TECHNICAL REPORT

ISO/TR 10400

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Petroleum and natural gas industries — Equations and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing

Industries du pétrole et du gaz naturel — Équations et calculs relatifs aux propriétés des tubes de cuvelage, des tubes de production, des tiges de forage et des tubes de conduites utilisés comme tubes de cuvelage et tubes de production

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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 2.

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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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

ISO/TR 10400 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 5, *Casing, tubing and drill pipe*.

This first edition of ISO/TR 10400 cancels and replaces ISO 10400:1993, which has been technically revised.

Introduction

Performance design of tubulars for the petroleum and natural gas industries, whether it is formulated by deterministic or probabilistic calculations, compares anticipated loads to which the tubular may be subjected to the anticipated resistance of the tubular to each load. Either or both the load and resistance may be modified by a design factor.

Both deterministic and probabilistic (synthesis method) approaches to performance properties are addressed in this Technical Report. The deterministic approach uses specific geometric and material property values to calculate a single performance property value. The synthesis method treats the same variables as random and thus arrives at a statistical distribution of a performance property. A performance distribution in combination with a defined lower percentile determines the final design equation.

Both the well design process itself and the definition of anticipated loads are currently outside the scope of standardization for the petroleum and natural gas industries. Neither of these aspects is addressed in this Technical Report. Rather, this text serves to identify useful equations for obtaining the resistance of a tubular to specified loads, independent of their origin. This Technical Report provides limit state equations (see annexes) which are useful for determining the resistance of an individual sample whose geometry and material properties are given, and design equations which are useful for well design based on conservative geometric and material parameters.

Whenever possible, decisions on specific constants to use in a design equation are left to the discretion of the reader.

Petroleum and natural gas industries — Equations and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing

1 Scope

This Technical Report illustrates the equations and templates necessary to calculate the various pipe properties given in International Standards, including

— pipe performance properties, such as axial strength, internal pressure resistance and collapse resistance,

— minimum physical properties,

— product assembly force (torque),

— product test pressures,

— critical product dimensions related to testing criteria,

— critical dimensions of testing equipment, and

— critical dimensions of test samples.

For equations related to performance properties, extensive background information is also provided regarding their development and use.

Equations presented here are intended for use with pipe manufactured in accordance with ISO 11960 or API 5CT, ISO 11961 or API 5D, and ISO 3183 or API 5L, as applicable. These equations and templates may be extended to other pipe with due caution. Pipe cold-worked during production is included in the scope of this Technical Report (e.g. cold rotary straightened pipe). Pipe modified by cold working after production, such as expandable tubulars and coiled tubing, is beyond the scope of this Technical Report.

Application of performance property equations in this Technical Report to line pipe and other pipe is restricted to their use as casing/tubing in a well or laboratory test, and requires due caution to match the heat-treat process, straightening process, yield strength, etc., with the closest appropriate casing/tubing product. Similar caution should be exercised when using the performance equations for drill pipe.

This Technical Report and the equations contained herein relate the input pipe manufacturing parameters in ISO 11960 or API 5CT, ISO 11961 or API 5D, and ISO 3183 or API 5L to expected pipe performance. The design equations in this Technical Report are not to be understood as a manufacturing warrantee. Manufacturers are typically licensed to produce tubular products in accordance with manufacturing specifications which control the dimensions and physical properties of their product. Design equations, on the other hand, are a reference point for users to characterize tubular performance and begin their own well design or research of pipe input properties.

This Technical Report is not a design code. It only provides equations and templates for calculating the properties of tubulars intended for use in downhole applications. This Technical Report does not provide any guidance about loads that can be encountered by tubulars or about safety margins needed for acceptable design. Users are responsible for defining appropriate design loads and selecting adequate safety factors to develop safe and efficient designs. The design loads and safety factors will likely be selected based on historical practice, local regulatory requirements, and specific well conditions.

All equations and listed values for performance properties in this Technical Report assume a benign environment and material properties conforming to ISO 11960 or API 5CT, ISO 11961 or API 5D and ISO 3183 or API 5L. Other environments may require additional analyses, such as that outlined in Annex D.

Pipe performance properties under dynamic loads and pipe connection sealing resistance are excluded from the scope of this Technical Report.

Throughout this Technical Report tensile stresses are positive.

2 Conformance

2.1 Normative references

In the interests of worldwide application of this Technical Report, ISO/TC 67 has decided, after detailed technical analysis, that certain of the normative documents listed in Clause 3 and prepared by ISO/TC 67 or other ISO Technical Committees are interchangeable in the context of the relevant requirement with the relevant document prepared by the American Petroleum Institute (API), the American Society for Testing and Materials (ASTM) or the American National Standards Institute (ANSI). These latter documents are cited in the running text following the ISO reference and preceded by or, for example, “ISO XXXX or API YYYY”. Application of an alternative normative document cited in this manner will lead to technical results different from the use of the preceding ISO reference. However, both results are acceptable and these documents are thus considered interchangeable in practice.

2.2 Units of measurement

In this Technical Report, data are expressed in both the International System (SI) of units and the United States Customary (USC) system of units. For a specific order item, it is intended that only one system of units be used, without combining data expressed in the other system.

For data expressed in the SI, a comma is used as the decimal separator and a space as the thousands separator. For data expressed in the USC system, a dot (on the line) is used as the decimal separator and a space as the thousands separator.

3 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.

ISO 3183:2007, *Petroleum and natural gas industries — Steel pipe for pipeline transportation systems*

ISO 10405, *Petroleum and natural gas industries — Care and use of casing and tubing*

ISO 11960:2004, *Petroleum and natural gas industries — Steel pipes for use as casing or tubing for wells*

ISO 11961, *Petroleum and natural gas industries — Steel drill pipe*

ISO 13679, *Petroleum and natural gas industries — Procedures for testing casing and tubing connections*

ANSI-NACE International Standard TM0177, *Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in* H_2S *Environments*

API 5B, *Threading, Gauging and Thread Inspection of Casing, Tubing, and Line Pipe Threads (US Customary Units)*

API RP 579, *Recommended Practice for Fitness-for-Service*, January 2000

API RP 5C1, *Recommended Practice for Care and Use of Casing and Tubing*

API RP 5C5, *Recommended Practice on Procedures for Testing Casing and Tubing Connections*

API 5CT, *Specification for Casing and Tubing*

API 5D, *Specification for Drill Pipe*

API 5L:2004, *Specification for Line Pipe*

BS 7910, *Guide to methods for assessing the acceptability of flaws in metallic structures*

4 Terms and definitions

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

4.1
Cauchy stress
true stress
force applied to the surface of a body divided by the current area of that surface

4.2
coefficient of variance
dimensionless measure of the dispersion of a random variable, calculated by dividing the standard deviation by the mean

4.3
design equation
equation which, based on production measurements or specifications, provides a performance property useful in design calculations

NOTE A design equation can be defined by applying reasonable extremes to the variables in a limit state equation to arrive at a conservative value of expected performance. When statistically derived, the design equation corresponds to a defined lower percentile of the resistance probability distribution curve.

4.4
deterministic
approach which assumes all variables controlling a performance property are known with certainty

NOTE Pipe performance properties generally depend on one or more controlling parameters. A deterministic equation uses specific geometric and material property values to calculate a single performance property value. For design formulations, this value is the expected minimum.

4.5
ductile rupture
failure of a tube due to internal pressure and/or axial tension in the plastic deformation range

4.6
e
Euler's constant
2,718 281 828

4.7
effective stress
combination of pressure and axial stress used in this Technical Report to simplify equations

NOTE Effective stress as used in this Technical Report does not introduce a distinct, physically defined stress quantity. Effective stress is a dependent quantity, which is determined as a combination of axial stress, internal pressure, external pressure and pipe dimensions, and provides a convenient grouping of these terms in some equations. The effective stress is sometimes called the Lubinski fictitious stress.

4.8
engineering strain
dimensionless measure of the stretch of a deforming line element, defined as the change in length of the line element divided by its original length

4.9
engineering stress
force applied to the surface of a body divided by the original area of that surface

4.10
fracture pressure
internal pressure at which a tube fails due to propagation of an imperfection

4.11
inspection threshold
maximum size of a crack-like imperfection which is defined to be acceptable by the inspection system

4.12
J-integral
measure of the intensity of the stress-strain field near the tip of a crack

4.13
label 1
dimensionless designation for the size or specified outside diameter that may be used when ordering pipe

4.14
label 2
dimensionless designation for the mass per unit length or wall thickness that may be used when ordering pipe

4.15
limit state equation
equation which, when used with the measured geometry and material properties of a sample, produces an estimate of the failure value of that sample

NOTE A limit state equation describes the performance of an individual sample as closely as possible, without regard for the tolerances to which the sample was built.

4.16
logarithmic strain
dimensionless measure of the stretch of a deforming line element, defined as the natural logarithm of the ratio of the current length of the line element to its original length

NOTE Alternatively, the logarithmic strain can be estimated as the natural logarithm of one plus the engineering strain.

4.17
mass
label used to represent wall thickness of tube cross section for a given pipe size

4.18
pipe body yield
stress state necessary to initiate yield at any location in the pipe body

4.19
principal stress
stress on a principal plane for which the shear stress is zero

NOTE For any general state of stress at any point, there exist three mutually perpendicular planes at that point on which shearing stresses are zero. The remaining normal stress components on these three planes are principal stresses. The largest of these three stresses is called the maximum principal stress.

4.20
probabilistic method
approach which uses distributions of geometric and material property values to calculate a distribution of performance property values

4.21
synthesis method
probability approach which addresses the uncertainty and likely values of pipe performance properties by using distributions of geometric and material property values

NOTE These distributions are combined with a limit state equation to determine the statistical distribution of a performance property. The performance distribution in combination with a defined lower percentile determines the final design equation.

4.22
template
procedural guide consisting of equations, test methods and measurements for establishing design performance properties

4.23
TPI
threads per inch

NOTE 1 thread per inch = 0,039 4 threads per millimetre; 1 thread per millimetre = 25,4 threads per inch.

4.24
true stress-strain curve
plot of Cauchy stress (ordinate) vs. logarithmic strain (abscissa)

4.25
yield
permanent, inelastic deformation

4.26
yield stress bias
ratio of actual yield stress to specified minimum yield stress

5 Symbols

A hand-tight standoff

A_c empirical constant in historical API collapse equation

A_{crit} area of the weaker connection component at the critical cross section

A_{gbtj} critical dimension on guided bend test jig, denoted as dimension A in ISO 3183 or API 5L

A_{jc} area of the coupling cross section; $A_{jc} = \pi/4\ (W^2 - d_1^2)$

A_{jp} area of the pipe cross section under the last perfect thread

A_p area of the pipe cross section; $A_p = \pi/4\ (D^2 - d^2)$

$A_{p\ ave}$ average area of the pipe cross section; $A_{p\ ave} = \pi/4\ [D_{ave}^2 - (D_{ave} - 2\ t_{c\ ave})^2]$

A_s cross-sectional area of the tensile test specimen in square millimetres (square inches), based on specified outside diameter or nominal specimen width and specified wall thickness, rounded to the nearest 10 mm^2 (0.01 in^2), or 490 mm^2 (0.75 in^2) whichever is smaller

A_x maximum diameter at the extreme-line pin seal tangent point

a for a limit state equation, the maximum actual depth of a crack-like imperfection; for a design equation, the maximum depth of a crack-like imperfection that could likely pass the manufacturer's inspection system

a_N imperfection depth associated with a specified inspection threshold, i.e. the maximum depth of a crack-like imperfection that could reasonably be missed by the pipe inspection system. For example, for a 5 % imperfection threshold inspection in a 12,7 mm (0.500 in) wall thickness pipe, a_N = 0,635 mm (0.025 in)

$a_{t/D}$ average value of t/D ratios used in the regression

B specified inside diameter of the extreme-line connection, in accordance with API 5B

B_c empirical constant in historical API collapse equation

B_f maximum bearing face diameter, special bevel, in accordance with ISO 11960 or API 5CT

b Weibull shape parameter

C_c empirical constant in historical API collapse equation

C_{iR} random variable that represents model uncertainty

c tube curvature, the inverse of the radius of curvature to the centreline of the pipe

D specified pipe outside diameter

D_{ac} average outside diameter after cutting

D_{ave} average pipe outside diameter

D_{bc} average outside diameter before cutting

D_i inside diameter of extreme-line box upset, in accordance with API 5B

D_{max} maximum pipe outside diameter

D_{min} minimum pipe outside diameter

D_p extreme-line pin critical section outside diameter; $D_p = H_x + \delta - \varphi$

D_4 major diameter, in accordance with API 5B

d pipe inside diameter, $d = D - 2t$

d_b inside diameter of the critical section of the extreme-line box; $d_b = I_x + 2h_x - \Delta + \theta$

d_{iu} inside diameter of pin upset, in accordance with ISO 11960 or API 5CT

d_j extreme-line specified joint inside diameter, made up

d_{ou} inside diameter at end of upset pipe

d_{wall} inside diameter based on $k_{wall}\, t$; $d_{wall} = D - 2k_{wall}\, t$

d_1 diameter at the root of the coupling thread at the end of the pipe in the power-tight position

E Young's modulus

E_c pitch diameter, at centre of coupling

E_{ec} pitch diameter, at end of coupling

E_s pitch diameter, at plane of seal

E_0 pitch diameter, at end of pipe

E_1 pitch diameter at the hand-tight plane, in accordance with API 5B

E_7 pitch diameter, in accordance with API 5B

ec eccentricity

e_m mass gain due to end finishing

F_a axial force

F_{eff} effective axial force

F_c empirical constant in historical API collapse equation

F_{YAPI} axial force at yield, historical API equation

f degrees of freedom = $N_t - 1$

$f(\vec{x})$ joint probability density function of the variables in $\vec{x}$

f_{rn} root truncation of the pipe thread of API line pipe threads, as follows:
0,030 mm (0.001 2 in) for 27 TPI,
0,046 mm (0.001 8 in) for 18 TPI,
0,061 mm (0.002 4 in) for 14 TPI,
0,074 mm (0.002 9 in) for 11-1/2 TPI,
0,104 mm (0.004 1 in) for 8 TPI

f_u tensile strength of a representative tensile specimen

f_{uc} tensile strength of a representative tensile specimen from the coupling

f_{umn} specified minimum tensile strength

f_{umnc} specified minimum tensile strength of the coupling

f_{umnp} specified minimum tensile strength of the pipe body

f_{up} tensile strength of a representative tensile specimen from the pipe body

f_y yield strength of a representative tensile specimen

f_{yax} equivalent yield strength in the presence of axial stress

f_{ye} equivalent yield stress in the presence of axial stress

f_{ymn} specified minimum yield strength

f_{ymnc} specified minimum yield strength of the coupling

f_{ymnp} specified minimum yield strength of the pipe body

f_{ymx} specified maximum yield strength

f_{yp} yield strength of a representative tensile specimen from the pipe body

G_c empirical constant in historical API collapse equation

G_0 influence coefficient for fracture limit state FAD curve

G_1 influence coefficient for fracture limit state FAD curve

G_2 influence coefficient for fracture limit state FAD curve

G_3 influence coefficient for fracture limit state FAD curve

G_4 influence coefficient for fracture limit state FAD curve

g length of imperfect threads, in accordance with API 5B

$g(\bar{x})$ limit state function

H is the thread height of a round-thread equivalent Vee thread, as follows:
0,815 mm (0.032 1 in) for 27 TPI,
1,222 mm (0.048 1 in) for 18 TPI,
1,755 mm (0.069 1 in) for 14 TPI,
1,913 mm (0.075 3 in) for 11-1/2 TPI,
2,199 6 mm (0.086 60 in) for 10 TPI,
2,749 6 mm (0.108 25 in) for 8 TPI

Ht_{des} decrement factor, as given in Table F.9

Ht_{ult} a decrement factor

H_x maximum extreme-line root diameter at last perfect pin thread

h_B buttress thread height: 1,575 for SI units, 0.062 for USC units

h_n stress-strain curve shape factor

h_s round thread height

h_x minimum box thread height for extreme-line casing, as follows:
1,52 mm (0.060 in) for 6 TPI
2,03 mm (0.080 in) for 5 TPI

I moment of inertia of the pipe cross section; $I = \pi/64\ (D^4 - d^4)$

I_{ave} average moment of inertia of the pipe cross section; $I = \pi/64\ (D_{ave}{}^4 - (D_{ave} - 2\ t_{c\ ave})^4)$

I_B length from the face of the buttress thread coupling to the base of the triangle in the hand-tight position: 10,16 mm (0.400 in) for Label 1: 4-1/2; 12,70 mm (0.500 in) for sizes between Label 1: 5 and Label 1: 13-3/8, inclusive; and 9,52 mm (0.375 in) for sizes greater than Label 1: 13-3/8

I_x minimum extreme-line crest diameter of box thread at Plane H

J distance from end of pipe to centre of coupling in power-tight position, in accordance with API 5B

J_{Ic} fracture resistance of the material

J_{Imat} fracture resistance of the material in a particular environment

J_{p} polar moment of inertia of the pipe cross section; $J_{\mathrm{p}} = \pi/32\ (D^4 - d^4)$

J_{r} stress intensity ratio based on the J-Integral

K stress intensity factor at the crack tip

K_{Imat} fracture toughness of a material in a particular environment

K_{p} ratio of internal pressure stress to yield strength, or $p_{\mathrm{i}}\ D/(2\ f_{\mathrm{ymnp}}\ t)$

K_{r} stress intensity ratio

k_{A} variable intermediate term in ISO 13679 or API RP 5C5 representation of von Mises yield criterion

k_{a} burst strength factor, having the numerical value 1,0 for quenched and tempered (martensitic structure) or 13Cr products and 2,0 for as-rolled and normalized products based on available test data; and the default value set to 2,0 where the value has not been measured. The value of k_{a} can be established for a specific pipe material based on testing

k_{B} variable intermediate term in ISO 13679 or API RP 5C5 representation of von Mises yield criterion

k_{C} variable intermediate term in ISO 13679 or API RP 5C5 representation of von Mises yield criterion

k_{c} constant used in elastic collapse equation

k_{dr} correction factor based on pipe deformation and material strain hardening, having the numerical value $[(1/2)^{n+1} + (1/\sqrt{3})^{n+1}]$

k_{e} bias factor for elastic collapse

$k_{\mathrm{e\ des}}$ down-rating factor for design elastic collapse

k_{el} elongation constant, equal to 1942,57 for SI units and 625 000 for USC units

$k_{\mathrm{e\ uls}}$ calibration factor for ultimate elastic collapse, 1,089

k_{i} factor used to determine minimum wall thickness for transverse impact specimens:
1,00 for full-size specimens
0,75 for three-quarter size specimens
0,50 for one-half size specimens

k_{lsl} length conversion factor, equal to 0,001 for SI units and 1/12 for USC units

k_{m} mass correction factor, 1,000 for carbon steel, 0,989 for martensitic chromium steel

k_{n} stress conversion factor, equal to $1,18 \times 10^{-4}\ \mathrm{MPa}^{-1}$ for SI units and $8.12 \times 10^{-7}\ \mathrm{psi}^{-1}$ for USC units

k_{pi} upper quadrant geometry factor in ISO 13679 or API RP 5C5 representation of von Mises yield criterion

k_{po} lower quadrant geometry factor in ISO 13679 or API RP 5C5 representation of von Mises yield criterion

k_{wall} factor to account for the specified manufacturing tolerance of the pipe wall. For example, for a tolerance of −12,5 %, $k_{\mathrm{wall}} = 0,875$

k_{wpe} mass per unit length conversion factor, equal to 0,024 661 5 for SI units and 10.69 for USC units