DIN CEN ISO/TR 10400

ICS 75.180.10

Ersatz für
DIN CEN ISO/TR 10400
(DIN SPEC 91040):2011-07

Erdöl- und Erdgasindustrie – Formeln und Berechnungen der Eigenschaften von Futterrohren, Steigrohren, Bohrgestängen und Leitungsrohren (ISO/TR 10400:2018); Englische Fassung CEN ISO/TR 10400:2021

Petroleum and natural gas industries –
Formulae and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing (ISO/TR 10400:2018);
English version CEN ISO/TR 10400:2021

Industries du pétrole et du gaz naturel –
Formules 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 (ISO/TR 10400:2018);
Version anglaise CEN ISO/TR 10400:2021

Gesamtumfang 255 Seiten

DIN-Normenausschuss Erdöl- und Erdgasgewinnung (NÖG)

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Nationales Vorwort

Technische Reporte sind nicht Bestandteil des Deutschen Normenwerks.

Der Text von ISO/TR 10400:2018 wurde vom Technischen Komitee ISO/TC 67 „Oil and gas industries including lower carbon energy“ der Internationalen Organisation für Normung (ISO) erarbeitet und als CEN ISO/TR 10400:2021 durch das Technische Komitee CEN/TC 12 „Materialien, Ausrüstungen und Offshore-Bauwerke für die Erdöl-, petrochemische und Erdgasindustrie“ übernommen, dessen Sekretariat von AFNOR (Frankreich) gehalten wird.

Das zuständige deutsche Normungsgremium ist der Arbeitsauskreis NA 109-00-01-05 AK „Futter-, Steig- und Bohrrohre — Spiegelausschuss zu ISO/TC 67/SC 5“ im DIN-Normenausschuss Erdöl- und Erdgasgewinnung (NÖG).

Dieses Dokument enthält unter Berücksichtigung des DIN-Präsidialbeschlusses 1/2004 nur die Englische Fassung von CEN ISO/TR 10400:2021.

Dieses Dokument enthält neben den gesetzlichen Einheiten auch die Einheiten „ft“, „ft-lb“, „gal (galone)“, „in (inch)“, „kip“, „ksi“, „lb (pound)“, „lb/gal“, „lbf“ und „psi (psig)“, die in Deutschland nicht zugelassen sind. Es wird ausdrücklich darauf hingewiesen, dass die Anwendung dieser Einheiten im nationalen amtlichen und geschäftlichen Verkehr auf Grund des Gesetzes über Einheiten im Messwesen und die Zeitbestimmung (EinhZeitG) nicht zulässig ist. Die Angabe dieser Einheiten dient lediglich als Hilfe im amtlichen und geschäftlichen Verkehr (z. B. bei Einfuhr und Ausfuhr) mit solchen Staaten, die diese Einheiten anwenden.

Umrechnung:

Nicht zugelassene Einheit	Zugelassene Einheit	Umrechnung
ft	m	1 ft = 0,304 8 m
ft-lb	Nm	1 ft-lb = 1,35 Nm
gal (galone)	l	1 gal = 3,785 l
in (inch)	mm	1 inch = 25,4 mm
kip	N	1 kip = 4448,22 N
ksi	MPa	1 ksi = 6,894 757 MPa
lb (pound)	kg	1 lb = 0,453 592 37 kg
lb/gal	kg/m^3	1 lb/gal = 0,118 kg/dm^3
lbf	N	1 lbf = 4,448 222 N
psi (psig)	kPa	1 psi = 6,894 757 kPa

Für die in diesem Dokument zitierten Dokumente wird im Folgenden auf die entsprechenden deutschen Dokumente hingewiesen:

ISO 3183	siehe	DIN EN ISO 3183
ISO 10405	siehe	DIN EN ISO 10405
ISO 11960	siehe	DIN EN ISO 11960
ISO 11961	siehe	DIN EN ISO 11961
ISO 13679	siehe	DIN EN ISO 13679

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Änderungen

Gegenüber DIN CEN ISO/TR 10400 (DIN SPEC 91040):2011-07 wurden folgende Änderungen vorgenommen:

a) technische Änderung;

b) Dokument redaktionell überarbeitet.

Frühere Ausgaben

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Nationaler Anhang NA
(informativ)

Begriffe und Symbole

Reihenfolge und Inhalt der folgenden Begriffe sind identisch mit denen im Abschnitt Begriffe der Englischen Fassung.

3 Begriffe

Für die Anwendung dieses Dokuments gelten die folgenden Begriffe.

ISO und IEC stellen terminologische Datenbanken für die Verwendung in der Normung unter den folgenden Adressen bereit:

— ISO Online Browsing Platform: verfügbar unter https://www.iso.org/obp

— IEC Electropedia: verfügbar unter http://www.electropedia.org/

3.1
Cauchy-Spannung
wahre Spannung
auf die Oberfläche eines Körpers aufgebrachte Kraft, dividiert durch die momentane Fläche dieser Oberfläche

3.2
Variationskoeffizient
dimensionsloses Maß für die Streuung einer Zufallsvariable, das durch Division der Standardabweichung durch den Mittelwert berechnet wird

3.3
Konstruktionsformel
Formel, die auf der Grundlage von Produktionsmessungen oder -festlegungen eine Leistungseigenschaft liefert, die für Konstruktionsberechnungen hilfreich ist

Anmerkung 1 zum Begriff: Eine Konstruktionsformel kann festgelegt werden, indem angemessene Extremwerte auf die Variablen in einer Grenzzustandsformel angewendet werden, um zu einem konservativen Wert für die erwartete Leistung zu gelangen. Wurde die Konstruktionsformel statistisch hergeleitet, entspricht sie einem bestimmten niedrigeren Perzentil der Wahrscheinlichkeitsverteilungskurve der Festigkeit.

3.4
deterministisch
Ansatz, der davon ausgeht, dass alle Variablen, die eine Leistungseigenschaft steuern, mit Sicherheit bekannt sind

Anmerkung 1 zum Begriff: Rohrleistungseigenschaften hängen im Allgemeinen von einem oder mehreren Steuerparametern ab. Eine deterministische Formel verwendet bestimmte geometrische Werte und Werte von Werkstoffeigenschaften für die Berechnung eines einzelnen Wertes für eine Leistungseigenschaft. Für Konstruktionsansätze stellt dieser Wert den erwarteten Mindestwert dar.

3.5
Verformungsbruch
Versagen eines Rohres auf Grund des Innendrucks und/oder einer axialen Kraft im plastischen Verformungsbereich

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3.6
e
Euler-Konstante
2,718 281 828

3.7
effektive Axialkraft
Axialkraft des Werkstoffs (Axialspannung der Rohrwand, multipliziert mit der Querschnittsfläche), die bezüglich der Wirkung des Innen- und Außendrucks angepasst ist

Anmerkung 1 zum Begriff: Wenn ein Rohr seitlich zu einem Kreisbogen gebogen wird, bringen die Drücke eine seitliche gleichmäßig verteilte Last (UDL, en: uniform distributed load) von $(p_i A_i - p_o A_o)/R$ auf. Bei kleinen Durchbiegungen ist die Krümmung als $1/R \cong d^2y/dx^2$ definiert, so dass dieser Term somit mit dem Term für die Spannung $F\, d^2y/dx^2$ in der maßgeblichen Differentialgleichung eingruppiert werden kann. Beim Biegen und Knicken wirkt das Rohr daher, als wäre es mit der *effektiven Axialkraft* $F_{eff} = F_a - p_i A_i + p_o A_o$ belastet [141]. Die effektive Axialkraft sollte als passende Eingruppierung von Termen gesehen werden, die das Strukturverhalten bestimmt: sie existiert nicht als physikalische Axialkraft.

3.8
technische Dehnung
dimensionsloses Maß für die Dehnung eines sich verformenden Leitungselementes, das als Längenänderung des Leitungselementes, dividiert durch seine ursprüngliche Länge festgelegt ist

3.9
technische Spannung
auf die Oberfläche eines Körpers aufgebrachte Kraft, die durch die ursprüngliche Fläche dieser Oberfläche dividiert wird

3.10
Bruchdruck
Innendruck, bei dem es zum Bruch des Rohres auf Grund der Fortpflanzung einer Fehlstelle kommt

3.11
Kontrollgrenzwert
höchste Größe einer rissartigen Fehlstelle, die für das Kontrollsystem als annehmbar festgelegt ist

3.12
J-Integral
Maß für die Intensität des Spannungs-Dehnungs-Feldes in der Nähe der Spitze eines Risses

3.13
Label 1
dimensionslose Bezeichnung für die Größe oder den festgelegten Außendurchmesser, die bei der Bestellung von Rohren verwendet werden darf

3.14
Label 2
dimensionslose Bezeichnung für die Masse je Längeneinheit oder die Wanddicke, die bei der Bestellung von Rohren verwendet werden darf

3.15
Grenzzustandsformel
Formel, die wenn sie mit den gemessenen geometrischen und Werkstoffeigenschaften einer Probe angewendet wird, zu einer Abschätzung des Versagenswertes dieser Probe führt

Anmerkung 1 zum Begriff: Eine Grenzzustandsformel beschreibt die Leistung einer einzelnen Probe so genau wie möglich, ohne dabei die Grenzabmaße, mit denen die Probe gebaut wurde, zu beachten.

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3.16
logarithmische Dehnung
dimensionsloses Maß für die Dehnung eines sich verformenden Leitungselementes, das als natürlicher Logarithmus des Verhältnisses der momentanen Länge des Leitungselementes zu seiner ursprünglichen Länge festgelegt ist

Anmerkung 1 zum Begriff: Alternativ dazu kann die logarithmische Dehnung als natürlicher Logarithmus von Eins plus die technische Dehnung abgeschätzt werden.

3.17
Masse
Label, das zur Darstellung der Wanddicke eines Rohrquerschnitts für eine bestimmte Rohrnennweite verwendet wird

3.18
Fließen des Rohrkörpers
Spannungszustand, der notwendig ist, um an einer beliebigen Stelle im Rohrkörper ein Fließen zu initiieren

3.19
Hauptspannung
Spannung in einer Hauptebene, für die die Schubspannung gleich Null ist

Anmerkung 1 zum Begriff: Für jeden allgemeinen Spannungszustand an einer beliebigen Stelle gibt es an der Stelle, an der die Schubspannungen gleich Null sind, drei senkrecht zueinanderstehende Ebenen. Die übrigen Normalspannungskomponenten auf diesen drei Ebenen sind Hauptspannungen. Die größte dieser drei Spannungen wird als Höchst-Hauptspannung bezeichnet.

3.20
probabilistisches Verfahren
Ansatz, bei dem für die Berechnung einer Verteilung von Leistungseigenschaftswerten Verteilungen von Werten geometrischer Eigenschaften und Werkstoffeigenschaften verwendet werden

3.21
Syntheseverfahren
Ansatz der Wahrscheinlichkeitsrechnung, bei dem die Unsicherheit und wahrscheinliche Werte von Rohrleistungseigenschaften behandelt werden, indem Verteilungen von Werten geometrischer Eigenschaften und Werkstoffeigenschaften verwendet werden

Anmerkung 1 zum Begriff: Zur Ermittlung der statistischen Verteilung einer Leistungseigenschaft werden diese Verteilungen mit einer Grenzzustandsformel kombiniert. Die Leistungsverteilung bestimmt in Kombination mit einem bestimmten niedrigeren Perzentil die endgültige Konstruktionsformel.

3.22
Vorlage
Verfahrensanleitung, die aus Formeln, Prüfverfahren und Messungen zur Feststellung von Konstruktionsleistungseigenschaften besteht

3.23
TPI, en: threads per inch
Gewindegänge je Zoll

Anmerkung 1 zum Begriff: 1 Gewindegang je Zoll = 0,039 4 Gewindegänge je Millimeter; 1 Gewindegang je Millimeter = 25,4 Gewindegänge je Zoll.

3.24
wahre Spannungs-Dehnungs-Kurve
grafische Darstellung der Cauchy-Spannung (Ordinate) im Verhältnis zur logarithmischen Dehnung (Abszisse)

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3.25
Fließen
dauerhafte unelastische Verformung

3.26
systematischer Fehler der Fließspannung
Verhältnis der tatsächlichen Fließspannung zur festgelegten Mindestfließspannung

4 Symbole

A	handfest verschraubter Abstandsbolzen, Drehungen
A_c	empirische Konstante in der historischen Kollaps-Formel nach API (en: American Petroleum Institute)
A_{crit}	Fläche des schwächeren Anschlussteils am kritischen Querschnitt
A_{gbtj}	kritisches Maß der geführten Biegeprüfvorrichtung, in ISO 3183 bzw. API 5L als Maß A bezeichnet
A_i	Fläche zum Rohrinnendurchmesser; $A_i = \pi d^2/4$
A_{jc}	Querschnittsfläche der Muffe; $A_{jc} = \pi/4(W^2 - {d_1}^2)$
A_{jp}	Querschnittsfläche des Rohres unter dem letzten einwandfreien Gewinde
A_o	Fläche zum Rohraußendurchmesser; $A_o = \pi D^2/4$
A_p	Querschnittsfläche des Rohres; $A_p = A_o - A_i$
$A_{p\ ave}$	mittlere Querschnittsfläche des Rohres; $A_{p\ ave} = \pi/4\ [{D_{ave}}^2 - (D_{ave} - 2\ t_{c\ ave})^2]$
A_s	Querschnittsfläche des Probekörpers für die Zugprüfung in Quadratmillimeter (Quadratzoll), auf der Grundlage des festgelegten Außendurchmessers oder der Nennbreite des Probekörpers und der festgelegten Wanddicke, auf 10 mm^2 (0,01 $Zoll^2$) bzw. 490 mm^2 (0,75 $Zoll^2$) gerundet, wobei das jeweils kleinere Maß gilt
a	bei einer Grenzzustandsformel die größte tatsächliche Tiefe einer rissartigen Fehlstelle; bei einer Konstruktionsformel die größte Tiefe einer rissartigen Fehlstelle, die das Kontrollsystem des Herstellers möglicherweise passieren könnte
a_N	Tiefe einer Fehlstelle, die mit einem festgelegten Kontrollgrenzwert verbunden ist, d. h. die größte Tiefe einer rissartigen Fehlstelle, die vom Rohrkontrollsystem möglicherweise nicht erkannt werden könnte. Beispielsweise ist bei einer Fehlstellen-Grenzwertüberwachung von 5 % in einem Rohr mit einer Wanddicke von 12,7 mm (0,500 Zoll) a_N = 0,635 mm (0,025 Zoll)
$a_{t/D}$	Mittelwert der in der Regression verwendeten Verhältnisse t/D
B_c	empirische Konstante in der historischen Kollaps-Formel nach API
B_f	größter Durchmesser der Auflagefläche, besondere Abfasung, nach ISO 11960 oder API 5CT

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b	Weibull-Formparameter
C_c	empirische Konstante in der historischen Kollaps-Formel nach API
C_{iR}	Zufallsvariable, die die Modellunsicherheit angibt
c	Rohrkrümmung, Kehrwert des Krümmungsradius zur Mittellinie des Rohres
D	festgelegter Außendurchmesser des Rohres
D_{ac}	mittlerer Außendurchmesser nach dem Schneiden
D_{ave}	mittlerer Außendurchmesser des Rohres
D_{bc}	mittlerer Außendurchmesser vor dem Schneiden
D_{max}	größter Außendurchmesser des Rohres
D_{min}	kleinster Außendurchmesser des Rohres
D_4	größerer Durchmesser, nach API 5B
d	Innendurchmesser des Rohres; $d = D - 2t$
d_{iu}	Innendurchmesser der Stauchung des Einsteckendes, nach ISO 11960 oder API 5CT
d_{ou}	Innendurchmesser am Ende des gestauchten Rohres
d_{wall}	Innendurchmesser auf der Grundlage von $k_{wall}\, t$; $d_{wall} = D - 2k_{wall}\, t$
$d1$	Durchmesser am Gewindegrund des Muffengewindes am Rohrende in der Dichtungsposition
E	Elastizitätsmodul
E_c	Flankendurchmesser, in der Mitte der Muffe
E_{ec}	Flankendurchmesser, am Ende der Muffe
E_s	Flankendurchmesser, an der Dichtungsebene
E_0	Flankendurchmesser, am Rohrende
E_1	Flankendurchmesser in der Ebene der handfest zusammengeschraubten Position, nach API 5B
E_7	Flankendurchmesser nach API 5B
ec	Exzentrizität
e_m	Zunahme der Masse auf Grund der Endverarbeitung
F_a	Axialkraft des Werkstoffs

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F_{eff}	effektive Axialkraft; $F_{eff} = F_a - p_i A_i + p_o A_o$
F_c	empirische Konstante in der historischen Kollaps-Formel nach API
F_{YAPI}	Axialkraft des Werkstoffs bei Fließen, historische API-Formel
f	Freiheitsgrade = $N_t - 1$
$f(\vec{x})$	gemeinsame Wahrscheinlichkeitsdichtefunktion der Variablen in $\vec{x}$
f_{rn}	Abflachung des Rohrgewindegrundes von API-Leitungsrohr-Gewinden, wie folgt: 0,030 mm (0,001 2 Zoll) für 27 TPI 0,046 mm (0,001 8 Zoll) für 18 TPI 0,061 mm (0,002 4 Zoll) für 14 TPI 0,074 mm (0,002 9 Zoll) für 11 — 1/2 TPI 0,104 mm (0,004 1 Zoll) für 8 TPI
f_u	Zugfestigkeit eines repräsentativen Probekörpers für die Zugfestigkeitsprüfung
f_{uc}	Zugfestigkeit eines repräsentativen Probekörpers aus der Muffe für die Zugfestigkeitsprüfung
f_{umn}	festgelegte Mindestzugfestigkeit
f_{umnc}	festgelegte Mindestzugfestigkeit der Muffe
f_{umnp}	festgelegte Mindestzugfestigkeit des Rohrkörpers
f_{up}	Zugfestigkeit eines repräsentativen Probekörpers aus dem Rohrkörper für die Zugfestigkeitsprüfung
f_y	Fließgrenze eines repräsentativen Probekörpers für die Zugfestigkeitsprüfung
f_{yax}	äquivalente Fließgrenze bei Vorhandensein einer Axialspannung
f_{ye}	äquivalente Fließspannung bei Vorhandensein einer Axialspannung
f_{ymn}	festgelegte Mindestfließgrenze
f_{ymnc}	festgelegte Mindestfließgrenze der Muffe
f_{ymnp}	festgelegte Mindestfließgrenze des Rohrkörpers
f_{ymx}	festgelegte höchste Fließgrenze
f_{yp}	Fließgrenze eines repräsentativen Probekörpers aus dem Rohrkörper für die Zugfestigkeitsprüfung
G_c	empirische Konstante in der historischen Kollaps-Formel nach API

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G_0	Einflusskoeffizient für die Fehlerbewertungskurve (FAD, en: failure assessment diagram) des Bruchgrenzzustands
G_1	Einflusskoeffizient für die Fehlerbewertungskurve (FAD) des Bruchgrenzzustands
G_2	Einflusskoeffizient für die Fehlerbewertungskurve (FAD) des Bruchgrenzzustands
G_3	Einflusskoeffizient für die Fehlerbewertungskurve (FAD) des Bruchgrenzzustands
G_4	Einflusskoeffizient für die Fehlerbewertungskurve (FAD) des Bruchgrenzzustands
g	Länge von unvollständigen Gewinden, nach API 5B
$g(\vec{x})$	Grenzzustandsfunktion
H	Gewindehöhe eines einem Rundgewinde gleichwertigen Spitzgewindes, wie folgt: 0,815 mm (0,032 1 Zoll) für 27 TPI 1,222 mm (0,048 1 Zoll) für 18 TPI 1,755 mm (0,069 1 Zoll) für 14 TPI 1,913 mm (0,075 3 Zoll) für 11 — 1/2 TPI 2,199 6 mm (0,086 60 Zoll) für 10 TPI 2,749 6 mm (0,108 25 Zoll) für 8 TPI
Ht_{des}	Dekrementfaktor für die Bemessungs-Kollapsfestigkeit wie in Tabelle F.9 angegeben
Ht_{ult}	Dekrementfaktor für die endgültige Kollapsfestigkeit wie in Gleichung (F.4) festgelegt
h_{B}	Höhe des Sägengewindes: 1,575 für SI-Einheiten, 0,062 für USC-Einheiten
h_{n}	Formfaktor der Spannungs-Dehnungs-Kurve
h_{s}	Höhe des Rundgewindes
I	Trägheitsmoment des Rohrquerschnitts; $I = \pi/64\ (D^4 - d^4)$
I_{ave}	mittleres Trägheitsmoment des Rohrquerschnitts; $I = \pi/64\ [{D_{\text{ave}}}^4 - (D_{\text{ave}} - 2\ t_{\text{c ave}})^4]$
I_{B}	Länge von der Stirnfläche der Muffe des Sägengewindes bis zur Dreieckbasis in der handfest verschraubten Stellung: 10,16 mm (0,400 Zoll) für Label 1: 4 — 1/2; 12,70 mm 0,500 Zoll) für Größen zwischen Label 1: 5 und Label 1: 13 — 3/8 einschließlich; und 9,52 mm (0,375 Zoll) für größere Größen als Label 1: 13 — 3/8
J	Abstand vom Rohrende bis zur Mitte der Muffe in der Dichtungsposition, nach API 5B
J_{Ic}	Bruchbeständigkeit des Werkstoffs
J_{Imat}	Bruchbeständigkeit des Werkstoffs in einer bestimmten Umgebung
J_{p}	polares Trägheitsmoment des Rohrquerschnitts; $J_{\text{p}} = \pi/32\ (D^4 - d^4)$

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J_r	Spannungsintensitätsverhältnis auf der Grundlage des J-Integrals
K	Spannungsintensitätsfaktor an der Rissspitze
K_{Imat}	Bruchzähigkeit eines Werkstoffs in einer bestimmten Umgebung
K_p	Verhältnis der Innendruckspannung zur Fließgrenze, oder $p_i\, D/2(f_{ymnp}\, t)$
K_r	Spannungsintensitätsverhältnis
k_A	variabler Zwischenwert bei der Darstellung der von-Mises-Fließbedingung in ISO 13679 oder API RP 5C5
k_a	Berstfestigkeitsfaktor mit dem numerischen Wert 1,0 für abgeschreckte und angelassene Produkte (martensitische Struktur) oder 13Cr-Produkte und mit dem numerischen Wert 2,0 für gewalzte und normalgeglühte Produkte auf der Grundlage verfügbarer Prüfdaten; der Standardwert wird auf 2,0 eingestellt, wenn der Wert nicht gemessen wurde. Auf der Grundlage von Prüfungen kann der Wert von k_a für einen bestimmten Rohrwerkstoff ermittelt werden
k_B	variabler Zwischenwert bei der Darstellung der von-Mises-Fließbedingung in ISO 13679 oder API RP 5C5
k_C	variabler Zwischenwert bei der Darstellung der von-Mises-Fließbedingung in ISO 13679 oder API RP 5C5
k_c	in der elastischen Kollaps-Formel verwendete Konstante
k_{dr}	Korrekturfaktor auf der Grundlage der Rohrverformung und Kaltverfestigung des Werkstoffs, der den numerischen Wert von $[(1/2)^{n+1} + (1/\sqrt{3})^{n+1})]$ einnimmt
k_e	Faktor für den systematischen Fehler bei elastischem Kollaps
$k_{e\ des}$	Herabstufungsfaktor für den elastischen Kollaps der Konstruktion
k_{el}	Konstante für die Dehnung, die für SI-Einheiten 1 942,57 und für USC-Einheiten 625 000 beträgt
$k_{e\ uls}$	Kalibrierfaktor für den endgültigen elastischen Kollaps, der 1,089 beträgt
k_i	Faktor zur Bestimmung der Mindestwanddicke von Prüfstücken für die Schlag-Biege-Prüfung: 1,00 für Prüfstücke in Originalgröße 0,75 für Prüfstücke in drei Viertel der Originalgröße 0,50 für Prüfstücke in der Hälfte der Originalgröße
k_{lsl}	Faktor für die Längenumrechnung, der für SI-Einheiten 0,001 und für USC-Einheiten 1/12 beträgt
k_m	Korrekturfaktor für die Masse, der für unlegierten Stahl 1,000 und für martensitischen Chromstahl 0,989 beträgt

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k_n	Umrechnungsfaktor für die Spannung, der für SI-Einheiten $1{,}18 \times 10^{-4}\,\text{MPa}^{-1}$ und für USC-Einheiten $8{,}12 \times 10^{-7}\,\text{psi}^{-1}$ beträgt
k_{pi}	Geometriefaktor für den oberen Quadranten zur Darstellung der von-Mises-Fließbedingung in ISO 13679 oder API RP 5C5
k_{po}	Geometriefaktor für den unteren Quadranten zur Darstellung der von-Mises-Fließbedingung in ISO 13679 oder API RP 5C5
k_{wall}	Faktor zur Berücksichtigung der festgelegten Fertigungstoleranz der Rohrwand. Zum Beispiel: für eine Toleranz von −12,5 % beträgt k_{wall} = 0,875.
k_{wpe}	Umrechnungsfaktor für die Masse je Längeneinheit, der für SI-Einheiten 0,024 661 5 und für USC-Einheiten 10,69 beträgt
k_y	Faktor für den systematischen Fehler bezüglich des Fließspannungs-Kollapses
$k_{y\,des}$	Herabstufungsfaktor für den Bemessungs-Fließspannungs-Kollaps
$k_{y\,uls}$	Kalibrierfaktor für den endgültigen Fließspannungs-Kollaps, beträgt 0,991 1
L	Länge
L_c	Mindestlänge von Vollgewinden ab Rohrende nach API 5B
L_{ef}	Rohrlänge einschließlich Endverarbeitung
L_{et}	Einschraubtiefe, [= $L_4 - M$] für Nennverschraubung nach API 5B
L_{eu}	Länge vom Rohrende bis zum Beginn der Verjüngung, nach ISO 11960 oder API 5CT
L_{iu}	Länge der Stauchung des Einsteckendes, nach ISO 11960 oder API 5CT
L_j	Länge eines genormten Rohrstückes
L_r	Lastverhältnis
L_1	Länge vom Rohrende bis zur handfest verschraubten Ebene, nach API 5B
L_7	Länge von einwandfreien Gewinden, nach API 5B
M	Länge von der Stirnfläche der Muffe bis zur handfest verschraubten Ebene für Leitungsrohre sowie Futter- und Steigrohre mit Rundgewinde, nach API 5B
M_b	Biegemoment
m_c	Masse der Muffe
m_{cB}	Masse der Muffe von Futterrohren mit Sägengewinde
m_{crsb}	Masse der Muffe, die durch die Sonderabfasung entfernt wird

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m_{csb}	Masse der Muffe mit Sonderabfasung
m_{eu}	Länge der Verjüngung der Stauchung des Aufnahmeteils, nach ISO 11960 oder API 5CT
m_{exu}	Masse der äußeren Stauchung
m_{eiu}	Masse der äußeren-inneren Stauchung
m_{irt}	Masse des Integralverbinders, die durch das Gewindeschneiden und Ausfräsen entfernt wird
m_{inu}	Masse der inneren Stauchung
m_{iu}	Länge der Verjüngung der Stauchung des Einsteckendes, nach ISO 11960 oder API 5CT
m_{prt}	durch das Gewindeschneiden entfernte Masse des Einsteckendes
m_{rt}	durch Gewindeschneiden entfernte Masse
mu	Modellunsicherheit
N	Anzahl der Gewindegänge bei der Herstellung
N_L	Länge der Muffe nach ISO 11960 oder API 5CT
N_t	Anzahl der Prüfungen
n	dimensionsloser Verfestigungsindex zur Erreichung einer Kurvenanpassung (siehe B.2.3.3) der aus der einachsigen Zugprüfung abgeleiteten wahren Spannungs-Dehnungs-Kurve
ov	Ovalität
P_j	Verbindungsfestigkeit
p	Gewindesteigung 3,175 mm (0,125 Zoll) für Futterrohre mit Rundgewinde 5,080 mm (0,200 Zoll) für Futterrohre mit Sägengewinde
p_c	Kollapsdruck
p_{ci}	Kollapsdruck bei vorhandenem Innendruck
p_{des}	Bemessungskollapsdruck
p_{desi}	um den Innendruck korrigierter Bemessungskollapsdruck
$p_{des\ e}$	um die Axialspannung und den Innendruck korrigierter Kollapsdruck
p_e	Benennung für den elastischen Kollaps
p_{ec}	Druckdifferenz bei elastischem Kollaps

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$p_{e\ des}$	Benennung für den elastischen Bemessungskollaps
$p_{e\ ult}$	Benennung für den endgültigen elastischen Kollaps
p_E	Druck für den elastischen Kollaps
p_{ht}	hydrostatischer Prüfdruck
p_i	Innendruck
p_{iF}	Innendruck bei Bruch
p_{iL}	Innendruck bei Undichtheit
p_{iR}	Innendruck bei Verformungsbruch eines Rohres mit Rohrverschluss
p_{iRa}	bezüglich Axiallast und Außendruck angepasster p_{iR}
p_{iYAPI}	Innendruck im Fließbereich für ein dünnes Rohr
p_{iYc}	Innendruck im Fließbereich für die Muffe
p_{iYLc}	Innendruck im Fließbereich für ein dickes Rohr mit Rohrverschluss
p_{iYLo}	Innendruck im Fließbereich für ein nicht verschlossenes dickes Rohr
p_o	Außendruck
$p_{o\ ult}$	endgültiger Außendruck bei Kollaps
p_P	Druck bei plastischem Kollaps
p_{Pav}	Druck für mittleren plastischen Kollaps
p_T	Druck für Kollapsübergang
p_{ult}	endgültiger Kollapsdruck
p_y	Benennung für den Kollaps im Fließbereich
p_{yc}	Druckdifferenz bei Kollaps im Fließbereich
$p_{y\ des}$	Benennung für den Kollaps im Bemessungsfließbereich
p_{yM}	durch die Rohrwand gemessener Fließdruckunterschied nach von Mises
p_{Yp}	Druck für Fließgrenzenkollaps
$p_{y\ Tresca}$	Fließdruck für den Kollaps nach Tresca

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$p_{y\ ult}$	Benennung für den endgültigen Kollaps im Fließbereich
$p_{y\ vme}$	Fließdruck für den Kollaps nach von Mises
Q	Durchmesser der Aussparung für die Muffe, nach API 5B
r	Radialkoordinate, $(d/2) \leq r \leq (D/2)$
rs	Eigenspannung (Kompression an der Innendruckfläche ist negativ)
S	Abstand zwischen Abflachungsplatten
S_p	Standardfehler des Schätzwertes der Regressionsformel
s_{rn}	Abflachung am Rohrgewindegrund bei Rundgewinden 0,36 mm (0,014 Zoll) für 10 TPI, 0,43 mm (0,017 Zoll) für 8 TPI
$s_{t/D}$	Normabweichung der in der Regression verwendeten Verhältnisse t/D
T	aufgebrachtes Drehmoment
T_d	Verjüngung (im Durchmesser)
t	festgelegte Rohrwanddicke
t_{ave}	tatsächliche mittlere Rohrwanddicke ohne Berücksichtigung von rissartigen Fehlstellen
$t_{c\ ave}$	tatsächliche mittlere Rohrwanddicke
$t_{c\ max}$	höchste Rohrwanddicke
$t_{c\ min}$	Mindestrohrwanddicke
t_{max}	tatsächliche Höchstrohrwanddicke ohne Berücksichtigung von rissartigen Fehlstellen
t_{min}	tatsächliche Mindestrohrwanddicke ohne Berücksichtigung von rissartigen Fehlstellen
t_p	einem Vertrauensniveau von p entsprechendes Toleranzintervall, das den Anteil der nicht enthaltenen Grundgesamtheit nicht überschreitet
W	festgelegter Außendurchmesser der Muffe, nach ISO 11960 oder API 5CT
u_p	dem Vertrauensniveau p entsprechendes Quantil
$u_{1-\theta}$	Quantil, Abweichung vom Mittelwert einer Standardnormalverteilung, die die Fraktion $1 - \theta_p$ der Grundgesamtheit einschließt
W_L	berechnete Masse eines Rohrstücks der Länge L
w_{ij}	Stauch- und Gewindemasse je Längeneinheit
w_{pe}	Masse von Rohrenden je Längeneinheit

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w_{tc}	Gewinde- und Muffenmasse je Längeneinheit
w_u	Masse der Stauchung je Längeneinheit
$\vec{x}$	Vektor von Zufallsvariablen
Z_p	Korrekturfaktor für die Abweichung von t/D vom Mittelwert
α	Empfindlichkeitsfaktor
β	Zuverlässigkeitsindex erster Ordnung
ε_{eng}	technische Dehnung
ε_{el}	Mindestdehnung der Messlänge auf 50,8 mm (2,0 Zoll) in Prozent, gerundet auf 0,5 % wenn der Wert unter 10 % liegt und auf ein Prozent, wenn er bei 10 % oder darüber liegt
ε_{ln}	logarithmische Dehnung
ε_{ymn}	Dehnung, bei der die festgelegte Mindestfließgrenze ermittelt wird
μ	Mittelwert
μ_{ec}	mittlere berechnete Exzentrizität als prozentualer Anteil [Exzentrizität = $100(t_{c\,max} - t_{c\,min})/t_{c\,ave}$]
μ_{fy}	mittlere berechnete f_y als prozentualer Anteil
μ_{ov}	mittlere berechnete Ovalität als prozentualer Anteil, [Ovalität = 100 $(D_{max} - D_{min})/D_{ave}$]
μ_{rs}	mittlere berechnete Eigenspannung (Kompression an der Innendruckfläche ist negativ)
ν	Poissonzahl
π	Umfang eines Kreises, geteilt durch seinen Durchmesser, zugewiesener Wert von 3,141 6
ϕ_f	Ausfallwahrscheinlichkeit
θ_p	Anteil der nicht enthaltenen Grundgesamtheit
σ	Standardabweichung
σ_a	Komponente der Axialspannung, die nicht auf Biegung zurückzuführen ist
σ_b	Komponente der Axialspannung auf Grund von Biegung
σ_c	wahre (Cauchy)-Spannung
σ_e	Vergleichsspannung
σ_{eff}	effektive Axialspannung; $\sigma_{eff} = F_{eff}/A_p$

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σ_f	Faserspannung, die dem prozentualen Anteil der festgelegten Fließgrenze nach Tabelle 11 entspricht
σ_h	Umfangs- oder Ringspannung
σ_{pmx}	Höchst-Hauptspannung
σ_r	Radialspannung
σ_{res}	Eigenspannung
σ_{th}	Schwellenwertspannung
σ_{ye}	äquivalente Fließgrenze bei axialer Zugspannung
σ_{ymne}	äquivalente Mindestfließgrenze bei axialer Zugspannung
τ_{ha}	Torsions-(schub-)spannung

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Nationaler Anhang NB
(informativ)

Literaturhinweise

DIN EN ISO 3183, *Erdöl- und Erdgasindustrie — Stahlrohre für Rohrleitungstransportsysteme*

DIN EN ISO 10405, *Erdöl- und Erdgasindustrie — Pflege und Gebrauch von Futterrohren und Steigrohren*

DIN EN ISO 11960, *Erdöl- und Erdgasindustrie — Stahlrohre zur Verwendung als Futter- oder Steigrohre für Bohrungen*

DIN EN ISO 11961, *Erdöl- und Erdgasindustrie — Stahl-Bohrrohre*

DIN EN ISO 13679, *Erdöl- und Erdgasgewinnung — Prüfverfahren an Verbindungen für Futter- und Steigrohre*

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Erdöl- und Erdgasindustrie - Formeln und Berechnungen der Eigenschaften von Futterrohren, Steigrohren, Bohrgestängen und Leitungsrohren (ISO/TR 10400:2018)

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European foreword

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The text of ISO/TR 10400:2018 has been approved by CEN as CEN ISO/TR 10400:2021 without any modification.

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document 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 second edition cancels and replaces the first edition (ISO/TR 10400:2007), which has been technically revised.

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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 can be subjected to the anticipated resistance of the tubular to each load. Either or both of the load and resistance can be modified by a design factor.

Both deterministic and probabilistic approaches to performance properties are addressed in this document. The deterministic approach uses specific geometric and material property values to calculate a single performance property value. The probabilistic 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 formula.

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 document. Rather, it serves to identify useful formulae for obtaining the resistance of a tubular to specified loads, independent of their origin. It provides limit state formulae (see annexes) which are useful for determining the resistance of an individual sample whose geometric and material properties are given, and design formulae which are useful for well design based on conservative geometric and material parameters.

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

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

1 Scope

This document illustrates the formulae 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 formulae related to performance properties, extensive background information is also provided regarding their development and use.

Formulae 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 formulae and templates can be extended to other pipe with due caution. Pipe cold-worked during production is included in the scope of this document (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 document.

Application of performance property formulae in this document 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 is exercised when using the performance formulae for drill pipe.

This document and the formulae 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 formulae in this document are not to be understood as a manufacturing warranty. Manufacturers are typically licensed to produce tubular products in accordance with manufacturing specifications which control the dimensions and physical properties of their product. Design formulae, 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 document is not a design code. It only provides formulae and templates for calculating the properties of tubulars intended for use in downhole applications. This document 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 formulae and listed values for performance properties in this document assume a benign environment and material properties conforming to ISO 11960 or API 5CT, ISO 11961 or API 5D and

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ISO 3183 or API 5L. Other environments can 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 document.

Throughout this document tensile stresses are positive.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
Cauchy stress
true stress
force applied to the surface of a body divided by the current area of that surface

3.2
coefficient of variance
dimensionless measure of the dispersion of a random variable, calculated by dividing the standard deviation by the mean

3.3
design formula
formula which, based on production measurements or specifications, provides a performance property useful in design calculations

Note 1 to entry: A design formula can be defined by applying reasonable extremes to the variables in a limit state formula to arrive at a conservative value of expected performance. When statistically derived, the design formula corresponds to a defined lower percentile of the resistance probability distribution curve.

3.4
deterministic
approach which assumes all variables controlling a performance property are known with certainty

Note 1 to entry: Pipe performance properties generally depend on one or more controlling parameters. A deterministic formula uses specific geometric and material property values to calculate a single performance property value. For design formulations, this value is the expected minimum.

3.5
ductile rupture
failure of a tube due to internal pressure and/or axial force in the plastic deformation range

3.6
e
Euler's constant
2,718 281 828

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3.7
effective axial force
material axial force (pipe wall axial stress times cross-sectional area) adjusted for the effect of internal and external pressure

Note 1 to entry: When a tubular is bent laterally into a circular arc, the pressures apply a lateral uniform distributed load (UDL) of $(p_i A_i - p_o A_o)/R$. For small deflections, the curvature is defined as $1/R \cong d^2y/dx^2$, thus, this term can be grouped with the tension term $F\, d^2y/dx^2$ in the governing differential formula. For bending and buckling, the tubular therefore acts as if it were loaded by the *effective axial force* $F_{eff} = F_a - p_i A_i + p_o A_o$[141]. It should be seen as a convenient grouping of terms, which determines the structural response: it does not exist as a physical axial force.

3.8
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

3.9
engineering stress
force applied to the surface of a body divided by the original area of that surface

3.10
fracture pressure
internal pressure at which a tube fails due to propagation of an imperfection

3.11
inspection threshold
maximum size of a crack-like imperfection which is defined to be acceptable by the inspection system

3.12
J-integral
measure of the intensity of the stress-strain field near the tip of a crack

3.13
label 1
dimensionless designation for the size or specified outside diameter that may be used when ordering pipe

3.14
label 2
dimensionless designation for the mass per unit length or wall thickness that may be used when ordering pipe

3.15
limit state formula
formula which, when used with the measured geometry and material properties of a sample, produces an estimate of the failure value of that sample

Note 1 to entry: A limit state formula describes the performance of an individual sample as closely as possible, without regard for the tolerances to which the sample was built.

3.16
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 1 to entry: Alternatively, the logarithmic strain can be estimated as the natural logarithm of one plus the engineering strain.

3.17
mass
label used to represent wall thickness of tube cross section for a given pipe size

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3.18
pipe body yield
stress state necessary to initiate yield at any location in the pipe body

3.19
principal stress
stress on a principal plane for which the shear stress is zero

Note 1 to entry: 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.

3.20
probabilistic method
approach which uses distributions of geometric and material property values to calculate a distribution of performance property values

3.21
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 1 to entry: These distributions are combined with a limit state formula to determine the statistical distribution of a performance property. The performance distribution in combination with a defined lower percentile determines the final design formula.

3.22
template
procedural guide consisting of formulae, test methods and measurements for establishing design performance properties

3.23
TPI
threads per inch

Note 1 to entry: 1 thread per inch = 0,039 4 threads per millimetre; 1 thread per millimetre = 25,4 threads per inch.

3.24
true stress-strain curve
plot of Cauchy stress (ordinate) versus logarithmic strain (abscissa)

3.25
yield
permanent, inelastic deformation

3.26
yield stress bias
ratio of actual yield stress to specified minimum yield stress

4 Symbols

A	hand-tight standoff, turns
A_c	empirical constant in historical API collapse formula
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_i	area to pipe inside diameter; $A_i = \pi d^2/4$

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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_o	area to pipe outside diameter; $A_o = \pi D^2/4$
A_p	area of the pipe cross section; $A_p = A_o - A_i$
$A_{p\ ave}$	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	for a limit state formula, the maximum actual depth of a crack-like imperfection; for a design formula, 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_c	empirical constant in historical API collapse formula
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 formula
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_{max}	maximum pipe outside diameter
D_{min}	minimum pipe outside diameter
D_4	major diameter, in accordance with API 5B
d	pipe inside diameter, $d = D - 2t$
d_{iu}	inside diameter of pin upset, in accordance with ISO 11960 or API 5CT
d_{ou}	inside diameter at end of upset pipe
d_{wall}	inside diameter based on $k_{wall}\ t$; $d_{wall} = D - 2k_{wall}\ t$
$d1$	diameter at the root of the coupling thread at the end of the pipe in the power-tight position

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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	material axial force
F_{eff}	effective axial force; Feff = Fa − pi Ai + po Ao
F_c	empirical constant in historical API collapse formula
F_{YAPI}	material axial force at yield, historical API formula
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

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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 formula
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
$g(\vec{x})$	limit state function
H	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 for design collapse strength, as given in Table F.9
Ht_{ult}	a decrement factor for ultimate collapse strength, as defined in Formula (F.4)
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
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
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; $J_p = \pi/32\ (D^4 - d^4)$
J_r	stress intensity ratio based on the J-Integral
K	stress intensity factor at the crack tip

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

K_p ratio of internal pressure stress to yield strength, or $p_i\, D/(2\, f_{ymnp}\, t)$

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 formula

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

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

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

$k_{e\,uls}$ 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 $1{,}18 \times 10^{-4}$ MPa^{-1} for SI units and 8.12×10^{-7} 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 %, $k_{wall} = 0{,}875$

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

k_y bias factor for yield collapse

$k_{y\,des}$ down-rating factor for design yield collapse

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$k_{y\ uls}$	calibration factor for ultimate yield collapse, 0,991 1
L	length
L_c	minimum length of full crest threads from end of pipe, in accordance with API 5B
L_{ef}	length of pipe including end finish
L_{et}	engaged thread length, [= $L_4 - M$] for nominal make-up, in accordance with API 5B
L_{eu}	length from end of pipe to start of taper, in accordance with ISO 11960 or API 5CT
L_{iu}	length of pin upset, in accordance with ISO 11960 or API 5CT
L_j	length of a standard piece of pipe
L_r	load ratio
L_1	length from the end of the pipe to the hand-tight plane, in accordance with API 5B
L_7	length of perfect threads, in accordance with API 5B
M	length from the face of the coupling to the hand-tight plane for line pipe and for round thread casing and tubing, in accordance with API 5B
M_b	bending moment
m_c	coupling mass
m_{cB}	coupling mass of buttress thread casing
m_{crsb}	coupling mass removed by special bevel
m_{csb}	coupling mass with special bevel
m_{eu}	length of box upset taper, in accordance with ISO 11960 or API 5CT
m_{exu}	external upset mass
m_{eiu}	external-internal upset mass
m_{irt}	integral joint mass removed by threading and recessing
m_{inu}	internal upset mass
m_{iu}	length of pin upset taper, in accordance with ISO 11960 or API 5CT
m_{prt}	pin mass removed by threading
m_{rt}	mass removed by threading
mu	model uncertainty
N	number of thread turns make-up
N_L	coupling length, in accordance with ISO 11960 or API 5CT
N_t	number of tests
n	dimensionless hardening index used to obtain a curve fit (see B.2.3.3) of the true stress-strain curve derived from the uniaxial tensile test

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ov	ovality
P_j	joint strength
p	thread pitch 3,175 mm (0.125 in) for round thread casing 5,080 mm (0.200 in) for buttress thread casing
p_c	collapse pressure
p_{ci}	collapse pressure in the presence of internal pressure
p_{des}	design collapse pressure
p_{desi}	design collapse pressure corrected for internal pressure
$p_{des\ e}$	collapse pressure corrected for axial stress and internal pressure
p_e	elastic collapse term
p_{ec}	elastic collapse pressure difference
$p_{e\ des}$	design elastic collapse term
$p_{e\ ult}$	ultimate elastic collapse term
p_E	pressure for elastic collapse
p_{ht}	hydrostatic test pressure
p_i	internal pressure
p_{iF}	internal pressure at fracture
p_{iL}	internal pressure at leak
p_{iR}	internal pressure at ductile rupture of an end-capped pipe
p_{iRa}	p_{iR} adjusted for axial load and external pressure
p_{iYAPI}	internal pressure at yield for a thin tube
p_{iYc}	internal pressure at yield for coupling
p_{iYLc}	internal pressure at yield for a capped-end thick tube
p_{iYLo}	internal pressure at yield for an open-ended thick tube
p_o	external pressure
$p_{o\ ult}$	ultimate external pressure for collapse
p_P	pressure for plastic collapse
p_{Pav}	pressure for average plastic collapse
p_T	pressure for transition collapse
p_{ult}	ultimate collapse pressure
p_y	yield collapse term

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p_{yc}	yield collapse pressure difference
$p_{y\,des}$	design yield collapse term
p_{yM}	through-wall von Mises yield pressure difference
p_{Yp}	pressure for yield strength collapse
$p_{y\,Tresca}$	Tresca yield pressure for collapse
$p_{y\,ult}$	ultimate yield collapse term
$p_{y\,vme}$	von Mises yield pressure for collapse
Q	diameter of coupling recess, in accordance with API 5B
r	radial coordinate, $(d/2) \leq r \leq (D/2)$
rs	residual stress (compression at ID face is negative)
S	distance between flattening plates
S_p	standard error of estimate of the regression formula
s_{rn}	root truncation of the pipe thread of round threads, 0,36 mm (0.014 in) for 10 TPI, 0,43 mm (0.017 in) for 8 TPI
$s_{t/D}$	standard deviation of t/D ratios used in the regression
T	applied torque
T_d	taper (on diameter)
t	specified pipe wall thickness
t_{ave}	actual average pipe wall thickness disregarding crack-like imperfections
$t_{c\,ave}$	actual average pipe wall thickness
$t_{c\,max}$	maximum pipe wall thickness
$t_{c\,min}$	minimum pipe wall thickness
t_{max}	actual maximum pipe wall thickness disregarding crack-like imperfections
t_{min}	actual minimum pipe wall thickness disregarding crack-like imperfections
t_p	tolerance interval corresponding to a confidence level of p that the proportion of the population not included does not exceed
W	specified coupling outside diameter, in accordance with ISO 11960 or API 5CT
u_p	fractile corresponding to confidence level p
$u_{1\text{-}\theta}$	fractile, the deviation from the mean of a standardized normal cumulative distribution that includes the fraction $1 - \theta_p$ of the population
W_L	calculated mass of a piece of pipe of length L
w_{ij}	upset and threaded mass per unit length

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w_{pe}	plain-end mass per unit length
w_{tc}	threaded and coupled mass per unit length
w_u	upset mass per unit length
$\vec{x}$	vector of random variables
Z_p	correction factor for variation in t/D from average
α	sensitivity factor
β	first-order reliability index
ε_{eng}	engineering strain
ε_{el}	minimum gauge length extension in 50,8 mm (2.0 in), in percent, rounded to the nearest 0,5 % below 10 % and to the nearest unit percent for 10 % and larger
ε_{ln}	logarithmic strain
ε_{ymn}	strain at which specified minimum yield strength is determined
μ	mean
μ_{ec}	mean calculated eccentricity as a percent, [eccentricity = 100 $(t_{c\,max} - t_{c\,min})/t_{c\,ave}$]
μ_{fy}	mean calculated f_y as a percent
μ_{ov}	mean calculated ovality as a percent, [ovality = 100 $(D_{max} - D_{min})/D_{ave}$]
μ_{rs}	mean calculated residual stress (compression at ID face is negative)
ν	Poisson's ratio
π	circumference of a circle divided by its diameter, assigned a value of 3,141 6
ϕ_f	probability of failure
θ_p	the proportion of the population not included
σ	standard deviation
σ_a	component of axial stress not due to bending
σ_b	component of axial stress due to bending
σ_c	true (Cauchy) stress
σ_e	equivalent stress
σ_{eff}	effective axial stress; $\sigma_{eff} = F_{eff}/A_p$
σ_f	fibre stress corresponding to the percent of specified yield strength as given in Table 11
σ_h	circumferential or hoop stress
σ_{pmx}	maximum principal stress
σ_r	radial stress

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σ_{res} residual stress

σ_{th} threshold stress

σ_{ye} equivalent yield strength in the presence of axial tension

σ_{ymne} equivalent minimum yield strength in the presence of axial tension

τ_{ha} torsional (shear) stress

5 Conformance

5.1 References

In the interests of worldwide application of this document, ISO/TC 67 has decided, after detailed technical analysis, that some of the documents listed in the Bibliography 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 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.

5.2 Units of measurement

In this document, 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.

6 Triaxial yield of pipe body

6.1 General

The criterion for triaxial pipe body yield is that proposed by von Mises. The elastic state leading to incipient yield consists of the superposition of:

a) radial and circumferential stress as determined by the Lamé formulae for a thick cylinder;

b) uniform axial stress due to all sources except bending;

c) axial bending stress for a Timoshenko beam;

d) torsional shear stress due to a moment aligned with the axis of the pipe.

Details of the derivation of the design formula can be found in Annex A.

6.2 Assumptions and limitations

6.2.1 General

Formulae (1) to (7) are based on the assumptions given in 6.2.2 to 6.2.5.

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6.2.2 Concentric, circular cross-sectional geometry

The formulae for radial stress, circumferential or hoop stress, bending and torsion presume the pipe cross section to consist of inner and outer surfaces that are circular and concentric.

6.2.3 Isotropic yield

The yield strength of the material of which the pipe is composed is assumed to be independent of direction. An axial sample and a circumferential sample are assumed to possess identical elastic moduli and yield stress in both tension and compression.

6.2.4 No residual stress

For determination of the onset of yield, residual stresses due to manufacturing processes are assumed to be negligible, and are ignored.

6.2.5 Cross-sectional instability (collapse) and axial instability (column buckling)

Particularly in instances where $p_o > p_i$, it is possible for the pipe cross section to collapse due to instability prior to yield. For external pressure greater than internal pressure, see Clause 8 on collapse. Similarly, if $\sigma_{eff} < 0$, it is possible for the pipe to buckle as a column prior to yield, and the bending stress due to buckling should be included in the yield check.

6.3 Data requirements

The following input data are required to complete the calculation for triaxial yield of the pipe body:

— c: tube curvature, the inverse of the radius of curvature to the centreline of the pipe;

— D: specified pipe outside diameter;

— E: Young's modulus;

— F_a: axial force;

— f_{ymn}: specified minimum yield strength;

— k_{wall}: factor to account for the specified manufacturing tolerance of the pipe wall. For example, for a tolerance of –12,5 %, $k_{wall} = 0{,}875$;

— p_i: internal pressure;

— p_o: external pressure;

— T: applied torque;

— t: specified pipe wall thickness.

6.4 Design formula for triaxial yield of pipe body

The onset of yield is defined as:

$$\sigma_e = f_{ymn} \tag{1}$$

where

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$\sigma_e < f_{ymn}$ corresponds to elastic behaviour;

f_{ymn} is the specified minimum yield strength;

σ_e is the equivalent stress.

The equivalent stress is defined as:

$$\sigma_e = [\sigma_r^2 + \sigma_h^2 + (\sigma_a + \sigma_b)^2 - \sigma_r\sigma_h - \sigma_r(\sigma_a + \sigma_b) - \sigma_h(\sigma_a + \sigma_b) + 3\tau_{ha}^2]^{1/2} \quad (2)$$

with:

$$\sigma_r = [(p_i d_{wall}^2 - p_o D^2) - (p_i - p_o) d_{wall}^2 D^2/(4r^2)]/(D^2 - d_{wall}^2) \quad (3)$$

$$\sigma_h = [(p_i d_{wall}^2 - p_o D^2) + (p_i - p_o) d_{wall}^2 D^2/(4r^2)]/(D^2 - d_{wall}^2) \quad (4)$$

$$\sigma_a = F_a/A_p \quad (5)$$

$$\sigma_b = \pm M_b r/I = \pm Ecr \quad (6)$$

$$\tau_{ha} = Tr/J_p \quad (7)$$

where

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

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

D is the specified pipe outside diameter;

d is the pipe inside diameter, $d = D - 2t$;

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

E is Young's modulus;

F_a is the axial force;

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

J_p is the polar moment of inertia of the pipe cross section, $J_p = \pi/32\ (D^4 - d^4)$;

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

M_b is the bending moment;

p_i is the internal pressure;

p_o is the external pressure;

r is the radial coordinate, $(d/2) \le r \le (D/2)$ for σ_a, σ_b and τ_{ha}, $(d_{wall}/2) \le r \le (D/2)$ for σ_r and σ_h;

T is the applied torque;

t is the specified pipe wall thickness;

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σ_a is the component of axial stress not due to bending;

σ_b is the component of axial stress due to bending;

σ_e is the equivalent stress;

σ_h is the circumferential or hoop stress;

σ_r is the radial stress;

τ_{ha} is the torsional (shear) stress.

The ± sign in Formula (6) indicates that the component of axial stress due to bending can be positive (tension) or negative (compression), depending on the location of the point in the cross section. Points in the pipe cross section closer to the centre of tube curvature than the centreline of the pipe experience compressive bending stress. Points in the pipe cross section farther from the centre of tube curvature than the centreline of the pipe experience tensile bending stress.

The variable c has units of radian/length, which are not the norm for the petroleum industry. The more common measure of c in the industry is °/30 m (°/100 ft). If, therefore, the required units for c are radians/metre, and c is expressed in °/30 m (°/100 ft), the right-hand side of Formula (6) should be multiplied by the constant $\pi/(180 \times 30) = 5{,}817\ 8 \times 10^{-4}$ rad-m/°–30 m [$\pi/(180 \times 100) = 1{,}645\ 3 \times 10^{-4}$ rad-ft/°–100 ft].

In the presence of bending, Formula (2) should be evaluated four times, i.e. at the inner and outer radii on both the tensile and compressive sides of the cross section. In the presence of torsion, Formula (2) should be evaluated two times, i.e. at the inner and outer radii. In the absence of both bending and torsion, Formula (2) should be evaluated once, at the minimum value of the radius. In all cases, the maximum computed value of σ_e should be used in Formula (1).

The purpose of the design formula is to determine the stress state which results in the onset of pipe yield when the properties of the pipe are at their worst-case, minimum allowable values. The wall thickness of the pipe at all times accounts for the extreme allowable thin-wall eccentricity which comes about naturally as part of the pipe manufacturing process.

6.5 Application of design formula for triaxial yield of pipe body to line pipe

The pipe body yield strength of line pipe can be calculated by means of formulae presented in this clause, minding the limitations given in 6.2.

6.6 Example calculations

6.6.1 Initial yield of pipe body, Lamé formula for pipe when external pressure, bending and torsion are zero

6.6.1.1 General

The Lam formulae for the radial and hoop stresses of the pipe are based on the three-dimensional formulae of equilibrium for a linear elastic cross section. As such, these formulae are triaxial formulae and provide the most accurate calculation of pipe stresses. Two formulae are provided, open-end with zero axial stress, and closed-end with axial stress due to internal pressure acting on the end cap.

6.6.1.2 Yield design formula, special case for capped-end conditions

Initial yield of a capped-end thick tube is a special case of Formulae (1) and (2) when external pressure, bending and torsion are zero. The axial stress is generated solely by the action of internal pressure on the ends of the sample (e.g. the capped-end condition.)

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A design formula for initial yield of the pipe body with capped-end conditions and using the Lam formulae for the radial and hoop stresses should be formulated from Formula (2), evaluated at the inner diameter. The resulting design formula is

$$p_{iYLc} = f_{ymn}/\{(3\,D^4 + d_{wall}{}^4)/(D^2 - d_{wall}{}^2)^2 + d^4/(D^2 - d^2)^2 - 2d^2 d_{wall}{}^2/[(D^2 - d^2)\,(D^2 - d_{wall}{}^2)]\}^{1/2} \quad (8)$$

where

D is the specified pipe outside diameter;

d is the pipe inside diameter, $d = D - 2t$;

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

f_{ymn} is the specified minimum yield strength;

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

p_{iYLc} is the internal pressure at yield for a capped-end thick tube;

t is the specified pipe wall thickness.

There is no adjustment to Formula (8) for axial tension, as all axial tension is generated by the action of internal pressure on the (closed) ends of the pipe. The more general case, where axial stress is generated by other than the action of internal pressure on the ends of the pipe, is addressed by the triaxial yield criterion, Formulae (1) and (2).

6.6.1.3 Yield design formula, special case for internal pressure only and zero axial load

Initial yield of an open-ended thick tube is a special case of Formulae (1) and (2) when the uniform axial stress, external pressure, bending and torsion are zero.

A design formula for initial yield of the pipe body with open-end conditions and using the Lam formulae for the radial and hoop stresses should be formulated from Formula (2) evaluated at the inner diameter. The resulting design formula is

$$p_{iYLo} = f_{ymn}(D^2 - d_{wall}{}^2)/(3\,D^4 + d_{wall}{}^4)^{1/2} \quad (9)$$

where

D is the specified pipe outside diameter;

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

f_{ymn} is the specified minimum yield strength;

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

p_{iYLo} is the internal pressure at yield for an open-end thick tube;

t is the specified pipe wall thickness.

The more general case, where axial stress is non-zero, is addressed by the triaxial yield criterion, Formulae (1) and (2).

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6.6.2 Yield design formula, special case for thin wall pipe with internal pressure only and zero axial load

6.6.2.1 General

The Barlow formula represents the thin wall approximation to the biaxial VME / Lam failure pressure. Barlow's paper[138] was published in 1836, when elasticity theory (that is, stresses in solid media) was in its infancy, and well before the development of material failure theories (Tresca 1864[139], Von Mises 1913[140]). The formula is for thick wall hoop stress, with failure taken to occur when the ID stress reaches yield. This is not a material failure condition. Moreover, the derivation is incorrect, because it violates the equilibrium condition[142]. However, the Barlow formula has been retained because it happens to represent the thin wall approximation to the biaxial VME/Lam failure pressure, see section A.2.6.

6.6.2.2 Historical yield pressure design formula

Initial yield of a thin tube is defined by the following expression:

$$p_{\mathrm{iYAPI}} = 2 f_{\mathrm{ymn}} k_{\mathrm{wall}} t/D \tag{10}$$

where

D is the specified pipe outside diameter;

f_{ymn} is the specified minimum yield strength;

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

p_{iYAPI} is the internal pressure at yield for a thin tube;

t is the specified pipe wall thickness.

This formula is subject to the same assumptions and limitations as the more general expressions from which it is derived (see A.1.3.3).

6.6.3 Pipe body yield strength

Pipe body yield strength is the axial load required to yield the pipe in the absence of internal and external pressure, bending and torsion. It is taken as the product of the cross-sectional area and the specified minimum yield strength for the particular grade of pipe:

$$F_{\mathrm{YAPI}} = f_{\mathrm{ymn}} A_{\mathrm{p}} \tag{11}$$

where

A_{p} is the area of the pipe cross section, $A_{\mathrm{p}} = \pi/4\ (D^2 - d^2)$;

D is the specified pipe outside diameter;

d is the pipe inside diameter, $d = D - 2t$;

F_{YAPI} is the axial force at yield, historical API formula;

f_{ymn} is the specified minimum yield strength;

t is the specified pipe wall thickness.

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6.6.4 Yield in the absence of bending and torsion

If bending and torsion are zero, Formula (2) reduces to

$$\sigma_e = [\sigma_r^2 + \sigma_h^2 + \sigma_a^2 - \sigma_r\sigma_h - \sigma_r\sigma_a - \sigma_h\sigma_a]^{1/2} \quad (12)$$

Consider, for example, the case of a tube being lowered open-ended into a vertical well full of fluid with mass density 1,080 kg/dm^3 (9 lb/gal). The internal and external pressure at any depth are equal, and the bottom of the tube is exposed to an axial compression equal to the product of the fluid pressure and the tube cross-sectional area. Ignoring connections, let the tube be of outside diameter 244,48 mm (9.625 in), of wall thickness 13,84 mm (0.545 in) and have k_{wall} = 0,875. Assume the mass density of steel is 7,85 kg/dm^3 (0.283 6 lb/in^3). Compute the yield state of the uppermost cross section of the tube when the tube is at a depth of 3 000 m (9 842.5 ft). The tube has a minimum yield stress of 551,6 MPa (80 000 psi).

Table 1 presents the results of the calculation in both SI and USC units.

Since both bending and torsion are zero in this example, there is no need to calculate σ_e at both the inner and outer radii of the tube, as yield will always occur at the inner radius. The calculations have been included here for completeness.

As the equivalent stress is less than the yield stress, the tube does not yield at its uppermost cross section.

Table 1 — Example calculations — Yield in the absence of bending and torsion

Term	SI		USC	
	Value	Units	Value	Units
Load				
F_a	1 997 797	N	449 205	lb
p_i	31,73	MPa	4 602	psi
p_o	31,73	MPa	4 602	psi
c	0	°/30 m	0	°/100 ft
T	0	N-m	0	ft-lb
Geometry				
D	244,48	mm	9.625	in
t	13,84	mm	0.545	in
k_{wall}	0,875		0.875	
Material				
E	206 842	MPa	30 000 000	psi
Calculations				
d	216,80	mm	8.535	in
d_{wall}	220,26	mm	8.671	in
A_p	10 028	mm^2	15.55	in^2
I	66 920 762	mm^4	160.8	in^4
J_p	133 841 524	mm^4	321.6	in^4
σ_a	199,22	MPa	28 894	psi
Inner radius				
σ_b	0	MPa	0	psi
σ_h	−31,73	MPa	−4 602	psi
σ_r	−31,73	MPa	−4 602	psi

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Table 1 *(continued)*

Term	SI		USC	
	Value	Units	Value	Units
τ_{ha}	0	MPa	0	psi
σ_e, σ_b+	230,95	MPa	33 496	psi
σ_e, σ_b-	230,95	MPa	33 496	psi
Outer radius				
σ_b	0	MPa	0	psi
σ_h	−31,73	MPa	−4 602	psi
σ_r	−31,73	MPa	−4 602	psi
τ_{ha}	0	MPa	0	psi
σ_e, σ_b+	230,95	MPa	33 496	psi
σ_e, σ_b-	230,95	MPa	33 496	psi

7 Ductile rupture of the pipe body

7.1 General

The formulae for ductile rupture pertain to the actual failure of the pipe body due to internal pressure. While the yield formulae of Clause 6 are intended to describe the onset of permanent plastic deformation and not loss of pressure integrity, the rupture formulae are intended to describe the ultimate pressure capacity of the pipe at a pressure which fails the pipe body with loss of internal pressure integrity.

The formulae for ductile rupture depend on the minimum physical wall thickness, the pipe outer diameter, the maximum depth of imperfections which have a reasonable probability of passing through the inspection process undetected, the fracture toughness of the material, the work hardening of the material and the ultimate tensile strength of the pipe. Yield strength has no direct impact on the ductile rupture pressure except through the correlation of the work hardening parameter *n*.

The ductile rupture formulae can be derived from the mechanics of pipe equilibrium combined with a model of pipe plasticity and a model of the effect of imperfections. The selection of the basic formula, the application of the basic formula to ISO/API tubular products, and the verification of the formula with actual test data are discussed in detail in Annex B. The ductile rupture limit state and design formulae consist of three interlinked concepts:

a) a formula for equilibrium-plasticity based rupture of a pipe with known physical wall thickness and diameter;

b) reduction in performance due to wall loss in proportion to depths of imperfections which may not be detected by the manufacturing and inspection system;

c) a criterion for minimum toughness at which ductile rupture applies.

These formulae are applicable to direct pressure and axial loading, but do not describe the capacity of the pipe under fatigue loading. The subtraction to the pipe wall for the presence of imperfections and the interrelated role of pipe toughness are based on a fracture mechanics approach relating J_{Ic} toughness measurements of sample pipes to numerically calculated crack-tip intensities (J-Integrals) as a function of imperfection depth. This is explained in detail in Annex B.

7.2 Assumptions and limitations

These formulae are applicable only when the pipe material in its environment has sufficient toughness to meet a minimum criterion such that the deformation of the pipe, in its environment, through to rupture is ductile and not brittle, even in the presence of small imperfections.

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Bending stresses (for instance, due to buckling or bending due to curvature of the well trajectory) are not included in the formula for ductile rupture pressure. Hence, the ductile rupture formula may not apply to pipe which is buckled (nor to pipe in a dogleg).

7.3 Data requirements

7.3.1 General

The following input data are required to complete the calculation for ductile rupture of the pipe body.

— 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).

— D: specified pipe outside diameter.

— f_{umn}: specified minimum tensile strength.

— 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_{wall}: factor to account for the specified manufacturing tolerance of the pipe wall. For example, for a tolerance of –12,5 %, k_{wall} = 0,875.

— n: dimensionless hardening index used to obtain a curve fit (see B.2.3.3) of the true stress-strain curve derived from the uniaxial tensile test.

— t: specified pipe wall thickness.

7.3.2 Determination of the hardening index

In the absence of stress-strain information, the following values of n are suggested.

Table 2 — Suggested values for hardening index in ductile rupture formula

Grade	n
H40	0,14
J55	0,12
K55	0,12
N80	0,10
L80 Type 1	0,10
L80 Chrome	0,10
C90	0,10
R95	0,09
T95	0,09
P110	0,08
Q125	0,07

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If the grade of the material is unknown but is not high-hardening, the hardening index can alternatively be determined from the following correlation.

$$n = 0{,}169\ 3 - k_n f_y \tag{13}$$

where f_y has units of MPa (psi) and

f_y is the yield strength of a representative tensile specimen;

k_n is the stress conversion factor, equal to $1{,}18 \times 10^{-4}$ MPa^{-1} for SI units and 8.12×10^{-7} psi^{-1} for USC units;

n is the dimensionless hardening index used to obtain a curve fit (see B.2.3.3) of the true stress-strain curve derived from the uniaxial tensile test.

The effort expended to determine n should be weighed against the fact that the formula for ductile rupture is relatively insensitive to this quantity for commonly used Oil Country Tubular Goods (OCTG). However, if a high-hardening material such as duplex steel is used, it is important to determine n to avoid a non-conservative rupture strength prediction. Values of n for these materials can be as high as 0,30.

7.3.3 Determination of the burst strength factor, k_a

7.3.3.1 General

The burst strength factor k_a quantifies the impact that the material toughness has on ductile rupture when a crack of depth a_N is present. The value of k_a does not need to be determined for each pipe order; instead, it is recommended that k_a be determined for a fixed tubular product line with a fixed process control plan. For a material with high material toughness, k_a will be 1,0 or lower, and the influence the crack has on the ductile rupture pressure will be no greater than the depth of the crack. However, for a pipe material with lower material toughness, k_a can be larger, say 2,0, so that the penalty from having the crack is as though the crack had twice its actual depth.

When k_a has not been determined for the pipe material, use a k_a value of 2,0. The value of k_a has been measured to be 1,0 for quenched and tempered (martensitic structure) pipe and for 13Cr products. The value of k_a can be established for a specific pipe material based on testing. One of two methods presented below can be used to calculate k_a.

7.3.3.2 Analytical method for determining k_a

The following procedure should be used.

a) Construct a finite element model of a pipe with three separate cases of crack depth: zero, 5 %, and 12,5 %. Model the crack as an infinitely long, longitudinal crack on the ID of the pipe. In the finite element model, use the specified pipe wall thickness (do not reduce the pipe wall for manufacturing eccentricity) and a typical stress-strain curve for the material being analysed.

b) Use the finite element model to simulate applying internal pressure to the pipe model in order to calculate the value of the J-integral of the pipe as a function of internal pressure (see B.7.2 for examples).

c) Experimentally measure the critical J_{1c} value of the pipe material in air. J_{1c} is a parameter similar to K_{1c}, but based on a different type of test. See ASTM E1152-95[15] for the precisely defined test methodology.

d) Terminate each of the finite element J-integral curves at the critical value of J_{1c} measured in the test. The internal pressure corresponding to this terminal point (where the J-integral equals J_{1c}) represents the rupture pressure in the presence of the crack, for a material with toughness reflected by J_{1c}.

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e) Next, divide the rupture pressure for pipe with a crack depth 5 % by the rupture pressure for pipe with no crack, using the finite element results combined with the J_{1c} measurement. Next, set this ratio equal to $(1\text{-}k_a a/t)$ where a/t is the ratio of the crack depth to the specified pipe wall thickness (i.e. 5 % in this case). Solve this formula for the value of k_a.

f) Repeat the above calculation using the finite element model results for the crack with 12,5 % depth.

g) Average the two values of k_a from steps e) and f) and use the average in the rupture formula.

7.3.3.3 Experimental method for determining k_a

An alternative way to measure k_a in lieu of the J_{1c} measurement and the finite element calculation is to conduct full-scale pipe burst tests (see Annex C for guidance on rupture test procedure) using a pipe with no measurable crack-like imperfection, another pipe with a crack-like imperfection of 5 % depth, and another pipe with a crack-like imperfection of 12,5 % depth. Then construct the ratios of the rupture pressures as described above and calculate k_a. The limitation and difficulty with this approach is that it is not valid unless the imperfection is sharp, and crack-like. A mechanical or EDM notch is not adequate for this purpose. This means that the crack-like imperfection needs to be generated either as part of the pipe manufacturing process or else through fatigue precracking. In general, the finite element approach combined with the J_{1c} measurement is easier to pursue.

7.3.3.4 Sensitivity of k_a

It turns out that k_a is a weakly sensitive parameter in regard to the grade of the pipe; that is, k_a primarily depends on the manufacturing process and does not vary much by grade within a fixed process. This is understandable since k_a only represents a potential amplification of the pipe's response to the presence of the crack while being loaded to rupture. Because of this, it is recommended that k_a only be determined for a specific grade of product and not for specific sizes or orders of product.

7.4 Design formula for capped-end ductile rupture

Minimum ductile rupture of a tube is defined by:

$$p_{iR} = 2k_{dr}f_{umn}(k_{wall}t - k_a a_N)/[D - (k_{wall}t - k_a a_N)] \quad (14)$$

where

a_N is the 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);

D is the specified pipe outside diameter;

f_{umn} is the specified minimum tensile strength;

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

k_{wall} is the factor to account for the specified manufacturing tolerance of the pipe wall. For example, for a tolerance of –12,5 %, k_{wall} = 0,875;

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n is the dimensionless hardening index used to obtain a curve fit (see B.2.3.3) of the true stress-strain curve derived from the uniaxial tensile test;

p_{iR} internal pressure at ductile rupture of an end-capped pipe;

t specified pipe wall thickness.

The value selected for k_{dr} renders p_{iR} the average of rupture pressures predicted using Tresca's yield condition and von Mises' yield condition.

The factor k_{wall} addresses minimum pipe body wall thickness without considering imperfections. This value may be adjusted if minimum wall is guaranteed by a particular process or purchasing agreement.

Crack-like imperfections are accounted for by a_N. The term $k_a a_N$ represents a further reduction in minimum wall thickness associated with crack-like imperfections which are outside the sensitivity setting of the inspection equipment and assumed coincident with the location of minimum wall thickness. This stacking of minimum wall thickness and a crack-like imperfection depends on the frequency of occurrence of thin wall and the frequency of occurrence of sharp-bottomed imperfections approaching the depth of the inspection threshold.

For the deterministic calculation of rupture pressure, it is necessary to calculate a conservative ductile rupture design pressure. In this case, the frequency of occurrence of the imperfection is set to 100 % and the imperfection depth equals the inspection threshold.

For the probabilistic calculation of rupture pressure (see Annex B), the depth of the imperfection still equals the depth of the inspection threshold, but the calculation takes account of the actual frequency of occurrence of thin wall and the actual frequency of occurrence of sharp-bottomed imperfections with depth comparable to the inspection threshold.

7.5 Adjustment for the effect of axial force and external pressure

7.5.1 General

The ductile rupture strength Formula (14) was developed for the situation of an end-capped pipe, where the axial tension is determined by the internal pressure acting on the closed inner pipe surface area. This is a special case of a more general situation where a pipe may reach a maximum internal pressure load, that is a rupture load, under the simultaneous action of arbitrary external pressure and arbitrary axial force. The combined loads together determine when the pipe is going to yield and how it will plastically deform towards the point of rupture. A fundamental criterion when this rupture load is attained can still be expressed, but this will now be a more involved formula governed by the formulation of the von Mises or Tresca yield surface in terms of axial stress, radial stress and hoop stress.

Moreover, rupture is the prevailing failure mechanism only if the axial force is not too large. For large axial tension and smaller internal over-pressure, a maximum axial load (a precursor to necking and axial splitting of the pipe) is reached before the maximum pressure phenomenon occurs.

Below, formulae for both rupture and necking under combined loads are described, together with a criterion to identify which phenomenon occurs first. The formula is given in terms of "effective axial force" associated with "effective axial stress" defined in A.1.3.2.4. For effective axial force, these approximate formulae are very accurate when compared to the exact theoretical formula[38]; performance against combined loading test data is given in B.6.2.

For negative values of effective axial force, i.e. effective axial compression, the pipe can buckle as a column, depending on the quality of lateral support. If buckling is adequately suppressed, the formula for rupture under combined loads is valid also for effective axial compression. However, for higher values of effective axial compression, it is the phenomenon of local buckling of the pipe wall ("wrinkling") that presents the governing failure mechanism. Therefore, there exists a value of effective axial compression that limits the validity of the exact combined loading rupture formula.

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