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Petroleum and natural gas industries — Calculation of heater-tube thickness in petroleum refineries

Industries du pétrole et du gaz naturel — Calcul de l'épaisseur des tubes de tours de raffineries de pétrole

Reference number
ISO 13704:2001(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13704 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum and natural gas industries*, Subcommittee SC 6, *Processing equipment and systems*.

Annexes C, E and F form an integral part of this International Standard. Annexes A, B, D, G and H are for information only.

Introduction

This International Standard is based on API standard 530 [30], fourth edition, October 1996.

Petroleum and natural gas industries — Calculation of heater-tube thickness in petroleum refineries

1 Scope

This International Standard specifies the requirements and gives recommendations for the procedures and design criteria used for calculating the required wall thickness of new tubes for petroleum refinery heaters. These procedures are appropriate for designing tubes for service in both corrosive and non-corrosive applications. These procedures have been developed specifically for the design of refinery and related process 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 International Standard does not give recommendations for tube retirement thickness; annex A describes a technique for estimating the life remaining for a heater tube.

2 Terms and definitions

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

2.1
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.

2.2
corrosion allowance
δ_CA
additional material thickness added to allow for material loss during the design life of the component

2.3
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.

2.4
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 2.7) and adding an appropriate temperature allowance (see 2.15). A procedure for calculating the maximum tube metal temperature from the heat flux density is included in annex B. When the equivalent tube metal temperature is used, the maximum operating temperature can be higher than the design metal temperature.

2.5
elastic allowable stress
σ_el
allowable stress for the elastic range (see 5.2)

NOTE See 3.2.3 for information about tubes that have longitudinal welds.

2.6
elastic design pressure

p_{el}
maximum pressure that the heater coil will sustain for short periods of time

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

2.7
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 linearly changing metal temperature (see 4.8)

2.8
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.

2.9
minimum thickness

δ_{min}
minimum required thickness of a new tube, taking into account all appropriate allowances [see equation (5)]

2.10
outside diameter

D_{o}
outside diameter of a new tube

2.11
rupture allowable stress

σ_{r}
allowable stress for the creep-rupture range (see 4.4)

NOTE See 3.2.3 for information about tubes that have longitudinal welds.

2.12
rupture design pressure

p_{r}
maximum operating pressure that the coil section will sustain during normal operation

2.13
rupture exponent

n
parameter used for design in the creep-rupture range

See figures in annexes E and F.

2.14
stress thickness

δ_{σ}
thickness, excluding all thickness allowances, calculated from an equation that uses an allowable stress

2.15
temperature allowance
T_A
part of the design metal temperature that is included for process- or flue-gas maldistribution, 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 2.4).

3 General design information

3.1 Information required

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

a) the design life of the heater tube;

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

c) the temperature allowance, if any;

d) the 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:

f) a design life equal to 100 000 h;

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

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

i) the corrosion fraction given in Figure 1;

j) the elastic-range thermal-stress limits.

3.2 Limitations for design procedures

3.2.1 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 might result in small permanent strains in some applications; however, these small strains will not affect the safety or operability of heater tubes.

3.2.2 No considerations are included for adverse environmental effects such as graphitization, carburization, or hydrogen attack. Limitations imposed by hydrogen attack can be developed from the Nelson curves in API RP 941 [15].

3.2.3 These design procedures have been developed for seamless tubes. When they are applied to tubes that have a longitudinal weld, the allowable stress values should be multiplied by the appropriate joint efficiency factor. Joint efficiency factors shall not be applied to circumferential welds.

3.2.4 These design procedures have been developed for thin tubes (tubes with a thickness-to-outside-diameter ratio, δ_{min}/D_o, of less than 0,15). Additional considerations may apply to the design of thicker tubes.

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

3.2.6 The design loading includes only internal pressure. Limits for thermal stresses are provided in annex C. Limits for stresses developed by mass, supports, end connections, and so forth are not discussed in this International Standard.

3.2.7 Most of the Larson-Miller parameter curves in 5.6 are not Larson-Miller curves in the traditional sense but are derived from the 100 000-h rupture strength as explained in H.3. Consequently, the curves might not provide a reliable estimate of the rupture strength for a design life that is less than 20 000 h or more than 200 000 h.

4 Design

4.1 General

There is a fundamental difference between the behaviour 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 (1 110 °F). The steel operating at the higher temperature will creep, or deform 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 will eventually fail due to creep rupture, although no corrosion or oxidation mechanism is active. For the steel operating at the lower temperature, the effects of creep will be non-existent or negligible. Experience indicates that in this case the tube will last indefinitely unless a corrosion or an oxidation mechanism is active.

Since there is a fundamental difference between the behaviour 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, at lower temperatures, in which allowable stresses are based on the yield strength (see 4.3). Creep-rupture design (which is 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 4.4).

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 (1 100 °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.

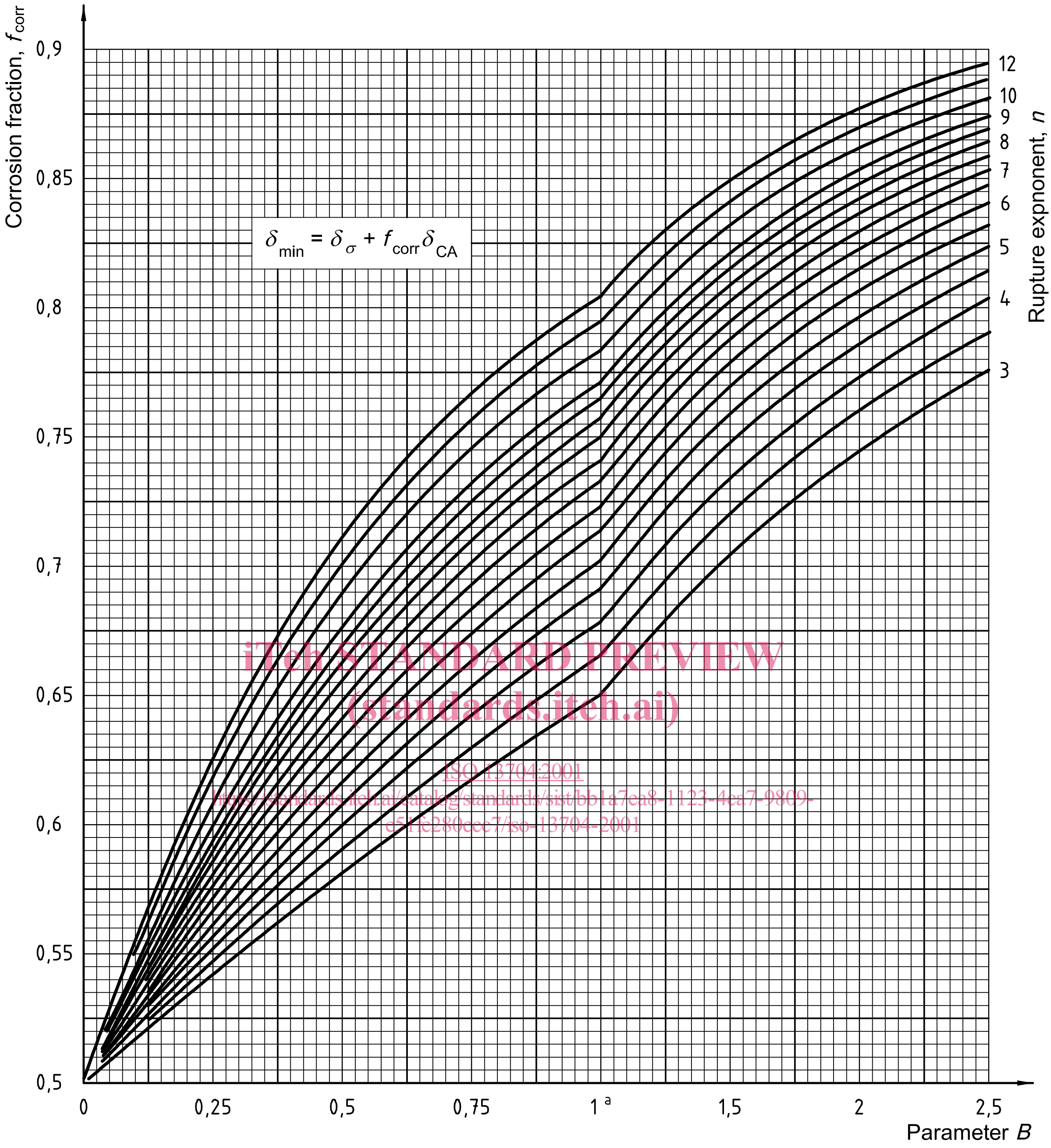
The rupture design pressure is usually less than the elastic design pressure. The characteristic that differentiates these two pressures is the relative length of time over which they are sustained. The rupture design pressure is a long-term loading condition that remains relatively uniform over a period 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 normal 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 δ_{min} should govern the design (see 4.5). A sample calculation that uses these methods is included in clause 6. Calculation sheets (see annex D) are available for summarizing the calculations of minimum thickness and equivalent tube metal temperature.

The allowable minimum thickness of a new tube is given in Table 1.

All of the design equations described in this clause are summarized in Table 2.



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

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

δ_{CA} is the corrosion allowance

D_o is the outside diameter

p_r is the rupture design pressure

σ_r is the rupture allowable stress

n is the rupture exponent

[a] Note change of scale.

Figure 1 — Corrosion fraction

4.2 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 will produce yielding through the entire tube wall in thin tubes (see 3.2.4 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. It is therefore a good equation to use in both the elastic range and the creep-rupture range [16], [17], [18] and [19]. The mean diameter equation for stress is as follows:

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

where

σ is the stress, expressed in megapascals [pounds per square inch[1]];

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

D_{o} is the outside diameter, expressed in millimetres (inches);

D_{i} is the inside diameter, expressed in millimetres (inches), including the corrosion allowance;

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

The equations for the stress thickness (δ_σ) in 4.3 and 4.4 are derived from equation (1).

4.3 Elastic design (lower temperatures)

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 $\delta_{\min}$ (see 4.6) are calculated as follows:

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

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

where

D_{i}^* is the inside diameter, expressed in millimetres (inches), with corrosion allowance removed;

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

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[1] The unit “pounds per square inch (psi)” is referred to as “pound-force per square inch (lbf/in^2)” in ISO 31.

4.4 **Rupture design** (higher temperatures)

The rupture design is based on preventing failure by creep rupture during the design life. With the rupture design, δ_σ and δ_{min} (see 4.6) are calculated as follows:

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

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

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;

where

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.

This design equation is 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.

4.5 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 annexes E and F, either elastic or rupture considerations will govern the design. In this temperature range, both the elastic and rupture designs are to be applied. The larger value of δ_{min} shall govern the design.

4.6 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. 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 5 shows which alloys are ferritic and which are austenitic). The minimum allowable thicknesses are 0,875 times the average thicknesses. These minima are based on industry practice. The minimum allowable thickness is not the retirement or replacement thickness of a used tube.

4.7 Minimum and average thicknesses

The minimum thickness (δ_{min}) is calculated as described in 4.3 and 4.4. Tubes that are purchased to this minimum thickness will have a greater average thickness. A thickness tolerance is specified in each ASTM specification. For most of the ASTM specifications shown in the figures given in annexes E and F, the tolerance on the minimum thickness is $\left(\begin{smallmatrix}0\\+28\end{smallmatrix}\right)$ % for hot-finished tubes and $\left(\begin{smallmatrix}0\\+22\end{smallmatrix}\right)$ % for cold-drawn tubes. This is equivalent to tolerances on the average thickness of ±12,3 % and ±9,9 %, respectively. The remaining ASTM specifications require that the minimum thickness be greater than 0,875 times the average thickness, which is equivalent to a tolerance on the average thickness of +12,5 %.

With a $\left(\begin{smallmatrix}0\\+28\end{smallmatrix}\right)$ % tolerance, a tube that is purchased to a 12,7 mm (0,500 in) minimum-thickness specification will have the following average thickness:

$$(12{,}7)(1 + 0{,}28/2) = 14{,}5 \text{ mm } (0{,}570 \text{ in})$$

To obtain a minimum thickness of 12,7 mm (0,500 in) in a tube purchased to a ± 12,5 % tolerance on the average thickness, the average thickness shall be specified as follows:

$$(12{,}7) / (0{,}875) = 14{,}5 \text{ mm } (0{,}571 \text{ in})$$

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 will be 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)

4.8 Equivalent tube metal temperature

In the creep-rupture range, the accumulation of damage is a function of the actual operating temperature. For applications in which there is a significant difference between start-of-run and end-of-run metal temperatures, a design based on the maximum temperature might be excessive, since the actual operating temperature will usually be 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}) can be calculated as shown below. A tube operating at the equivalent tube metal temperature will sustain the same creep damage as one that operates from the start-of-run to end-of-run temperatures.

$$T_{\text{eq}} = T_{\text{sor}} + f_T \left(T_{\text{eor}} - T_{\text{sor}}\right) \tag{6}$$

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.

The derivation of the temperature fraction is described in annex G. The temperature fraction is a function of two parameters, V and N:

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

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

where

n_0 is the rupture exponent at T_{sor};

ΔT^* (= $T_{\text{eor}} - T_{\text{sor}}$) is the temperature change, expressed in kelvins (degrees Rankine), during operating period, K (°R);

T^*_{sor} = $T_{\text{sor}} + 273$ K ($T_{\text{sor}} + 460$ °R);

ln is the natural logarithm;

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

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

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

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

σ_0 is the initial stress, expressed in megapascals (pounds per square inch), at start of 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.

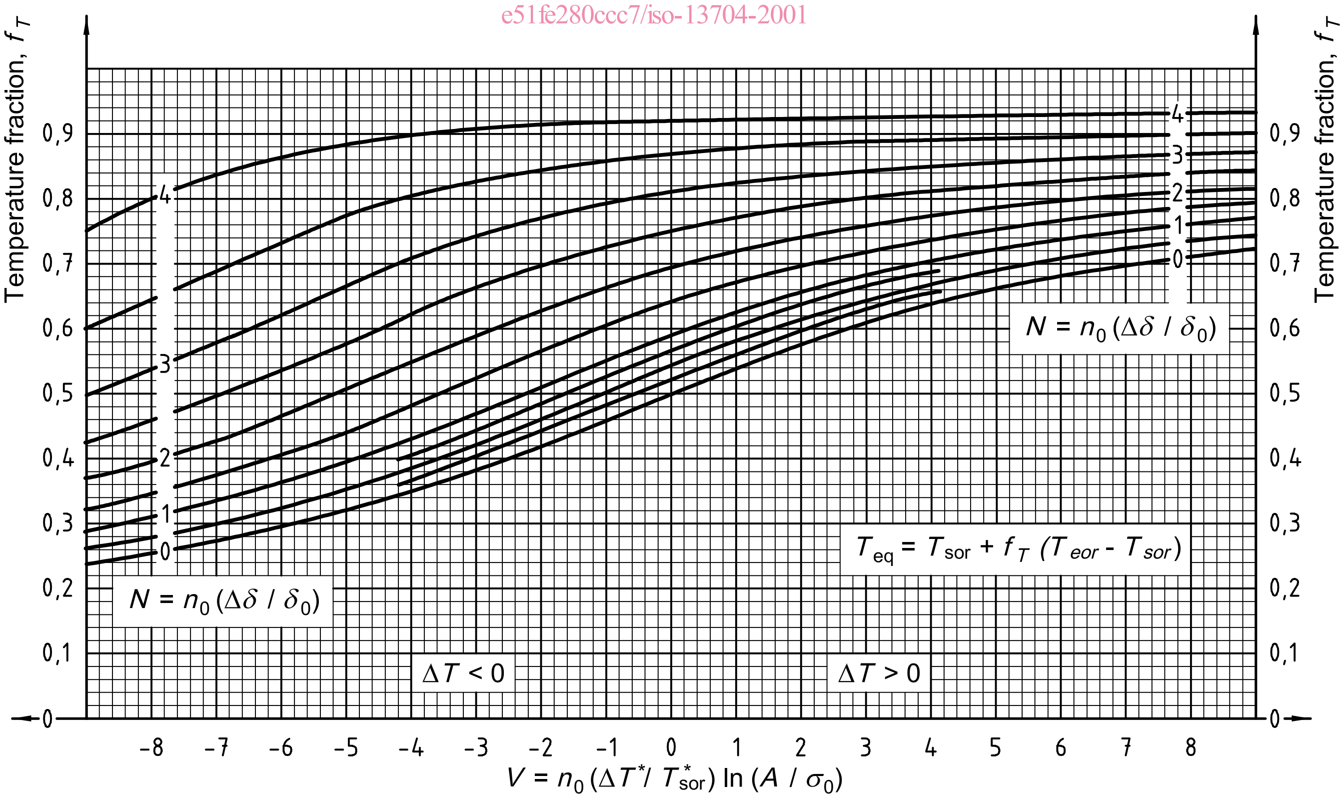

Figure 2 — Temperature fraction