A definition for rupture exponent should be added to Terms&Definitions.

Commented [HT11]: Add information in H.7 to describe the meaning of the rupture exponent.

2.2.3.5. The T_{eq} practice is only used for the rupture design case. The maximum, i.e., end-of-run, operating temperature, and the elastic design metal temperature, may be greater than the rupture design metal temperature. For example, for a heater tube design using an equivalent design basis, the T_{eq} is set to the rupture design TMT and the maximum end-of-run TMT is set to the elastic design TMT.

2.2.3.6. Operations that fall outside the design basis for the heater tubes may be considered in the end-users operating plan to ensure that excessive metal loss, creep damage, and/or other damage mechanisms would not occur during these periods. For example, the corrosion allowance consumed during the operation at a specified TMT is considered and is included into the corrosion allowance calculation.

2.2.3.7. The limiting design metal temperature is the upper limit for reliable, i.e., laboratory tested, rupture strength data. The rupture design TMT should not exceed the limiting design metal temperature to ensure adequate operating margin is provided for in-service tubes. However, in-service temperatures, up to 28 °C (50 °F) below the lower critical temperature, may exceed the limiting design metal temperature, such as those that exist during steam-air decoking, online spalling, or regeneration. For heater services, using an equivalent temperature practice, where the rupture design tube metal temperature is set to the limiting design metal temperature, the elastic design TMT is set to max end-of-run TMT, plus an appropriate allowance. Engineering judgement is used to manage the operating practices for designs where the maximum operating temperature will exceed the limiting design metal temperature. For example, the operating time, or other parameter, is managed during these periods to ensure the elastic design allowable stress is not exceeded and to limit creep and other damage mechanisms.

2.2.3.8. Operation at temperatures above the lower critical temperature can result in changes in the microstructure of the alloy. Austenitic steels do not have lower critical temperatures.

2.2.4. Design Material Properties

2.2.4.1. Allowable Stress

2.2.4.1.1. The allowable stress values provided in Annex E and Annex F are applicable for the design of heater tubes. These figures show two different allowable stresses; the elastic allowable stress and the rupture allowable stress.

2.2.4.1.2. The figures in Annex E and Annex F also show the yield and tensile strengths. These curves are included for reference only, with source information given in Annex H.

2.2.4.1.3. The allowable stress values are based on a consideration of yield strength and creep-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 the heater tubes.

2.2.4.1.4. The rupture allowable stress curves were developed from the information contained in Section 6 of WRC Bulletin 541 and reflect the mechanical property data obtained from tubes manufactured in accordance with ASTM standards using modern techniques.

Commented [HT12]: Review 541 and add verbiage reflecting the limitations provided in the 541 document.

2.2.4.1.5. The creep rupture design factor (F_{cr}) is used to reduce the rupture allowable stress for certain materials where the creep rupture testing has not fully defined the material's creep properties. The materials which have creep rupture design factor $F_{cr} < 1.0$ are 304L, 316L, 317L, 317AP, and Advanced 347APF; refer to Table 4, and WRC 541 3rd Edition, Addendum 1.

2.2.4.1.6. No considerations for material property changes are included for adverse environmental effects, such as graphitization, carburization, or hydrogen attack (API 941 [4]) Limitations imposed by environmental effects are considered in the operating practices.

2.2.5. Larson-Miller Parameter Creep Law

2.2.5.1.1. The relationship of a material 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 in 6.6 and H.5. The limiting design metal temperature ranges for each material for which the LMP applies are shown in Table 5.

2.2.5.1.2. At high temperatures, typically considered as greater than half the absolute melting temperature, fired heater tubes will continuously deform under load, even below their elastic yield stress. This time-dependent deformation of stressed components is known as creep. The rate of creep deformation, i.e., creep rate or strain rate, is a function of the material, applied stress, and temperature. For design purposes, the creep properties of a material are typically expressed in terms of the LMP, that combines the time to rupture and temperature into a single variable.

2.2.5.1.3. The LMP is a laboratory measured material property and is represented in the average and minimum creep rupture data provided in Annex E and F. For conservative designs, the minimum creep rupture data is commonly used in the calculations of minimum thicknesses.

2.2.5.1.4. Rupture design cases should also consider the design life (typically set to 100,000 hours (11.4 years)) since the LMP variable is a function of time. The curves in Annex E and F show the relationship of stress, temperature, and time, establishing a basis to determine a rupture design allowable stress, given the rupture design temperature and design life. The plot of the minimum rupture strength against the LMP is also included so that the rupture allowable stress can be determined for any design life.

2.2.5.1.5. The design rupture allowable stresses may be used for tube design lives between 20,000 and 200,000 hours (refer to Annex H.5). The design life is not necessarily the same as the retirement or replacement life. See API 579-1 for determination of operating life during service.

2.2.5.1.6. In past editions of this document, the Larson-Miller constant, C_{LM}, used was a single value used for broad material groups [i.e., $C_{LM} = 20$ for ferrous materials and

C_{LM} = 15 for high alloy and nonferrous (high-nickel) materials]. However, beginning with the seventh edition, the Larson-Miller constant has 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 Bulletin 541. Refer to Annex H.5 for a detailed description of how these curves were derived.

2.2.5.1.7. The LMP versus rupture strength curves are shown in Annex E and F for each individual material. These curves are derived from the material property data and equations provided in WRC Bulletin 541, which may be directly used to calculate specific combinations of stress, temperature, and time in the establishment of a rupture minimum thickness.

2.2.5.1.8. The rupture stress curves are intended for use where the design stress is greater than 6.9 MPa (1 ksi). The curves should not be used to determine rupture **design** allowable stresses for temperatures higher than the limiting design metal temperatures shown in Table 5. For a rupture design case using an equivalent TMT practice, the equivalent TMT may be set to the limiting design metal temperature.

2.2.5.2. Linear-damage Rule

2.2.5.2.1. The Linear-damage Rule [XX], or Robinson Life Fraction, provides a practice for determining the creep rupture design life for variable stress and non-linear temperature conditions. The essence of the practice is to divide the design life of the tube into uniform stress and temperature periods from which the creep rupture life and consumed creep life fraction for the period may be calculated. The period life fractions may then be summed, allowing the equivalent TMT and rupture allowable stress for the design life to be determined. Under the Linear-damage Rule the equivalent TMT and the rupture allowable stress would achieve the same rupture design life as the varying stress and temperature conditions. See G.2 for summary calculations of the Linear-damage Rule.

Commented [HT13]: E.L. Robinson//Trans. ASME 74 (1952) 777.
R5 (July 1995, Issue 2), Assessment procedure for the High Temperature Response of Structures (Berkeley Technology Center, Nuclear Electric plc., 1995)

2.2.5.2.2. There are three primary areas of uncertainty in Linear-damage Rule calculations. First, it is necessary to estimate the accumulated tube damage, i.e. the life fraction used up, based on the design conditions, i.e., predicting operating pressure, TMT, and wall thickness for each period. The uncertainties in these factors, particularly the ~~temperature~~ TMT, may have a significant effect on the estimate. Second, knowledge of the actual rupture strength of a given tube is not precise. This uncertainty is addressed by assuming minimum creep rupture strength in the design conditions. Third, it is necessary to consider the Linear-damage Rule as described in G.2. The limitations of this hypothesis are not well understood. Despite these uncertainties, the estimation that is made using the practice may provide information that assists in making decisions about design minimum thickness for the planned operating conditions of the tube.

2.2.5.2.3.

The Linear-damage Rule may be considered for heater services where special operating conditions occur that significantly vary from the normal operating conditions. Examples include steam-air decoking, online coke spalling, catalyst regeneration, or planned future operating cases that vary significantly from the heater design case, e.g., different feed characteristics, heater service, changes in operating severity, seasonally or in the future time.

Instead of assuming the worst-case design conditions, the Linear-damage Rule would allow for *a* more accurate *and a* less conservative assessment of the rupture design allowable stress.

2.2.6. Design Diameter

2.2.6.1. The diameter of the tube is a required input to calculate the stress thickness. Either nominal inside (D_i^*) or outside (D_o) diameter may be used in the calculation. Most often the outside diameter is used since the value is fixed throughout the design life of the tube. Corrosion is assumed to occur only on the inside surface of the tube, leading to a changing inside diameter and fixed outside diameter during the design life of the tube.

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

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

2.2.7. Design Corrosion Allowance

2.2.7.1. Corrosion allowance is an additional metal thickness on the stress thickness to account for metal loss during the design lifetime *of the tube*. The allowance may be set in accordance with API 560 guidelines or directly estimated from an analysis of the metal loss damage mechanism(s), e.g., predicted corrosion rate times design life. Internal and external metal loss mechanisms should both be included in the allowance.

2.2.7.2. The derivation of the corrosion fraction used in rupture design cases is described in Annex G and the results shown in Figure 1. It is recognized in this derivation that the operating stress at beginning of life is less than end of life; correspondingly, the actual rupture life of the tube is increased beyond the design rupture life when corrosion allowance is applied at beginning of life. By applying the corrosion fraction concept, the predicted rupture life would be equal to the design rupture life. However, if special circumstances require that the user choose a more conservative design, a corrosion fraction of unity ($f_{corr} = 1$) may be specified by the purchaser.

2.2.7.3. Additional corrosion/erosion allowance may be considered for heater services where special operations may consume the allowance faster than normal operation. For example, during on-line spalling and/or mechanical pigging in Coker service, the materials corrosion rate may be higher. Additional allowance for these periods could be calculated by estimating the decoking time during the design life multiplied by the expected corrosion/erosion rate.

2.3. Design Stress Thickness

2.3.1.1. The stress thickness (δ_σ) for both elastic design and rupture design conditions is calculated to determine which is the limiting design case for the design minimum thickness. The larger of the two calculated thicknesses should be the limiting design case that would achieve the design life of the tube. The process logic map shown in Figure XX illustrates the stress thickness calculation.

Commented [HT14]: Figure A.2 updated for design logic diagram.

2.3.1.2. A mean-diameter derivation of tube stress is used to calculate the stress thickness. The mean-diameter equation gives a good estimate of the pressure that produces yielding through the entire tube wall in thin tubes (see 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.

Commented [HT15]: Add references for this mean diameter equation from main body.

2.3.1.3. For an equivalent TMT rupture design case, the calculated stress thickness of a tube is a function of the rupture design temperature, which in turn, is a function of the start of service stress thickness. A few iterations may be necessary to arrive at the design. See the example calculation in A.2.7.

Commented [TH16]: All example calculations to be moved to the last section of Annex A.

2.3.1.4.

2.4. Design Minimum Thickness *(>>RW Heading OK)*

2.4.1.1. The design minimum thickness is determined by adding the design corrosion allowance to the stress thickness. The process logic map shown in Figure XX illustrates the design minimum thickness.

2.4.1.2. The design minimum thickness is not the retirement or replacement thickness of an in-service tube. Retirement or replacement thickness is determined through an API 579-1 assessment.

2.4.1.3. The design minimum thickness should be greater than or equal to the wall thicknesses provided in Table 1. The design minimum thickness provided in Table 1 are based on industry practice and defined in applicable ASTM specifications for manufacturing mill thickness tolerance. For ferritic steels, the minimum allowable thicknesses are for schedule 40 average wall pipe. For austenitic steels, the minimum allowable thicknesses are for schedule 10S average wall pipe. Table 6 shows which alloys are ferritic and which are austenitic.

Commented [HT17]: This is a Shall statement. Final editing to determine if it is stated here as well as in the main body.

Commented [HT18]: Move this statement to MAIN BODY

2.5. Fitting Design

2.5.1.1. The stress variations in a return bend or elbow 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 may 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.

Commented [HT19]: Figure 3 to be shown in main body. Better definition or naming is recommended on the figure parameters.

2.5.1.2. There is a distinction between standard component fittings and specially designed component fittings. See 5.9.

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

Commented [RW20]: In Section 2, if there ia a decision that ASTM specifications are not indispensable to the use of this standards, i.e. If pressure design codes other than ASME are permitted, then the ASTM specifications would be listed as an example, e.g. ASTM A234/A234M, ASTM A403/A403M etc and listed in the bibliography

2.6. Thermal-stress Limitations

Commented [HT21]: Annex C limitations re-stated here

Commented [RW22R21]: OK to leave this section for now and review / decide once the whole annex is completed

2.6.1. The thermal-stress of a tube during normal operation should be calculated in accordance with Annex C.

2.6.2. 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, resulting in significant tube bowing during operation.

2.6.3. 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.

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

2.7. Coil Replacement

2.7.1. General

2.7.2. Current Design Practices

2.7.2.1. Design Life Considerations (include Robinson Life Fraction Rule)

2.7.3. Re-Rate Opportunity

2.7.4. Management of Change

2.7.5. Example: Coker Radiant Coil Replacement

Commented [HT23]: Move this example to the New Examples Section. Example has not been written at this time.

Commented [HT24]: This section has not be written.

2.8.

3. Examples

3.1. 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 mm (6.625 in.)

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

T_d = 425 °C (800 °F)

δ_{CA} = 3.2 mm (0.125 in.)

From figures in Annex E (SI units) and Annex F (USC units) for type 347 stainless steel:

σ_{el} = 125 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 A.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 (6.625)	D_o =
Design pressure, gauge, MPa (psi)	p_{el} = 6.2 (900)	p_r =
Maximum or equivalent metal temperature, °C (°F)	T_{max} =	T_{max} =

Commented [HT25]: Example copied directly from the current edition Section 7. ‘Shall’ statements re-worded. References updated.

Commented [TH26R25]: Examples to be moved to the end of the Annex A.

Commented [HT27]: Check calculations before re-issuing.

Commented [HT28]: The outline had examples at the end of each section. If we are going to start another Section for the examples, then I would suggest moving the examples to the end of Annex A and moving all examples under this section header.

Commented [HT29]: Check that the allowable are up to date with latest properties

Temperature allowance, °C (°F)	T_A =	T_A =
Design metal temperature, °C (°F)	T_d = 425 (800)	T_d =
Design life, h	—	t_{DL} =
Allowable stress at T_d, Figure E.49 (Figure F.49), MPa (psi)	σ_{el} = 125 (18,130)	σ_r =
Stress thickness, Equation (2) or (4), mm (in.)	δ_σ = 4.1 (0.161)	δ_σ =
Corrosion allowance, mm (in.)	δ_{CA} = 3.2 (0.125)	δ_{CA} =
Corrosion fraction, Figure 1, n = B =	—	f_{corr} =
Minimum thickness, Equations (3) or (5), mm (in.)	δ_{min} = 7.3 (0.286)	δ_{min} =

Figure A.4—Sample Calculation for Elastic Design

3.2. Thermal-stress Check (for Elastic Range Only)

The thermal stress, σ_T, in the tube designed in accordance with A.2.6 is checked using the following values for the variables in the equations given in Annex C:

$\alpha = 1.81 \times 10^{-5}$ K^{-1} (10.05×10^{-6} R^{-1})	(thermal expansion coefficient taken from ASME B31.3, *Process Piping Code*);
$E = 1.66 \times 10^{5}$ MPa (24.1×10^{6} psi)	(modulus of elasticity taken from ASME B31.3, *Process Piping Code*);
$v = 0.3$	(Poisson's ratio value commonly used for steels);
$q_o = 63.1$ kW/m^2 [20,000 Btu/(h·ft^2)]	(assumed heat-flux);
$\lambda_S = 20.6$ W/(m·K) [11.9 Btu/(h·ft °F)]	(thermal conductivity).

Using SI units in Equation (C.2):

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

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

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

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 A.2.7.1.1 is the minimum. The average thickness is used in the thermal-stress calculation. The average thickness (see Main Body Section 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:

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

$y = 168.3/151.9 = 1.108$

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

In USC units:

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

$y = 6.625/5.977 = 1.108$

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:

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

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

In USC units:

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

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

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).

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

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

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

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

In USC units:

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

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

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

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

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

If a thicker tube is specified arbitrarily (such as Schedule 80S in this example), the actual average tube thickness from Schedule 80S is 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 mm

therefore

y = 168.3/146.3 = 1.150

In USC units:

D_{i} = 5.761 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:

σ_{Tmax} = (553.2) (0.146)

σ_{Tmax} = 80.9 MPa

In USC units:

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

σ_{Tmax} = 11,718 psi

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

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

In USC units:

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

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

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

In USC units:

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

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:

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

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

In USC units:

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

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

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

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

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

In USC units:

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

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

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

3.3. Rupture Design with Constant Temperature

A modification of the example in A.2.7.1.1 illustrates how the design equations are used for the creep-rupture range. Suppose the tube described in A.2.7.1.1 is designed for the following conditions:

T_{d} = 705 °C (1300 °F)

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

$p_{\mathrm{r}} = 5.8$ MPa gauge (840 psig)

From figures in Annex E (SI units) and Annex F (USC units) for 347 stainless steel:

$\sigma_{\mathrm{r}} = 20.7$ 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 figures in Annex E (SI units) and Annex F (USC units) for 347 stainless steel:

$n = 3.5$

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

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

Hence, using Equation (5):

In SI units:

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

$\delta_{\min} = 22.4$ 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:

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

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

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

In USC units:

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

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

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

Since δ_{min} based on rupture design is greater, it governs the design. This design calculation is summarized on the calculation sheet in Figure A.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)	$p_{el} =$ 6.2 (900)	$p_r =$ 5.8 (840)
Maximum or equivalent metal temperature, °C (°F)	$T_{max} =$	$T_{max} =$
Temperature allowance, °C (°F)	$T_A =$	$T_A =$
Design metal temperature, °C (°F)	$T_d =$ 705 (1300)	$T_d =$ 705 (1300)
Design life, h	—	$t_{DL} =$ 100,000
Allowable stress at T_d, Figure E.49 (Figure F.49), MPa (psi)	$\sigma_{el} =$ 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.)	$\delta_{CA} =$ 3.18 (0.125)	$\delta_{CA} =$ 3.18 (0.125)
Corrosion fraction, Figure 1, $n = 4.4$; $B = 0.264$	—	$f_{corr} =$ 0.53
Minimum thickness, Equation (3) or (5), mm (in.)	$\delta_{min} =$ 7.27 (0.285)	$\delta_{min} =$ 22.4 (0.88)

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

3.4. Rupture Design with Linearly Changing Temperature

Suppose the tube described in A.2.7.1.1 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, $n_0 = 4.96$. 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:

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

In USC units:

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

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 A.2.7.1.1 yields the following:

In SI units:

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

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

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

In USC units:

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

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

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

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:

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

In USC units:

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

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 A.6.

Commented [HT30]: Update reference.

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)	σ_{el} =	σ_r = 27.7 (4050)
Stress thickness, Equation (2) or (4), mm (in.)	δ_σ =	δ_σ = 16.0 (0.622)
Corrosion allowance, mm (in.)	δ_{CA} =	δ_{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.)	δ_{min} =	δ_{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)	ΔT^* = 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.)	δ_0 = 8.00 (0.315)
Corresponding initial stress, Equation (1), MPa (psi)	σ_0 = 58.1 (8,413)
Material constant, Table 3, MPa (psi)	$A = 3.74 \times 10^5$ (5.43×10^7)
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 A.6—Sample Calculation for Rupture Design (Changing Temperature)

3.5. Rupture Design with Non-Linearly Changing Temperature

Commented [HT31]: Update this example for Design Practices with non-linear temperature change.

Commented [RW32R31]: Formerly A.4 Estimation of Accumulated Creep Damage

>>>THIS SECTION TO BE DEVELOPED AND INSERTED WHEN COMPLETED.

4. Establishment of Operating Skin TMT Limits

Commented [RW33]: Formerly A.2

4.1. General

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.

Annex E and F figures may be used to establish TMT operating limits for fired heater tubes. The operating limits may be set to manage the creep damage rate of the tube, with limits typically set to keep the tube outside the creep range during an operating period. By using minimum creep properties and the 100,000 hour minimum property life curve, TMT operating limits may be set that are outside the creep range during an operating period that is equal to or less than 100,000 hours. Additional limit conservatism may be achieved by calculating a lifetime peak operating stress versus the operating stress during a given period. An example TMT operating limit is shown in Figure A.X. By operating in the green zone during the operating period, the creep damage rate would be controlled to greater than a 100,000 hour rupture life.

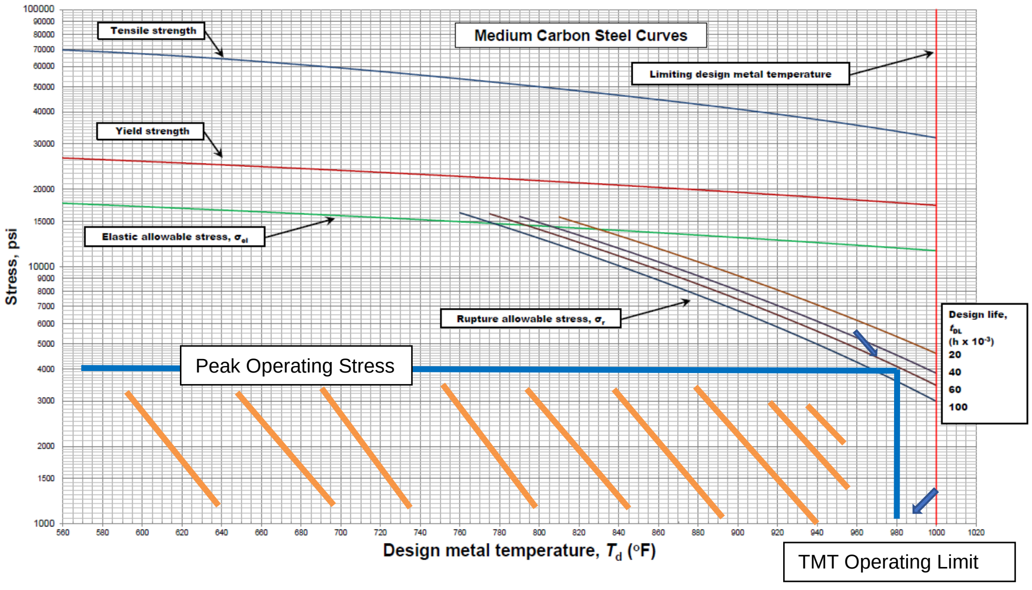

Figure F.4—Stress Curves (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Figure A.X – Example TMT Operating Limit for a Generic Tube Material.

Commented [HT34]: Figure to be changed to a generic material curves.

The following process may be used to set TMT operating limits. The operating stress based on the operating pressure and the future corrosion allowance is calculated using the standard equations for hoop stress (Eq 1). 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.

Commented [HT35]: Figures need to be updated.

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.

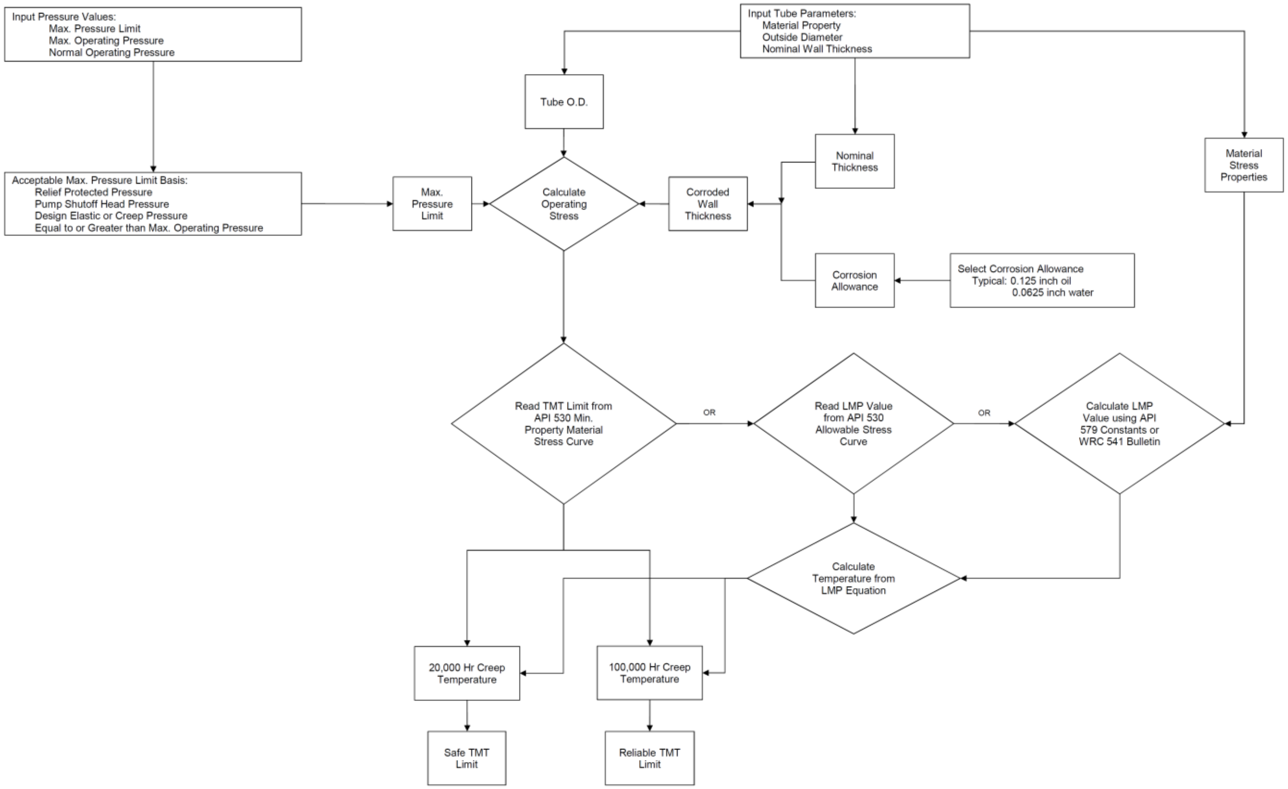

Figure A.1—Tube Metal Temperature Limit Process Logic Map

4.2. Determination of peak operating stress

The operating stress for a given set of conditions may be calculated and then used to establish a basis for the TMT operating limit during a given operating period. Like the design of a new tube thickness, the operating stress is a function of the pressure, thickness, and diameter. These parameters are selected to determine a peak operating stress during an operating period that may be used to control the creep damage rate during an operating period. Once the stress condition is established, then TMT operating limits may be determined from the Annex E and Annex F figures and/or tables.

Note the peak operating stress will not be greater than elastic allowable stress for a given temperature because the tube's design conditions will have established an operating stress below the elastic allowable stress. Only after in-service operation has consumed some or all corrosion allowance would the operating stress approach elastic limits. The peak operating stress may not exceed the elastic allowable stress for a given TMT. Once the calculated peak operating stress has reached elastic allowable stress, further engineering analysis (e.g., API 579-1) may be needed to evaluate an appropriate TMT operating limit.

4.2.1. Determination of maximum pressure limit

An operating pressure is selected that sets an upper limit on the pressure during an operating period. This pressure may be based on the following conditions, depending upon the engineering judgement of the end-user/operator:

1. Relief protected pressure: Either inlet or outlet relief protection adjusted for the pressure drop between the relief location and TMT location. For example, the outlet relief at the downstream reactor location would have the pressure drop from relief to the limit location added to the relief setpoint, establishing a max pressure at the TMT limit location.
2. Pump shutoff head pressure: If flow blockage downstream of the fired heater is possible, (allowing the full shut in pressure of the pump (or compressor) to be seen by the TMT limit location) then this pressure should be considered in the TMT limit basis. This shutoff condition is considered a short-term (and upset) operating condition and would normally only be applied to a short-term TMT limit setpoint.
3. Design elastic or rupture pressure: This pressure is the typical selection for operating pressure because its basis is usually the maximum allowable working pressure for the coil and is usually a setpoint limit for an operating pressure IOW limit. Common practice is to use design pressure to set lifetime TMT operating limits.
4. Equal to greater than max operating pressure: This pressure is considered for TMT limits based on pressure seen (or predicted) during a given operating period. It is typically used for establishment of Temporary TMT limits to manage the creep damage rate until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the IOW TMT limit.

4.2.2. Determination of future corroded wall thickness

The peak operating stress is based on a future wall thickness condition because the TMT operating limit is set to manage the future creep damage rate. For example, if start of run thickness is used to calculate the operating stress, then the peak operating stress would be increasing throughout the period, resulting in a higher than predicted creep damage rate during the period. By selecting a future corroded wall thickness, the actual operating stress during the period would be less than peak operating stress, leading to the actual creep damage rate being less than predicted.

The future corroded wall thickness may be based on the following conditions, depending upon the engineering judgement of the end-user/operator:

- Lifetime operating period: The future corroded wall thickness is set to the nominal thickness less the design corrosion allowance. This practice establishes a lifetime peak operating stress and TMT operating limit.
- Working corrosion allowance: For operating periods beyond the design corrosion allowance or end-user/operator defined periods, a working corrosion allowance may be calculated based upon the expected damage mechanisms and corrosion rate. The working corrosion allowance is determined, and then future corroded thickness is set to the current wall thickness less the allowance predicted to happen during the operating period. The resulting peak operating stress would be valid until the working corrosion allowance has been consumed.

4.2.3. Determination of diameter

The outside diameter is commonly used to calculate the peak operating stress. The metal loss is typically assumed to be from the inside wall surface, resulting in a constant outside diameter value throughout the tube's lifetime. This assumption would result in the peak operating stress being equal to or greater than the actual hoop stress.

4.3. Creep Material Property Strength

The creep rupture strength of the tube is selected to manage the creep damage rate during an operating period. Common practice for heater services that operate outside the creep range is to select the minimum strength properties to ensure the resulting TMT operating limit would keep the tube outside the creep range. The rupture life selection is selected to manage the creep damage rate either for a long period (e.g., 100,000 hour) or short period (e.g., 20,000 hour). Engineering judgement (e.g., API 579-1 FFS evaluation) is used when selecting rupture life values outside 20,000 to 200,000 hours. Average strength properties may be used, depending upon the end-user/operator operating period plan and/or the heater service. For example, short-term conditions may warrant a higher creep damage rate than established in the long-term operating plan, which may further be managed by selecting average strength properties.

4.4. Standard TMT Limit

Once the peak operating stress has been established, the IOW Standard TMT limit may be determined. By API 584 definition, the Standard limit is defined as a TMT value that if exceeded over a specified period could cause increased creep (degradation) damage rates or introduce new damage mechanisms (e.g., HTHA) beyond those anticipated. As shown in Figure X and A.1, the TMT at the intersection of the peak operating stress and selected operating period would be the operating limit. TMTs below the Standard limit would manage the creep damage rate during future operating period(s) to more than the rupture life curve selected (e.g., 100,000 hours).

4.4.1. Temporary TMT Limits

Temporary changes to the Standard TMT limit may be taken, following the Management of Change (MOC) practices of the end-user/operator. For example, internal tube fouling has increased the operating TMT to the established Standard limit, requiring certain action(s) and notification(s) to be taken per the end-user/operator practices. One action may be adjustment to the calculation of the peak operating stress, operating time, and/or material creep property strength that establish a new basis for a TMT operating limit. The basis of the Temporary limit should be fully documented and approved, following the end-user/operator's MOC practices. The TMT above which creep needs to be evaluated can be established using an API 579 Part 10 Level 1 assessment.

4.5. Critical TMT Limit

Once the peak operating stress has been established, the IOW Critical TMT limit may be determined. By API 584 definition, the Critical limit is defined as a TMT value that if exceeded could result in rapid creep (deterioration) damage rate or short-term overheat such that the operator is required to take immediate predetermined action(s) to return the TMT back below the limit to prevent tube failure and hazardous fluid release. The short-term operating time for the Critical limit should be based on end-user/operator practices, using a defined risk threshold. As shown in Figure X and A.1, the TMT at the intersection of the peak operating stress and selected operating period (e.g., 20,000 hours) would be the operating limit. TMTs below the Critical limit would prevent immediate tube failures during future operating period(s).

4.6. Other TMT Limit Considerations

4.6.1. Other Damage Mechanisms

API 571 and API 573 documents provide discussion about common tube damage mechanisms that affect fired heater tube integrity. Many of these damage mechanisms have more limiting TMT limit considerations than metal loss and/or creep damage. For example, carburization mechanism can cause tube failure from ductility loss and cracking that would require limiting TMT to eliminate this damage mechanism for certain materials and services.

4.6.2. Creep Prior Damage

TMT limits for future operation should consider creep damage that has occurred during prior operating periods. Although TMTs in future operating periods are typically managed to prevent or minimize creep damage, the prior damage may cause unexpected consequences during future operation. API 579 Part 10 evaluations may be accomplished to document creep prior damage and provide a basis for future operating TMT limits.

4.6.3. TMT Limits for Coils Operating in the Creep Range

Once the creep range is reached for a given set of operating conditions, the creep damage rate may be managed to prevent the consumption of the expected creep life during an operating period. A heater tube that is operating using an equivalent TMT basis is operating in the creep range. The TMT above which creep damage needs to be evaluated can be established using an API 579 Part 10 Level 1 assessment.

For fired heaters that routinely operate in the creep range the selection of the creep material strength is an important consideration. For these heaters the average creep material strength may be used 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. For heater services that operate in the creep range, either routinely or during a process upset, the fitness for service is evaluated using API 579-1 Part 10 assessment practices.

4.6.4. Uncertainty in measurements

TMT monitoring may be accomplished following industry practice provided in API 556 and API 573. All measurements of TMT are subject to errors and variations that may affect the decisions taken to manage the tube's creep damage rate. The TMT measurement uncertainty should be considered in the evaluation of measurement data collected during operation. Like material creep properties, where the minimum property strength is set to a 95% confidence level, the confidence level of the TMT measurement may be determined, following standard statistical practices. For example, the infrared measurement of TMT may have a statistical 95% confidence level of ±30 °F around the mean value. Typical practice would compare the mean value to the Standard limit to ensure long-term operation is managed to less than the limit, while the mean value plus the uncertainty is compared to the Critical limit to ensure short-term operation could not possibly lead to an immediate consequence. Chapter 5 of Radiation Thermometry: Fundamentals and Applications in the Petrochemical Industry [XX] provides a discussion of TMT measurement uncertainty for common infrared instrument and environmental errors.

Commented [HT36]: Saunders P., Radiation Thermometry: Fundamentals and Applications in the Petrochemical Industry, 1st ed., SPIE, Bellingham, 2007

4.7. Example: Naphtha Hydrotreater TMT Limits

Commented [HT37]: Move this example to New Examples Section at end of Annex A.

The following example illustrates the use of the operating skin TMT limit practice. The Naphtha Hydrotreater heater service has the highest incident of on-line tube failure in the industry. The failure is almost always caused by internal tube fouling that causes tube temperatures to exceed recommended limits. The conditions and recommended TMT limits for a typical Naphtha Hydrotreater Charge heater are summarized in Table X.

Table X. TMT Limit Basis Summary.

Naphtha Hydrotreater Parameters	Convection Process Coil	Radiant Process Coil	Unit	Reference
Maximum Pressure Limit	475	475	psig	Design
Nominal Tube Outside Diameter	5.625	6.625	inch	Design
Material Specification	A335 P9	A335 P9	--	Design
Creep Material Strength Property	Minimum	Minimum	--	API 530
Nominal Wall Thickness	0.258	0.280	inch	Design
Future Corrosion Allowance	0.125	0.125	inch	Design
Future Corroded Wall Thickness	0.133	0.155	inch	API 530
Peak Operating Stress	9.696	9.914	ksi	API 530
TMT Limit				
Critical (20,000 hr. rupture)	1034	1030	°F	WRC 541
Standard (100,000 hr. rupture)	994	990	°F	WRC 541

The maximum pressure limit has been set to the Design Elastic pressure from the original API 530 evaluation. The tube parameters are also taken from the original API 530 evaluation. The future corroded wall thickness is calculated based on the design conditions, resulting in a lifetime corroded thickness value of 3.4 mm (0.133 in.) and 3.9 mm (0.155 in.), respectively for each coil section. Using this thickness, the peak operating stress is calculated as follows:

In SI units:

Commented [HT38]: SI units to be added to example and table.

$$\sigma_o = \frac{x}{2}\left(\frac{168.3}{3.9} - 1\right) = xx\ \text{MPa}$$

In USC units:

Convection Coil : $\sigma_o = \frac{475}{2}\left(\frac{5.625}{0.133} - 1\right) = 9{,}696\ \text{psi}$

Radiant Coil : $\sigma_o = \frac{475}{2}\left(\frac{6.625}{0.155} - 1\right) = 9{,}914\ \text{psi}$

With this stress, Annex E and F figures may be used to select TMT Critical and Standard Limits. In this example the material property equations provided in WRC 541 were solved to determine the respective future operating TMT limits.

5. Determination of In-Service Threshold Wall Thickness

5.1. General

In accordance with API 579 Annex 2C the minimum required thickness for metal loss and creep damage may be determined utilizing these design practices and the allowable stress properties provided in this standard. In the case of metal loss damage, the stress thickness that satisfies the Elastic operating conditions may be determined, establishing an Elastic threshold thickness that prevents exceeding the elastic allowable stress during a future operating period. In the case of creep damage, a Rupture threshold wall thickness may be determined that keeps the tube outside the creep range during a future operating period. As shown in Figure XX, the threshold wall thickness evaluation establishes an operating zone for the future operating period that manages tube integrity within an end-user/operator risk profile.

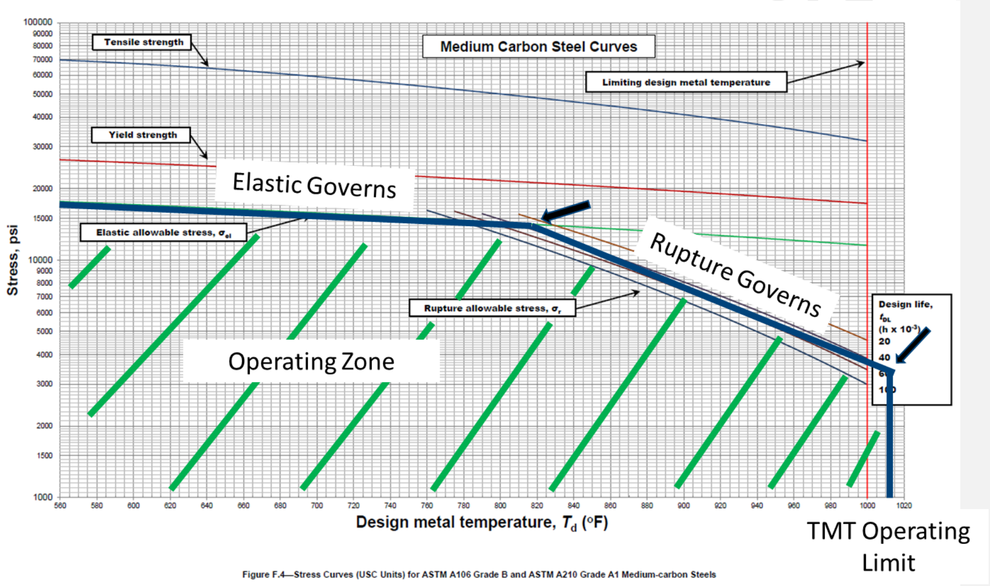

Figure F.4—Stress Curves (USC Units) for ASTM A106 Grade B and ASTM A210 Grade A1 Medium-carbon Steels

Figure XX Example Allowable Stress Operating Zone for Future Operating Period

Commented [HT39]: Figure to be changed to a generic material curves.

The in-service threshold wall thickness evaluation was developed to evaluate creep and metal loss damage to the heater tubes. The methodology follows the guidelines for a screening evaluation provided in API 579-1 Part 2.4.1.1. The screening evaluation methodology verifies that the current tube condition meets the original construction code (i.e., Design Maximum Allowable Working Pressure [MAWP] and Tube Metal Temperature [TMT]) and future in-service operating conditions. If the component fails this screening evaluation, a higher-level assessment (e.g., API 579-1 Level 1 or Level 2 per Parts 5 and 10) is required. Note, this screening evaluation establishes an in-service threshold thickness, allowing for future operation at specified conditions, considering metal loss and creep damage mechanisms. Other potential damage mechanisms (e.g., dents, laminations, gouges, bulges, etc.) have not been considered.

Threshold wall thickness evaluation should not be applied to tubes operating in the creep range. If creep damage (as indicated by measured strain damage) has been observed or is suspected based on the reported operating conditions, a higher-level assessment should be done. API 579-1 FFS is required to evaluate future creep damage and damage rate. For example, a Coker heater that routinely operates in the creep range may not be evaluated, even if measured creep strain damage has not been detected. See API 579 Part 10 Level 1 evaluation for determination of tubes operating in the creep range.

The essence of this evaluation may be outlined as follows. The stress thickness (δ_σ) to handle the future operating conditions is calculated using the standard equations for Elastic and Rupture hoop stresses. Based on expected operating time to the next inspection and measured damage rate, the maximum stress thickness of the Elastic and Rupture cases is increased to account for future metal loss, resulting in an estimate of the allowable (or required) threshold wall thickness (δ_{thd}) (Eq A.1) during future operating periods.

$$\delta_{\text{mm}} > \delta_{\text{thd}} = \delta_\sigma + \text{FCA} \qquad \text{(A.1)}$$

The threshold wall thickness may be used to evaluate the in-service condition of inspected tubes. The results of the screening evaluation are reported as either pass or fail. Each tube is evaluated by comparing the minimum measured wall thickness (δ_{mm}) to the screening threshold wall thickness. Satisfying this screening criterion indicates that the tube is acceptable for continued operation 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).

Finally, the time to reach the maximum stress thickness may be estimated based on the minimum measured wall thickness and measured damage rate. (Eq A.2)

$$\text{Time to reach stress thickness} = (\delta_{\text{mm}} - \delta_\sigma)/\text{corrosion damage rate} \qquad \text{(A.2)}$$

5.2. Elastic Stress Thickness Evaluation

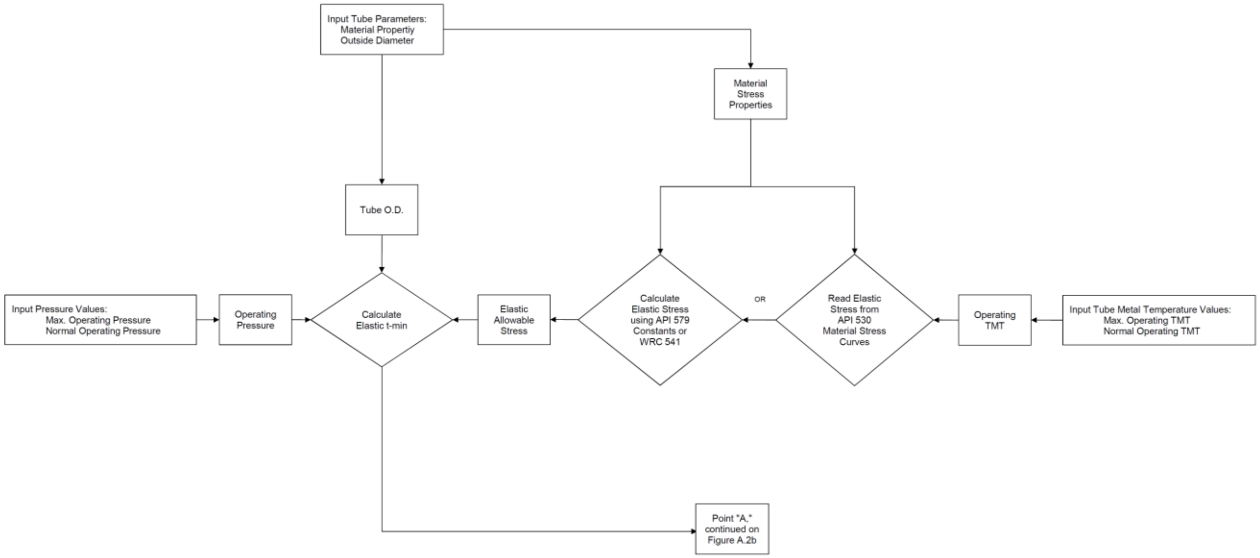

Figure A.2a— Elastic Stress Thickness Determination Process Logic Map

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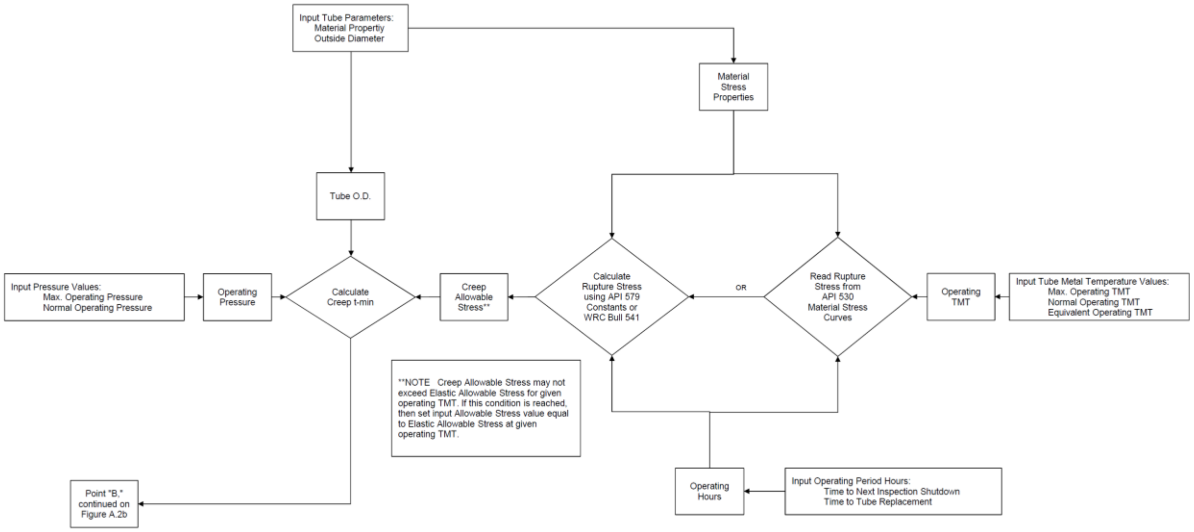
5.3. Rupture Stress Thickness Evaluation



**NOTE Creep Allowable Stress may not exceed Elastic Allowable Stress for given operating TMT. If this condition is reached, then set input Allowable Stress value equal to Elastic Allowable Stress at given operating TMT.

Figure A.2c—Rupture Stress Thickness Determination Process Logic Map (Continued)

5.4. Determination of Operating Stress Thickness

In determining the stress thickness for a future operating period(s), possible combinations of (long-term and short-term) temperature and pressure may be defined and evaluated. For the most conservative evaluation, the maximum operating conditions could be used, i.e., maximum pressure and tube metal temperature, to determine the elastic and rupture stress thicknesses. For the least conservative evaluation, the normal operating conditions could be used, i.e., normal pressure and tube metal temperature. For a moderately conservative evaluation, the normal operating pressure and maximum tube metal temperature could be used for the rupture stress thickness and the maximum operating pressure and normal tube metal temperature could be used for elastic stress thickness. Temporary changes to the basis of the stress thickness may be taken, following the Management of Change (MOC) practices of the end-user/operator.

Operations that fall outside the design basis for the heater tubes may be considered in the end-users operating plan to ensure that excessive metal loss, creep damage, and/or other damage mechanisms would not occur during these periods. For example, the corrosion allowance consumed during the operation at a specified TMT is considered and is included into the corrosion allowance calculation.

The input operating conditions for the stress thickness determination may be broken into two basic operating regimes: normal average and normal maximum. “Normal” term refers to operation that follows defined best practice or typical practices. Transient, or other nontypical, events are not captured in the evaluation, since these events are obviously not normal practice, not planned, and impossible to predict. If a significant event does occur, such as hot-spot on an individual tube, the event would need to be accounted for in an API 579 assessment, to capture the impact on the individual tube’s remaining life.

The calculation of the operating stress thickness is performed using the design stress thickness equations based upon future operating pressure, TMT, and allowable material stresses. The following considerations should be used in the selection of operating parameters.

5.4.1. Future Operating Pressure

The operating pressure for a future operating period(s) is selected that sets an upper boundary on the pressure during an operating period. This maximum and normal operating pressure may be based on the following conditions, depending upon the engineering judgement of the end-user/operator:

5.4.1.1. Normal Maximum Operating Pressure

The maximum operating pressure is typically used to establish the Elastic stress thickness, because the combination of max pressure, normal operating (or design) TMT, and elastic allowable stress would set a thickness that would be acceptable for normal operation during a future operating period. The following options may be considered in setting a maximum pressure for the stress thickness evaluation.

- Relief Protected Pressure

Either inlet or outlet relief protection adjusted for the pressure drop between the relief location and the tube location. For example, the outlet relief at the downstream reactor location would have the pressure drop from the relief to the tube location added to the relief setpoint, establishing a max pressure at the tube location during normal operation.

- Design Elastic Pressure

This pressure is the typical selection for maximum operating pressure because its basis is usually the maximum allowable working pressure for the coil and is usually a setpoint limit for an operating pressure IOW limit.

- Equal to or greater than max operating pressure

This pressure is considered for elastic stress thickness because it establishes an upper pressure seen (or predicted) during a given operating period. Operating pressure is typically used for the establishment of a Temporary stress thickness to manage acceptable operation until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the elastic stress thickness evaluation. Temporary operation within this pressure boundary would not result in an allowable stress exceedance during the operating period.

5.4.1.2. Normal Average Operating Pressure

The average operating pressure is typically used to establish the Rupture stress thickness, because the combination of average pressure, IOW TMT limit, and rupture allowable stress would set a stress thickness that would be outside the creep range for normal operation during the future operating period. The following options may be considered in setting a normal pressure for the stress thickness evaluation.

- Design Rupture Pressure

This pressure is the typical selection for normal operating pressure because its basis is usually the expected operating pressure for the coil during an operating period. If a Design Rupture Pressure is not known, then the normal average operating pressure expected during the period may be used.

- Equal to or greater than average operating pressure

This pressure is considered for the rupture stress thickness based on a normal pressure seen (or predicted) during a given operating period and given that creep damage is a long-term consideration versus a short-term pressure fluctuation that may routinely happen during a period. If a pressure increase is expected during the operating period, e.g., fouling service or process increase, then the EOR or peak expected operating pressure could be used to establish a conservative period operating severity. Operating pressure is typically used for the establishment of a Temporary stress thickness to manage acceptable operation until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the rupture stress thickness evaluation.

5.4.2. Future Operating TMT

The operating TMT for future operating period(s) is selected that sets an upper boundary on the TMT during an operating period. This TMT may be based on the following conditions, depending upon the engineering judgement of the end-user/operator:

5.4.2.1. Normal Average Operating TMT

The normal operating TMT is typically used to establish the Elastic stress thickness, because the combination of max pressure, normal operating (or design) TMT, and elastic allowable stress would set a thickness that would be acceptable for normal operation during a future operating period. The following options may be considered in setting a normal TMT for the stress thickness evaluation.

- Design Elastic or Rupture TMT

This TMT is the typical selection for normal operating TMT because its basis is usually the expected operating TMT for the coil during an operating period. If a Design Elastic or Rupture TMT is not known, then the normal average operating TMT expected during the period may be used.

- Equal to or greater than average operating TMT

This TMT is considered for the Elastic stress thickness because it establishes a basis for the normal (or predicted) TMT during a given operating period. If a TMT increase is expected during the operating period, e.g., fouling service or process increase, then the EOR or peak expected operating TMT could be used to establish a conservative period operating severity. Operating TMT with an added allowance is typically used for the establishment of a Temporary stress thickness to manage acceptable operation until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the Elastic stress thickness evaluation.

5.4.2.2. Normal Maximum Operating TMT

The maximum operating TMT is typically used to establish the Rupture stress thickness, because the combination of average pressure, IOW TMT limit, and rupture allowable stress would set a stress thickness that would be outside the creep range for normal operation during the future operating period. The following TMT cases may be considered in setting a maximum TMT for the stress thickness evaluation.

- IOW TMT Limit

This TMT is the typical selection for maximum operating TMT because its basis represents the maximum operating limit during any given operating period. In setting the operating TMT limits, an upper boundary on the TMT is set that would establish the basis for selecting an allowable rupture stress that keeps the operating conditions outside the creep range.

- Equal to or greater than maximum operating TMT

This TMT is considered for Rupture stress thickness because it represents the max TMT seen (or predicted) during a given operating period. This operating TMT (plus an allowance) is typically used for the establishment of a Temporary stress thickness to manage acceptable operation until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the rupture stress thickness evaluation. Temporary operation within this TMT boundary would not result in an allowable stress exceedance during the operating period.

5.4.3. Selection of operating stress during a future operating period

Based on the selection of the future operating TMT, an allowable material stress is selected to determine the Elastic and Rupture stress thickness for the future operating period. As in the Design allowable stress process, the selection would establish an upper boundary on the actual tube stress during the future operating period.

For the Rupture operating stress, the operating time and material creep strength should be selected on the basis that future operation would be outside the creep range, establishing a boundary on the operating stress during the future operating period. The time is typically set to the planned operating period between tube inspection or turnarounds. The material creep strength is typically set to the minimum value. The operating stress above which creep needs to be evaluated can be established using an API 579 Part 10 Level 1 assessment.

The establishment of a Temporary operating stress may be done to manage acceptable operation until a shutdown can be scheduled to correct an operating issue or other defined operating practice that has changed the normal basis for the stress thickness evaluation. The Temporary stress conditions should still satisfy the operation outside the creep range criteria to conform to this practice. For Temporary stress conditions not meeting these criteria, either during normal operation or a process upset, the fitness for service should be evaluated using API 579-1 assessment practices.

5.5. Minimum required threshold thickness evaluation

5.5.1. General

Once the Elastic and Rupture stress thicknesses have been established, the threshold thickness for the next operating period may be determined. First, the minimum required thickness is selected from the following criterion:

Minimum required thickness (δ_{min}): max[$\delta_{\sigma_{el}}$, δ_{σ_r} , or δ_{lim}] (A.x)

The required wall thickness is limited by FFS assessments. API 579 requirements limit the minimum in-service thickness for metal loss and creep damage mechanisms. If the limiting wall thickness (δ_{lim}) is reached during an operating period, then an FFS assessment per API 579 is required. The limiting wall thickness is set by the following criteria:

For metal loss: max[$0.2\delta_{nom}$, 0.100 in. (vessels) or 0.050 in. (pipe)] (A.x)

For creep: min[$0.9\delta_{nom}$, 0.100 in.] (A.x)

The future corrosion allowance is added to the minimum required thickness to compute the threshold thickness required during the next operating period. If the threshold thickness is greater than the minimum measured thickness, the screening evaluation fails, requiring a higher level evaluation to assess FFS. If the threshold thickness is less than the minimum measured thickness, the screening evaluation passes, indicating the minimum required thickness would be available throughout the next operating period (or the evaluated period). The time to reach the minimum required thickness may be calculated for tubes that pass the screening evaluation.

5.5.2. Threshold thickness evaluation

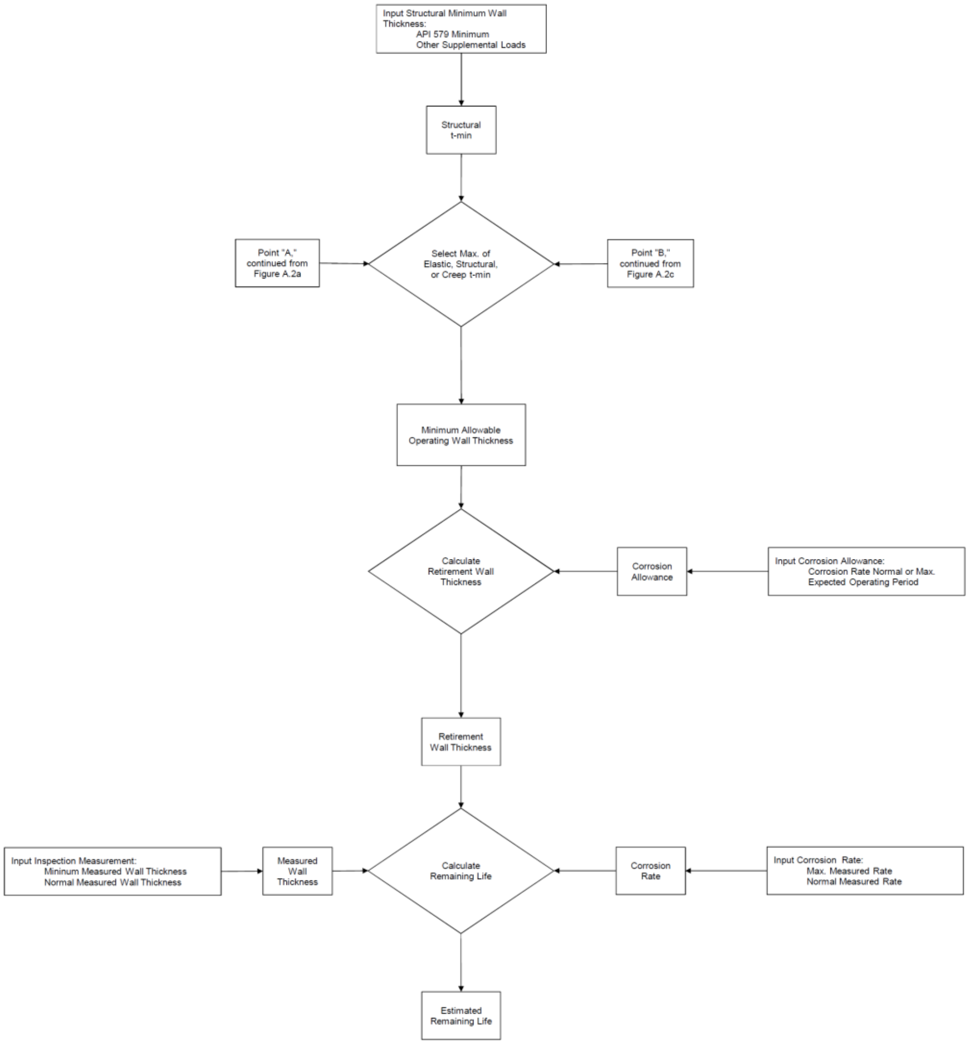


Figure A.2b— Threshold Thickness Determination Process Logic Map (Continued)

Commented [TH40]: Update map with new terminology for threshold thickness, limiting thickness, time to reach threshold thickness.

5.6. Other considerations

This methodology is provided to aid the operator in the determination of the threshold wall thickness to evaluate the operating limitations during future operating periods. No considerations are included for the effects of cyclic pressure or cyclic thermal loading. No considerations for supplemental loads are included in the tube thickness calculations, e.g., stresses imposed by tube/fluid weight, supports, end connections, etc.

API 571 and API 573 documents provide discussion about common tube damage mechanisms that affect fired heater tube integrity. Many of these damage mechanisms have more limiting considerations than metal loss and/or creep damage. For example, carburization mechanism can cause tube failure from ductility loss and cracking that would require additional thickness to manage this damage mechanism for certain materials and services.

The threshold wall thickness is based on a future wall thickness condition because the threshold is set to satisfied operation during the entire operating period. For example, if start of run thickness is set to the stress thickness, then the thickness would be decreasing throughout the period, resulting in a higher than predicted operating stress during the period. By increasing the stress thickness by the future corrosion allowance, the actual operating stress during the period would be less than threshold operating stress.

The future corrosion allowance may be based on the following conditions, depending upon the engineering judgement of the end-user/operator:

- Lifetime operating period: The future allowance is set to the design corrosion allowance less operating allowance already consumed by past operation.
- Working corrosion allowance: For operating periods beyond the design corrosion allowance or end-user/operator defined periods, a working corrosion allowance (operating time multiplied by the predicted corrosion rate) may be calculated based upon the expected damage mechanisms and corrosion rate. The working corrosion allowance is determined, and then the threshold thickness is set to the stress wall thickness plus the allowance predicted to happen during the operating period. The resulting threshold wall thickness would be valid during the defined operating period.

The minimum measured thicknesses used in the pass or fail evaluation should meet the requirements of API 573 and 579 for the quality and quantity of inspection data collected.

5.7. Example: Naphtha Hydrotreater Evaluation of threshold wall thickness

Commented [TH41]: Move Example to new section that contains all examples at end of the Annex A.

Table A.1—Threshold 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
Stress thickness, δ_σ				
Value	2.54 (0.100)	2.69 (0.106)	mm (inch)	API 579
Basis	Structural	Creep	—	API 579
Threshold wall thickness, δ_{thd}	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)