

Calculation of Heater-tube Thickness in Petroleum Refineries

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Notice

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

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

Calculation of Heater-tube Thickness in Petroleum Refineries

1 Scope

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

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

2 Normative References

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

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

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

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

ASME B31.3, *Process Piping*

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

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

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

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

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

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

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

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

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

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

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

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

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

3 Terms and Definitions

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

3.1

actual inside diameter

D_i

Inside diameter of a new tube.

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

3.2

component fitting

Fittings connected to the fired heater tubes.

EXAMPLES Return bends, elbows, reducers.

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

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

3.3

corrosion allowance

δ_{CA}

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

3.4

creep rupture design factor

F_{cr}

A factor applied to determine the rupture allowable stress.

NOTE The materials that have $F_{cr} < 1.0$ are 304L, 316L, 317L, and Advanced 347AP; refer to Table 4, and WRC 3rd Edition, Addendum 1.

3.5

design life

t_{DL}

Operating time used as a basis for tube design.

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

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

3.6

design metal temperature

T_d

Tube-metal or skin temperature used for design.

NOTE This is determined by calculating the maximum tube metal temperature (T_{max} in Annex B) or the equivalent tube metal temperature (T_{eq} in 3.8) and adding an appropriate temperature allowance (see 3.16). A procedure for calculating the maximum tube metal temperature from the heat-flux is included in Annex B. When the equivalent tube metal temperature is used, the maximum operating temperature can be greater than the design metal temperature. When the equivalent tube metal temperature is used to determine the design metal temperature, this design metal temperature is only applicable to the rupture design. It is necessary to develop a separate design metal temperature applicable to the elastic design. The design metal temperature applicable to the elastic design is the maximum calculated tube metal temperature among all operating cases plus the appropriate temperature allowance.

3.7

elastic allowable stress

time-independent allowable stress

σ_{el}

Allowable stress for the elastic range. See 6.2.

3.8

elastic design pressure

p_{el}

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

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

3.9

equivalent tube metal temperature

T_{eq}

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

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

3.10

inside diameter

D_i^*

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

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

3.11

minimum thickness

δ_{min}

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

NOTE See 5.4, Equation (5).

3.12**outside diameter** D_o

Outside diameter of a new tube.

3.13**rupture allowable stress****time-dependent allowable stress** σ_r

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

3.14**rupture design pressure** p_r

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

3.15**rupture exponent** n

Parameter used for design in the creep-rupture range.

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

3.16**rupture stress based on minimum LM-parameter and with $F_{cr} = 1.0$** σ_r^*

The minimum rupture strength for a specified design life within the limiting design metal temperatures shown in Table 5.

3.17**stress thickness** δ_σ

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

3.18**temperature allowance** T_A

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

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

4 General Design Information

4.1 Information Required

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

- a) design life of the heater tube;
- b) whether the equivalent-temperature concept is to be applied and, if so, the operating conditions at the start and at the end of the run;

- c) temperature allowance (see ANSI/API 560), if any;
- d) corrosion fraction (if different from that shown in Figure 1);
- e) whether elastic-range thermal-stress limits are to be applied.

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

- design life equal to 100,000 hours;
- design metal temperature based on the maximum metal temperature (the equivalent-temperature concept shall not apply);
- temperature allowance equal to 15 °C (25 °F);
- corrosion fraction given in Figure 1;
- elastic-range thermal-stress limits.

4.2 Limitations for Design Procedures

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

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

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

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

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

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

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

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

5 Design

5.1 General

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

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

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

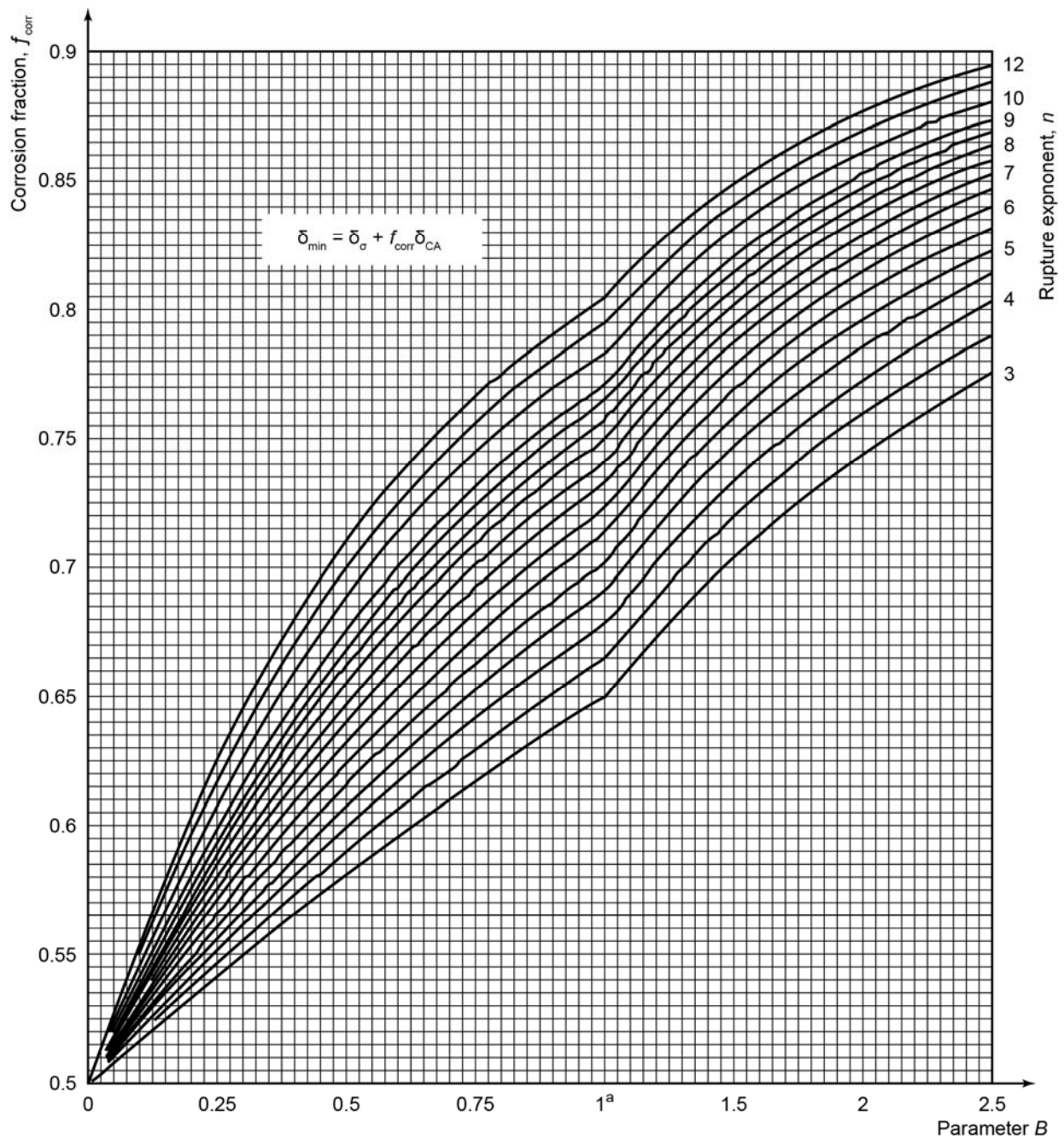
The rupture design pressure is never more than the elastic design pressure. The characteristic that differentiates these two pressures is the relative length of time over which they are sustained. The rupture design pressure is a long-term loading condition over a period of years. The elastic design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

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

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

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

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



Key

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

δ_{CA} is the corrosion allowance

D_o is the outside diameter

σ_r is the rupture allowable stress

p_r is the rupture design pressure

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

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

Figure 1—Corrosion Fraction

5.2 Equation for Stress

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

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

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

where

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

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

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

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

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

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

5.3 Elastic Design

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

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

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

where

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

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

5.4 Rupture Design

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

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

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

where

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

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

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

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

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

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

5.5 Intermediate Temperature Range

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

5.6 Minimum Allowable Thickness

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

5.7 Minimum and Average Thicknesses

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

Table 1—Minimum Allowable Thickness of New Tubes

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

5.8 Equivalent Tube Metal Temperature

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

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

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

where

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

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

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

f_T is the temperature fraction given in Figure 2.

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

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

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

where

n_0 is the rupture exponent at T_{sor} ;

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

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

$\ln$ is the natural logarithm;

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

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

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

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

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

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

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

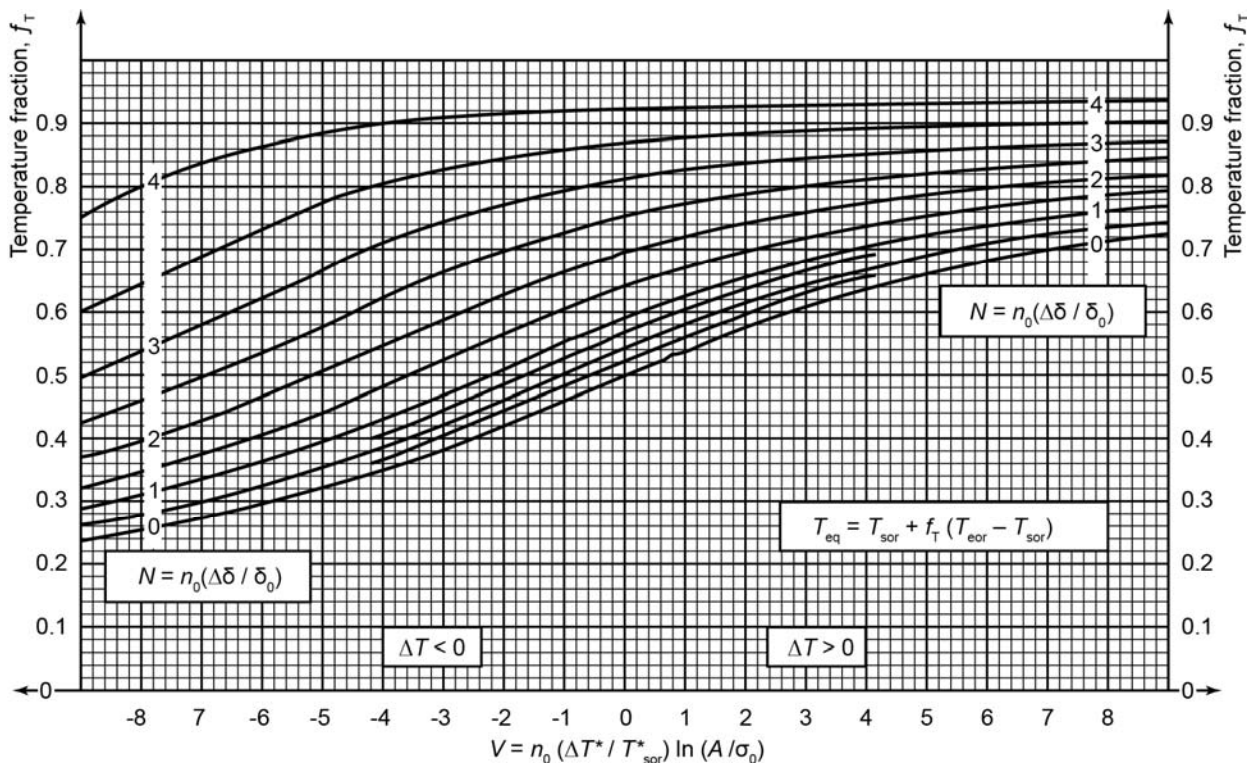


Figure 2—Temperature Fraction

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

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

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

Rupture design:

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

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

where

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

Equivalent tube metal temperature:

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

where

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

Table 3—Material Constant for Temperature Fraction

Material	Type or Grade	Constant 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)
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)			

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

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

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

5.9 Component Fittings

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

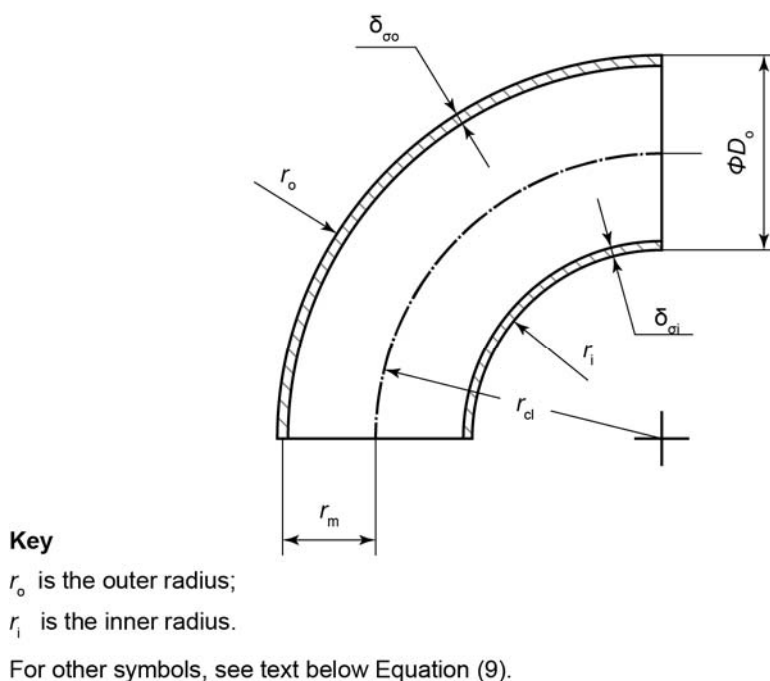


Figure 3—Return Bend and Elbow Geometry

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

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

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

where

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

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

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

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

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

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

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

where

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

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

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

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

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

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

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

where

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

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

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

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

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

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

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

6 Allowable Stresses

6.1 General

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

6.2 Elastic Allowable Stress

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

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

6.3 Rupture Allowable Stress

The rupture allowable stress, σ_r , is defined as:

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

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.

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 Standard 530 already include the appropriate F_{cr} .

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} . The Larson-Miller curves used are based on curves published in WRC 541 and reflect the mechanical property data obtained from tubes manufactured using modern techniques.

6.4 Rupture Exponent

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

6.5 Yield and Tensile Strengths

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

6.6 Larson-Miller Parameter Curves

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

When T_d is expressed in degrees Celsius:

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

When T_d is expressed in degrees Fahrenheit:

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

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

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

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

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

6.7 Limiting Design Metal Temperature

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

graphitization, carburization, and hydrogen attack. These factors shall be considered when furnace tubes are designed.

6.8 Allowable Stress Curves

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

Table 4—Larson-Miller Constants⁴

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)				

⁴ WRC Bulletin 541, 3rd Edition.

Table 5—Limiting Design Metal Temperature for Heater-tube Alloys⁵

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).

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)

7 Sample Calculations

7.1 Elastic Design

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

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

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

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

$$T_d = 425 \text{ }^{\circ}\text{C (800 }^{\circ}\text{F)}$$

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

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

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

Using Equations (2) and (3):

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

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

In USC units:

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

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

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

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

Figure 4—Sample Calculation for Elastic Design

7.2 Thermal-stress Check (for Elastic Range Only)

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

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

Using SI units in Equation (C.2):

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

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

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

Using USC units in Equation (C.2):

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

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

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

In SI units:

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

In USC units:

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

The actual inside diameter is calculated as follows:

In SI units:

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

$$y = 168.3/151.9 = 1.108$$

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

In USC units:

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

$$y = 6.625/5.977 = 1.108$$

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

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

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

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

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

In USC units:

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

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

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

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

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

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

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

In USC units:

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

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

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

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

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

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

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

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

therefore

$$y = 168.3/146.3 = 1.150$$

In USC units:

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

$$y = 6.625/5.761 = 1.150$$

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

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

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

$$\sigma_{T\max} = (553.2) (0.146)$$

$$\sigma_{T\max} = 80.9 \text{ MPa}$$

In USC units:

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

$$\sigma_{T\max} = 11,718 \text{ psi}$$

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

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

In USC units:

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

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

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

In USC units:

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

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

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

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

In USC units:

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

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

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

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

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

In USC units:

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

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

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

7.3 Rupture Design with Constant Temperature

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

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

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

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

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

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

Using Equation (4):

In SI units:

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

In USC units:

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

From this:

In SI units:

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

In USC units:

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

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

$$n = 3.5$$

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

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

Hence, using Equation (5):

In SI units:

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

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

In USC units:

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

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

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

In SI units:

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

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

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

In USC units:

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

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

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

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

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

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

7.4 Rupture Design with Linearly Changing Temperature

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

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

In SI units:

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

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

In USC units:

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

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

In SI units:

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

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

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

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

In USC units:

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

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

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

In SI units:

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

In USC units:

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

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

In SI units:

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

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

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

In USC units:

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

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

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

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

In SI units:

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

In USC units:

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

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

In SI units:

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

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

In USC units:

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

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

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

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

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

Annex A

(informative)

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

A.1 General

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

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

A.2 Establishment of Operating Skin TMT Limits

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

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

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

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