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Gas cylinders — Methods for establishing acceptance/rejection criteria for flaws in seamless steel and aluminium alloy cylinders at time of periodic inspection and testing

Bouteilles à gaz — Méthodes d'établissement des critères d'acceptation/de rejet des défauts dans les bouteilles en acier et en alliages d'aluminium, sans soudure, lors des contrôles et essais périodiques

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Foreword

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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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 22694 was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 4, *Operational requirements for gas cylinders*.

Introduction

Seamless steel cylinders and seamless aluminium-alloy cylinders used to transport high pressure gases are required to meet safety requirements based on ISO standards and the requirements of national authorities. These requirements cover the design, materials, manufacturing, initial inspection and testing, and periodic inspection and testing of the cylinders. As part of these requirements, the cylinders need to be periodically inspected and tested at regular intervals during their lifetime.

Periodic inspection and testing has traditionally been performed by a combination of visual inspection (internal and external) and hydrostatic pressure testing (sometimes including volumetric expansion measurements during pressurization). Using these traditional methods of retesting, the cylinders are rejected due to excessive volumetric expansion, excessively large surface flaws detected by visual examination, leaking or bursting. The maximum allowable size of surface flaws to cause rejection of the cylinders was essentially qualitative and was established from past service experience. None of the rejection criteria were based on quantitative assessment of the cylinder's performance or mechanical characteristics.

However, recently, methods of periodic inspection and testing the cylinders using ultrasonic inspection have been developed. These new retesting methods permit the quantitative determination of the cylinder wall thickness and the size of the flaws that are present in the cylinders. The ISO standards for periodic inspection and the requirements of certain national authorities permit the use of ultrasonic test methods for retesting seamless steel and aluminium-alloy cylinders. These ultrasonic test methods permit the quantitative determination of the size of any flaws that are detected in the cylinders. However, to use the ultrasonic test methods, it is required that quantitative "allowable flaw sizes" be established to set acceptance/rejection limits for the cylinders at the time of periodic inspection and testing.

NOTE The main conclusions and acceptance/rejection criteria are based on those provided by the United States Department of Transportation (DOT-designed cylinders) that have a working pressure to test-pressure ratio of 3:5. Application to ISO-designed cylinders, which use a working pressure to test-pressure ratio of 2:3, needs a further calculation.

Gas cylinders — Methods for establishing acceptance/rejection criteria for flaws in seamless steel and aluminium alloy cylinders at time of periodic inspection and testing

1 Scope

The aim of this Technical Report is to establish a technical basis for developing quantitative, allowable flaw sizes and for setting acceptance/rejection limits for cylinders at the time of periodic inspection and testing based on the performance and mechanical properties of the cylinders.

2 Normative references

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

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

3 Terms and definitions

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

3.1
allowable flaw size
largest flaw that will not grow to the critical flaw size during the periodic inspection and testing interval of the cylinder

3.2
burst
opening of the cylinder due to the internal pressure with substantial extension of the flaw

3.3
cluster of pits
small, approximately round, flaws that are close together in a limited area

3.4
corrosion
general loss of wall thickness of either the interior or exterior surface of the cylinder, or localized corrosion which may form a narrow longitudinal or circumferential line or strip, or isolated craters or pits that are almost connected in a line

3.5
crack
split in the metal

3.6
critical flaw size
CFS
flaw size that causes the cylinder to fail at a designated pressure

3.7
cut/gouge
sharp impression on the exterior of the cylinder where metal has been removed or redistributed and whose depth exceeds 5 % of the cylinder wall thickness

3.8
failure by plastic collapse
failure of the cylinder containing a flaw due to internal pressure in the cylinder by failure of the remaining ligament below the flaw without substantial extension of the flaw

3.9
fatigue crack growth rate
average flaw growth amount for each cycle of pressure loading

3.10
fracture
unstable extension of a flaw in the cylinder

3.11
fracture toughness
generic term for measure of resistance to extension of a crack

3.12
leak
release of gas pressure from the cylinder without significant extension of the flaw

NOTE This can occur due to internal pressure or due to corrosion.

3.13
local thin area
LTA
area of reduced wall thickness, the length and width of which are approximately equal

NOTE LTAs can be circular or rectangular.

3.14
notch
nominally a two-dimensional, long, narrow flaw with the width much smaller than the length

3.15
periodic inspection and testing
reference to a visual and/or ultrasonic examination and/or pressure test

3.16
residual strength factor
RSF
ratio of the failure pressure of a cylinder containing a flaw to the failure pressure of the same cylinder without a flaw

4 Cylinder symbols

A flaw area

a flaw depth

a_i	initial flaw depth
C	flaw width (circumferential dimension of the flaw)
D	nominal outside diameter of the cylinder
da/dN	fatigue crack growth rate
ID	inside cylinder diameter
K_{IC} (J)	fracture toughness obtained from J integral test method
L	flaw length (longitudinal dimension of flaw)
M_p	stress magnification factor for “part through flaw”
M_t	Folias stress magnification factor for “through-wall flaw”
N	number of pressure cycles
p_b	failure pressure for cylinder without a flaw
p_f	failure pressure for a cylinder with a flaw
p_f/p_b	residual strength factor[1)]
p_h	cylinder test pressure
p_s	cylinder working pressure
R_e	minimum guaranteed value of yield strength
R_m	actual value of tensile strength as determined by tensile test
$(R_m + R_e)/2$	flow stress
R_t	remaining wall thickness ratio (t_{mm}/t)
t	measured minimum wall thickness
t_a	actual wall thickness at the flaw
t_d	calculated minimum design wall thickness
t_{mm}	minimum ligament (material below the flaw) thickness

5 Technical approach

In this Technical Report, the performance of selected cylinders was evaluated based on the principles of structural integrity analysis. The effect of various types and sizes of flaws on the performance of seamless steel and aluminium-alloy cylinders was evaluated by analytical modelling that was verified by using data from other studies that involved testing of steel and aluminium-alloy cylinders containing artificially induced flaws.

1) Residual strength factor is sometimes referred to as the failure pressure ratio.

The periodic inspection of seamless cylinders requires that allowable flaw sizes be established for each type of flaw. Typical flaws that can occur in high-pressure seamless gas cylinders during service are cuts or gouges, cracks, general corrosion, local corrosion (LTA) and chain/line/pitting corrosion. To establish allowable flaw sizes, an assessment of typical flaws that (e.g. of an LTA) occur in seamless cylinders was carried out using the analytical procedures described in the API *Recommended Practice for Fitness-for-Service* (API RP 579, hereafter referred to as API 579). The analytical assessments were subsequently verified by experimental testing.

In using these procedures, first the critical flaw size(s) (CFS) are determined. The CFS is defined as the size (e.g. depth and length or area) of the flaw that will cause the cylinders to fail at a specified pressure, such as the test pressure or the working pressure of the cylinder. API 579 was used to calculate the CFS for a range of cylinder sizes and strength levels. Next, the allowable flaw sizes are determined by adjusting the CFS to account for any time-dependent degradation that can occur in service, such as crack growth by fatigue or corrosion.

Firstly, to determine the CFS, the procedures described in API 579 were used to predict, by analysis, the effect of various sizes of LTAs, pits, notches and cracks on the calculated cylinder burst pressure for selected sizes and strength levels of cylinders. Then, to verify the API 579 analysis procedures, experimental data from a number of hydrostatic burst tests on selected cylinders with various sizes of flaws were compared with the analytical results. These results showed that the analysis conducted according to API 579 reliably estimated the actual measured burst pressure of the cylinders for all flaw sizes and types.

CFSs were determined for various types of flaws at (1) the designated working pressure and (2) the hydrostatic test pressure of the cylinder. This establishes the CFS (depth versus area or length) for each type of flaw in any cylinder. The CFS calculated at the designated working pressure predicts the size of the flaws that could be expected to cause the cylinder to fail in service. The CFS calculated at the hydrostatic test pressure predicts the size of flaws that could be expected to cause the cylinder to fail during the hydrostatic pressure test.

After calculating the CFS to cause failure of the cylinders at both the test and working pressures, the allowable flaw sizes to be used as the acceptance or rejection criteria during periodic inspection and testing were established for a wide range of cylinder types and strength levels. This was done by modifying (reducing) the size of the CFS for each cylinder by adjusting for time-dependent degradation, such as fatigue crack growth or corrosion that may occur during the use of the cylinder. In the preparation of this Technical Report, only the effects of fatigue crack growth were evaluated. The fatigue procedure that was used to make this adjustment involved 3 500 cycles (approximately once per day filling for the 10 year retest interval) at the cylinder's designated working pressure. This resulted in the allowable flaw size that may be used to establish the acceptance or rejection criterion for the cylinders during periodic inspection and testing. The final acceptance or rejection criteria that are used during periodic inspection and testing may also take into account other factors, such as the capability of the inspection instruments and procedures.

The allowable flaw sizes are based on the assumption that there is no free moisture in the interior of the cylinder and consequently no risk of corrosion.

6 Modelling and analysis of flaw sizes

6.1 Basis and theory

The approach used to define allowable flaw sizes for seamless cylinders was to determine the effect of various types and sizes of flaws on the performance of the cylinders. In particular, the reduction in the failure pressure of the cylinders containing flaws was determined by analytical modelling. These analytical results were then verified by using data from studies involving the experimental testing of selected cylinders containing flaws.

To evaluate the significance of flaws in cylinders, the principles of structural integrity analysis are used. Several general theoretical, empirical or semi-empirical methods of analysis have been developed to model flaws in pressure vessels, such as cylinders, and to evaluate the significance of the flaws. The purpose of these methods of analysis is to determine how much the failure pressure of a cylinder containing a flaw is reduced compared to a similar cylinder that does not contain any flaws. Failure of the cylinder may occur by bursting, by fracture, by leaking or other failure modes. These methods of analysis can be used to make an assessment of the current state of the cylinder, that is, the current failure pressure of the cylinder. These methods of analysis can also be used to determine a projected future state of the cylinder due to increases in the size of the flaws over time by such mechanisms as fatigue, corrosion, stress corrosion, or other time-dependent degradation.

After reviewing the methods of analysis that have been developed to evaluate the significance of flaws in pressure vessels, the methods of analysis described in API 579 were chosen to evaluate the cylinders used in the preparation of this Technical Report and to develop CFS and allowable flaw sizes for seamless cylinders. The fitness-for-service method of analysis provides a quantitative evaluation of cylinders containing flaws to determine their suitability for continued use.

The fitness-for-service method of analysis can be used to evaluate all types of flaws commonly found in cylinders. Methods of analysis are available for analysing various types of flaws such as general corrosion, localised corrosion area (LTA), widespread pitting, localized pitting, cracks and crack-like flaws. Brittle fracture, fatigue cracking and environmental cracking can be evaluated.

6.2 Summary of the fitness-for-service method of analysis

6.2.1 Application of API 579 fitness-for-service method of analysis

The application of the API 579 fitness-for-service method of analysis requires the following steps:

1) identification of the type of flaw (crack, LTA, pit, etc.) and the type of damage that caused the flaw (corrosion, fatigue, cracking, cuts, gouges, etc.);

2) identification of the failure mode (brittle fracture, burst, leak);

3) selection of the specific method of analysis (fracture analysis, burst analysis, leak analysis, etc.);

4) obtaining the necessary data (material properties, applied stresses, flaw characterization and size, etc.);

5) selection of the level of assessment;

6) selection of the appropriate acceptance criteria;

7) evaluation of the remaining life of cylinder due to enlargement of the flaws.

6.2.2 Step 1, identification of type of flaw

The types of flaws that can occur in seamless steel cylinders and aluminium-alloy cylinders have been identified in ISO 6406, and ISO 10461 respectively. The types of flaws that have been identified are cracks, notches, gouges, general corrosion, localised corrosion area (e.g. corrosion of an LTA), pitting corrosion including isolated pit and multiple pits (i.e. line corrosion), arc burns and fire damage.

However, in this Technical Report, the only flaws evaluated are

— LTA,

— cracks,

— notches,

— general/local corrosion, and

— corrosion pits.

Therefore, in this Technical Report, the only types of damage evaluated are from flaws caused either by corrosion or mechanical damage subsequently propagated by fatigue.

6.2.3 Step 2, identification of failure mode

The failure modes that can cause seamless cylinders to fail in service are burst or leak type. Cylinders can fail by bursting when a flaw of sufficient size is present in the cylinder wall. The failure stress is dependent on the material's fracture toughness and flow strength properties. For relatively high-toughness material, which is the case for the high-pressure cylinders, the cylinder burst stress is primarily controlled by flow stress. Cylinders can fail by leaking when the flaw is sufficiently deep such that the remaining wall ruptures. Cylinders can fail in service by fracturing or fragmenting when the combination of a sufficiently large flaw and a high enough wall stress exceeds the fracture toughness of the cylinder.

6.2.4 Step 3, selection of specific method of analysis

Each of the different failure modes can be reliably evaluated by the fitness-for-service analysis procedures. However, each failure mode (burst or leak) must be analysed by a different analytical model. The selection of which failure mode is most likely to occur depends on the cylinder design, its material properties, and the size of the flaws in the cylinder. The only failure mode evaluated was failure by bursting due to the internal pressure in the cylinders.

6.2.5 Step 4, obtaining necessary data

The data required to conduct the fitness-for-service analysis of flaws in cylinders are (1) the material properties (i.e. yield strength, tensile strength, fracture toughness, etc.); (2) the applied stress due to the pressure in the cylinder; and (3) the size, shape and location of the flaws to be evaluated. Only applied stresses caused by the internal pressure in the cylinders are considered. When exact values of some of the necessary data are not available for the specific cylinder being evaluated, the necessary data may have to be assumed or generic data for a typical cylinder may have to be used.

6.2.6 Step 5, selection of level of assessment

The selection of the level of assessment depends on the available data and on the accuracy of the evaluation that is required. For example, the API 579 methods of analysis, Section 5 (Assessment of Local Metal Loss) permit three levels of assessment depending on the available data and on the accuracy of the evaluation that is required.

The Level 1 assessment requires a minimum amount of data on the flaw size, the applied stress and the material properties. This level of assessment is the easiest to use, but the predicted failure pressure of a cylinder with a specified flaw size may be significantly less than the actual measured failure pressure of the flawed cylinder.

The Level 2 assessment requires additional, more detailed data than the Level 1 assessment for the flaw size, the applied stress and the material properties. This level of assessment uses more calculations that are complex and gives a more exact prediction of the failure pressure of the cylinder. That is, the predicted failure pressure of a cylinder with a specified flaw size is closer to the actual measured failure pressure of the flawed cylinder.

The Level 3 assessment requires the use of advanced stress analysis and material modelling procedures and exact measurements of the flaw size. This level of assessment generally results in a good prediction of the failure pressure of the cylinder. That is, the predicted failure pressure of a cylinder with a specified flaw size is very close to the actual measured failure pressure of the flawed cylinder. However, because of the increased demands for additional data and the increased complexity of the calculations, the Level 3 assessment is used only in very demanding and specialized applications.

With regard to seamless cylinders, the Level 1 assessment procedures, which are conservative and concise, were used for the flaw size analysis.

6.2.7 Step 6, selection of appropriate basis for the acceptance criteria

The next step in using the fitness-for-service assessment procedures is the choice of the basis for the acceptance criteria. The basis for the acceptance criteria is chosen for each specific case that is analysed. The acceptance criteria may be (1) the maximum allowable stress, (2) the RSF, or (3) the failure assessment diagram.

The maximum allowable stress criterion is used where the design is based on a specified fraction of the yield strength or tensile strength. This is the criterion used to specify the wall thickness in the design of new cylinders. This criterion has limited use in the fitness-for-service analysis because suitable maximum allowable stress levels cannot easily be established for cylinders containing flaws. The only place where the criterion can be used is in evaluation of general corrosion where the stress in the remaining wall can be calculated and related to the maximum allowable wall stress.

The RSF can be used for the analysis of most types of flaws in cylinders. The acceptance criterion is then specified as a fixed value of RSF. This was the criterion primarily used in the preparation of this Technical Report.

For crack-like flaws, it is necessary to use the failure assessment diagram criterion.

Cylinders containing crack-like flaws can fail either by unstable fracture or by plastic collapse. Plastic collapse occurs in cylinders with relatively large flaws that are made from high-toughness materials. Most seamless steel gas cylinders containing crack-like flaws fail by the plastic collapse mechanism. The steel cylinders containing flaws that were evaluated in this Technical Report failed by plastic collapse. (This statement is valid for the flaws that are in the acceptance range in this Technical Report.)

6.2.8 Step 7, evaluation of remaining life of cylinder

After an assessment is made of the present state of the cylinder (i.e. the predicted failure pressure of the cylinder) containing a flaw, the fitness-for-service method of analysis may also be used to assess the remaining life of the cylinder, if required. The remaining-life assessment is used to account for any increase in the size of existing flaws during the anticipated service, for example by corrosion or fatigue. This assessment is used (1) to establish presently allowable flaw sizes and (2) to define appropriate retest intervals. An assessment of the effect of fatigue on the size of existing flaws in cylinders was made to establish allowable flaws sizes for setting retest requirements.

7 Experimental results

Steel and aluminium-alloy cylinders containing machined flaws were tested by monotonic or cyclical pressurization until failure occurred as part of a project being conducted by ISO/TC 58/SC 4/WG 1 on rejection criteria for metal cylinders.

Cylinders tested by monotonic pressurization contained machined flaws mostly on the exterior of the cylinder (OD flaws). A few of the cylinders that were tested by monotonic pressurization had flaws machined on the inside surface (ID flaws). The cylinders that contained OD machined flaws had flaws that simulated notches, round LTA, rectangular LTA, and pits (small round flaws). All the machined ID flaws simulated round LTA-type flaws. The simulated flaws on the cylinders that were tested by cyclic pressurization all had OD notch-type flaws. The results of these tests were used (1) to verify that the API 579 method of analysis can be reliably used to predict the failure pressure of cylinders containing flaws, (2) to verify the calculated CFS for cylinders and (3) to verify the calculated allowable flaw sizes for cylinders. The test results for the steel cylinders tested as part of the ISO/TC 5/SC 4/WG 1 programme are shown in Tables A.1, A.2, A.3, and A.4 of Annex A.

As part of earlier work conducted by ISO/TC 58/SC 3/WG 14 on toughness and acceptance levels of steel cylinders with strength levels from less than 750 MPa to more than 1 250 MPa, several hundred monotonic hydrostatic, flawed-cylinder burst tests were conducted to evaluate the fracture performance of a wide range of steel cylinders [5]. Each test cylinder had a longitudinal notch machined in the external wall of the cylinder (see Figures 1a and 1b).

a) Circumferential view **b) Longitudinal view**

Key

r_1 tip radius (0,2 mm)

r_2 radius (35 mm)

L flaw length

a flaw depth

Figure 1 — Longitudinal notch geometry used in the tested steel cylinders

In the ISO/TC 58/SC 3/WG 14 test programme [5], the cylinders tested ranged in tensile strength from 700 MPa to 1 400 MPa. The cylinders tested were divided into five groups of materials based on the tensile strength range of the material. The cylinders ranged in outer diameter (D) from 140 mm to 240 mm, in thickness (t_d) from 3,8 mm to 14,4 mm, and had flaw sizes (longitudinal machined notches) that ranged in depth from 20 % to 90 % of the actual wall thickness and in length from four times the cylinder wall thickness to 20 times the cylinder wall thickness.

In the ISO/TC 58/SC 3/WG 14 test programme [5], steel cylinders were tested to failure by monotonic pressurization. In the fitness-for-service analysis using API 579 procedures to calculate critical flaw sizes, the critical flaw sizes are calculated at specified pressures. For the analysis that was done, the specified pressures chosen were (1) the working pressure and (2) the test pressure. Therefore, to verify the analysis used (i.e. to determine if the analysis is reliable), the calculated values are compared with the experimental values. For this purpose, the only relevant experimental data is test data that was done at the same pressure as the pressure used in the analysis, that is, either their working pressure or the test pressure. Thus, only experimental data points where the cylinders failed at either working pressure or test pressure were chosen. The other test data where the cylinders failed at different pressure were not used as they were not relevant. The selected test results for the steel cylinders tested as part of the ISO/TC 58/SC 3/WG 14 programme that were used are shown in Table A.5 and A.6 of Annex A.

Similarly, using the same concept, ISO TC 58/SC 3/WG 19 has developed data for aluminium-alloy cylinders.

8 Verification of the flaw size analysis

8.1 Seamless steel cylinders

The API 579 fitness-for-service method of analysis provides a sound technical basis for evaluating the significance of flaws in any type of pressure vessel. To demonstrate that these methods of analysis can be applied reliably to the evaluation of flaws in seamless cylinders, a limited number of seamless steel cylinders containing flaws of different types and sizes were tested hydrostatically to failure by bursting. To verify that the API 579 method of analysis reliably predicts the performance of cylinders containing flaws, the results of these burst tests were compared with the burst pressure predicted by the API 579 analysis results.

The preliminary analysis showed that the failure of the steel cylinders that were tested could be evaluated by calculating the RSF for the cylinders containing flaws. For these cylinders, the fracture toughness was sufficiently high that failure of the cylinders containing flaws was by bursting when the stress in the cylinder wall caused failure by plastic collapse as the internal pressure increased.

For this verification analysis, both LTA-type flaws and notch-type flaws were evaluated. An LTA-type flaw is a flaw that represents a typical area of wall thickness reduction due to corrosion in the cylinder. The notch-type flaw used in this Technical Report is V-shaped, and the length of the flaw is many times greater than the width of the flaw. This type of flaw represents a crack-like flaw in the cylinder. For the examples analysed here, the API 579 Level 1 assessment method was found to be adequate. The stress in the cylinder wall at the location of the flaw was only caused by the internal pressure in the cylinder.

To verify the use of the API 579 procedures, the RSF was calculated for each cylinder that was tested. The RSF is defined here as the failure pressure ratio (p_f / p_b) where p_f is the failure pressure of the cylinder containing the flaw and p_b is the failure pressure of the same type and size of cylinder that does not contain a flaw.

For RSF or p_f / p_b, the ratio for Level 1 is calculated as:

$$\text{RSF} = R_t / [1-(1/M_t)(1-R_t)] \quad (1)$$

where

M_t is the Folias stress magnification factor for through-wall flaw

$$= (1 + 0{,}48\, \lambda^2)^{1/2} \quad (2)$$

where

$$\lambda = 1{,}285\, L / (D \bullet t)^{1/2} \quad (3)$$

R_t is the remaining thickness ratio $= t_{mm} / t$ (4)

The following provides a theoretical background for Equation 1.

The failure hoop stress in the presence of a flaw is given by the following equation:

$$\sigma_f = \sigma_{flow} / M_p \quad (5)$$

where M_p is the stress magnification factor for part through flaw.

M_p is given by the following equation:

$$M_p = [1-a/(t \bullet M_t)] / (1-a/t) \quad (6)$$

where M_t is the stress magnification factor for through-wall flaw of length L.

M_t can be obtained from Equation (2) above.

The ratio, σ_f / σ_{flow}, is defined as RSF.

Therefore from Equation (5),

$$\text{RSF} = 1/ M_p = [(1 - a/t) / (1-(a/t \bullet M_t))] \quad (7)$$

$$R_t = t_{mm} / t = (t - a) / t = 1-a/t \quad (8)$$

$$a/t = 1- R_t \quad (9)$$

Substituting a/t in terms of R_t in Equation (7) results in Equation (1).

The cylinders used in the verification test programme were designed and fabricated in accordance with the requirements of US DOT Exemption 9421 [12]. The test results for the cylinders tested in the verification programme are shown in Table 1.

Table 1 — Results of steel cylinder tests with flaw

Cylinder No. (See NOTE 1)	Flaw description	Measured min. wall thickness t mm	Flaw length L mm	Flaw width C mm	Flaw depth a mm	Burst pressure bar	Measured RSF (See NOTE 2)	Calculated RSF (See NOTE 3)
1	Unflawed burst	6,3	—	—	—	693 [a]	—	—
2	Unflawed burst	7,1	—	—	—	783 [a]	—	—
3	Longitudinal notch	6,4	64,3	—	0,66	672	0,91	0,95
4	Longitudinal notch	6,9	64,3	—	1,32	641	0,87	0,9
5	Longitudinal notch	6,6	64,3	—	1,98	610	0,83	0,84
6	Longitudinal notch	6,4	64,3	—	2,64	576	0,78	0,77
7	Longitudinal notch	6,8	64,3	—	3,30	572	0,78	0,68
8	Longitudinal notch	6,9	64,3	—	0,33	738	1	0,98
9	Longitudinal notch	7,0	64,3	—	0,66	745	1,01	0,95
10	Longitudinal notch	6,8	64,3	—	0,99	724	0,98	0,93
11	Rectangular LTA	6,9	64,3	44,5	0,33	697	0,94	0,98
12	Rectangular LTA	7,4	64,3	44,5	0,66	738	1	0,96
13	Rectangular LTA	7,2	64,3	44,5	0,99	697	0,94	0,94
14	Rectangular LTA	7,1	64,3	44,5	1,32	683	0,93	0,91
15	Rectangular LTA	7,4	64,3	44,5	1,98	717	0,97	0,86
16	Rectangular LTA	7,4	64,3	44,5	2,64	648	0,88	0,8
17	Rectangular LTA	7,0	64,3	44,5	3,30	559	0,76	0,72

NOTE 1 Cylinder ID = 222 mm (nominal).

NOTE 2 Measured RSF = measured burst pressure with flaw/average burst pressure without flaw (738 bar).

NOTE 3 Calculated RSF using Equation (1).

NOTE 4 Cylinder specifications:

Material = modified AISI 4130 quenched and tempered steel

Size D = 235 mm

R_m = 1 070 MPa to 1 207 MPa (typical)

R_e = 966 MPa to 1 103 MPa (typical)

Elongation = 12 %

K_{IC} (J) ⩾ 93,5 MNm – 3/2

t_d = 6,6 mm

p_s = 310 bar

p_h = 467 bar

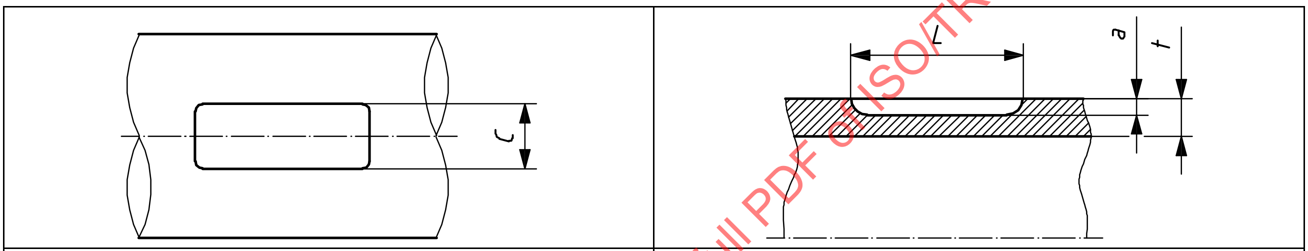
NOTE 5 All cylinders burst at the notches or the LTAs.

[a] The average burst pressure for a cylinder without a flaw was calculated without taking into account the variation in the measured minimum wall thickness of the cylinder. If variations in the measured minimum wall thicknesses had been taken into account, the measured RSF values would have been within 1,5 %.

Two cylinders in Table 1 (No. 1 and No. 2) without flaws were hydrostatically burst to establish the burst pressure (p_b) to be used to calculate the measured RSF (or p_f/p_b). Cylinder No. 1 burst at 693 bar psi pressure, and cylinder No. 2 burst at 783 bar psi pressure. This gave an average value for an unflawed cylinder of 738 bar ± 24 bar. This value will be used as the denominator to calculate the ratio p_f/p_b, which is the measured RSF for the tested cylinders.

Test cylinders numbered 3 through 10 in Table 1 had longitudinal notches machined on the outside surface. Table 1 shows the length (L) and depth (a) dimensions of the machined notches (see Figure 1a). The cylinders were hydrostatically burst. The measured burst pressure and ratio of the failure pressure of the flawed cylinder to the failure pressure of the unflawed cylinder (p_f/p_b), which is the measured RSF value, are also shown in Table 1. It should be noted that all cylinders burst at the machined notches.

Test cylinders numbered 11 through 17 had rectangular LTAs machined on the outside surface (see Figures 2a and 2b). Table 1 shows the LTA dimensions of the tested cylinders. The cylinders were hydrostatically burst. The measured burst pressure and ratio of the failure pressure of the flawed cylinder to the failure pressure of the unflawed cylinder (p_f/p_b), which is the measured RSF value, are shown in Table 1. It should be noted that all the cylinders burst at the machined LTA.



a) Top view

b) Longitudinal view

Key

L flaw length

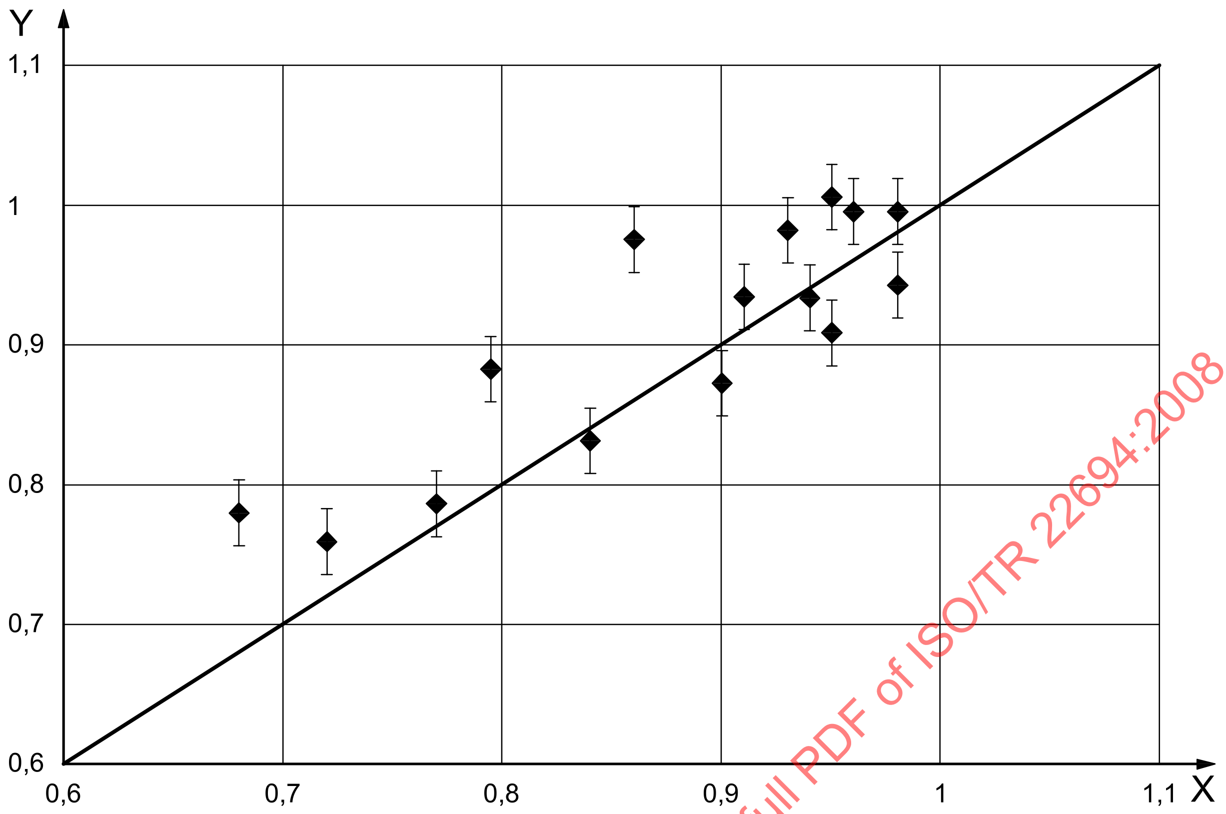
a flaw depth

t cylinder wall thickness

C flaw width

Figure 2 — Rectangular LTA geometry used in the tested cylinders

The RSF values of each tested cylinder were calculated using Equation (1). The ratio of the measured failure pressure (p_f) of a cylinder with a flaw to the measured failure pressure of a cylinder without a flaw (p_b = 738 bar), that is (p_f/p_b) is defined as the measured RSF for the tested cylinders. These results are shown in Table 1. A comparison of the measured RSF to the calculated RSF is shown in Figure 3 for all cylinders that were tested. The agreement between the calculated and measured RSF values confirms that, for seamless steel cylinders, the RSF analysis reliably predicts the pressure at which the cylinders will fail by bursting. This analysis is suitable for use to evaluate the effects of notches, cracks, LTAs, clusters of pits and general wall thinning due to corrosion. Therefore, the API 579 method of analysis can be used to calculate the CFS for these types of flaws in seamless steel cylinders.



Key

X calculated RSF (p_f/p_b)

Y measured RSF (p_f/p_b)

Figure 3 — Verification of API 579 analysis for seamless steel cylinders covering a range of compositions

8.2 Seamless aluminium alloy cylinders

As in the case for the steel cylinders described in 8.1, the API fitness-for-service method of analysis was used to evaluate the significance of flaws in seamless aluminium-alloy cylinders. API 579 Level 1 (flow-strength control) and Level 2 (fracture-toughness control) analyses were used by calculating the RSF for cylinders containing flaws in aluminium cylinders. For aluminium-alloy cylinders manufactured according to ISO 7866 [2], it was found that Level 1 analysis was reliable up to values of flaw depth, a/t, of 0,5. For flaw depths, a/t, greater than 0,5, the fracture toughness of the material should be taken into account in accordance with the above-referred Level 2 analysis.

The RSF values of each tested cylinder were calculated using Equation (1). The ratio of the measured failure pressure (p_f) of a cylinder with a flaw to the measured failure pressure of a cylinder without a flaw (p_b), that is (p_f/p_b), is defined as the measured RSF for the tested cylinders. The results for aluminium alloy AA6061 cylinders are shown in Table 2. A comparison of the measured RSF to the calculated RSF is shown in Figure 4 for the aluminium alloy AA6061 cylinders that were tested. The results for aluminium alloy AA7032 cylinders are shown in Table 3. A comparison of the measured RSF to the calculated RSF is shown in Figure 5 for the aluminium alloy AA7032 cylinders that were tested. The agreement between the calculated and measured RSF values confirms that, for seamless aluminium alloy cylinders, the RSF analysis reliably predicts the pressure at which the cylinders will fail by bursting.

Table 2 — Results for aluminium alloy AA6061 cylinder tests with flaw

Cylinder No. (See NOTE 1)	Flaw description	Design min. wall t_d mm	Flaw length L mm	Flaw width C mm	Flaw depth a mm	Burst pressure Bar	Measured RSF (See NOTE 2)	Calculated RSF (See NOTE 3)
Cylinder diameter 111 mm, p_s = 15,27 MPa								
1	Unflawed burst	5,08	0	0	0	393	1,000	—
2	Longitudinal notch	5,08	30,48	—	2,54	324	0,825	0,792
3	Longitudinal notch	5,08	40,64	—	2,54	303	0,772	0,732
4	Longitudinal notch	5,08	35,56	—	3,30	290	0,737	0,629
5	Longitudinal notch	5,08	40,64	—	3,30	262	0,667	0,595
6	Longitudinal notch	5,08	35,56	—	4,06	255	0,649	0,441
7	Longitudinal notch	5,08	40,64	—	4,06	250	0,632	0,405
Cylinder diameter 184,2 mm, p_s = 20,68 MPa								
8	Unflawed burst	12,74	0	0	0	546	1,000	—
9	Longitudinal notch	12,74	124,46	—	8,92	235	0,431	0,414
10	Longitudinal notch	12,74	124,46	—	8,92	255	0,468	0,414
11	Longitudinal notch	12,74	124,46	—	8,92	248	0,455	0,414
Cylinder diameter 203 mm, p_s = 22,05 MPa								
12	Unflawed burst	15,3	0	0	0	66	1,000	—
13	Longitudinal notch	15,3	68 (4T)	—	12,16	390	0,591	0,445
14	Longitudinal notch	15,3	91,2 (6T)	—	12,16	279	0,423	0,373
15	Longitudinal notch	15,3	152 (10T)	—	9,12	270	0,409	0,523
16	Longitudinal notch	15,3	152 (10T)	—	10,64	223	0,338	0,414
17	Longitudinal notch	15,3	91,2 (6T)	—	12,16	270	0,409	0,373
18	Longitudinal notch	15,3	76 (5T)	—	14,44	240	0,364	0,140
19	Longitudinal notch	15,3	68 (4T)	—	14,90	274	0,415	0,078

NOTE 1 Cylinder sizes: D = 111 mm, 182 mm and 203 mm.

NOTE 2 Measured RSF = measured burst pressure with flaw/average burst pressure without flaw.

NOTE 3 Calculated RSF using Equation (1).

NOTE 4 Cylinder specifications:

Material	=	AA6061
R_m	=	350 MPa (typical)
R_e	=	300 MPa (typical)
Elongation	=	14 %
t_d	=	5,08 mm; 12,74 mm; or 15,30 mm
p_s	=	153 bar; 207 bar; or 221 bar
p_h	=	255 bar; 345 bar; or 368 bar
K_{IC} (J)	⩾	35 MNm – 3/2

Table 3 — Results for aluminium alloy AA7032 cylinder tests with flaw

Cylinder No. (See NOTE 1)	Flaw description	Measured min. wall t mm	Flaw length L mm	Flaw width C mm	Flaw depth a mm	Burst pressure bar	Measured RSF (See NOTE 2)	Calculated RSF (See NOTE 3)
Cylinder diameter 111 mm, p_s = 15,27 MPa								
1	Unflawed burst	5,11	0	0	0	546	1	—
2	Unflawed burst	5,18	0	0	0	545	1	—
3	Longitudinal notch	4,98	29,87	—	2,49	407	0,75	0,74
4	Longitudinal notch	4,9	34,32	—	2,45	386	0,71	0,71
5	Longitudinal notch	4,93	39,42	—	2,46	345	0,63	0,68
6	Longitudinal notch	4,85	33,96	—	3,15	331	0,61	0,57
7	Longitudinal notch	4,85	38,81	—	3,15	276	0,51	0,54
8	Longitudinal notch	4,88	34,14	—	3,90	303	0,56	0,38
9	Longitudinal notch	4,95	37,64	—	3,96	283	0,52	0,36
10	Longitudinal notch	4,83	38,61	—	3,86	262	0,48	0,35
11	Longitudinal notch	4,98	249,92	—	1,99	269	0,49	0,63
12	Longitudinal notch	4,93	300,09	—	1,97	276	0,51	0,62
13	Longitudinal notch + cycle	5,28	51,41	—	5,02	207	0,38	0,09
14	Longitudinal notch + cycle	5,41	107,92	—	1,84	207	0,38	0,72
15	Longitudinal notch + cycle	4,93	198,88	—	2,10	207	0,38	0,61
16	Longitudinal notch + cycle	4,98	35,31	—	4,10	207	0,38	0,34
17	Longitudinal notch + cycle	5,03	40,83	—	4,90	207	0,38	0,05
18	Longitudinal notch + cycle	5,33	21,18	—	1,57	478	0,88	0,91
19	Longitudinal notch + cycle	5,26	20,80	—	1,63	464	0,85	0,91
20	Longitudinal notch + cycle	5,31	21,76	—	2,22	401	0,74	0,86
21	Longitudinal notch + cycle	5,08	22,44	—	3,75	298	0,55	0,59
22	Longitudinal notch + cycle	5,33	22,44	—	2,18	4 054	0,74	0,86

NOTE 1 Cylinder sizes: D = 111 mm.

NOTE 2 Measured RSF = measured burst pressure with flaw/average burst pressure without flaw.

NOTE 3 Calculated RSF using Equation (1).

NOTE 4 Cylinder specifications:

Material = AA7032

R_m = 510 MPa (typical)

R_e = 440 MPa (typical)

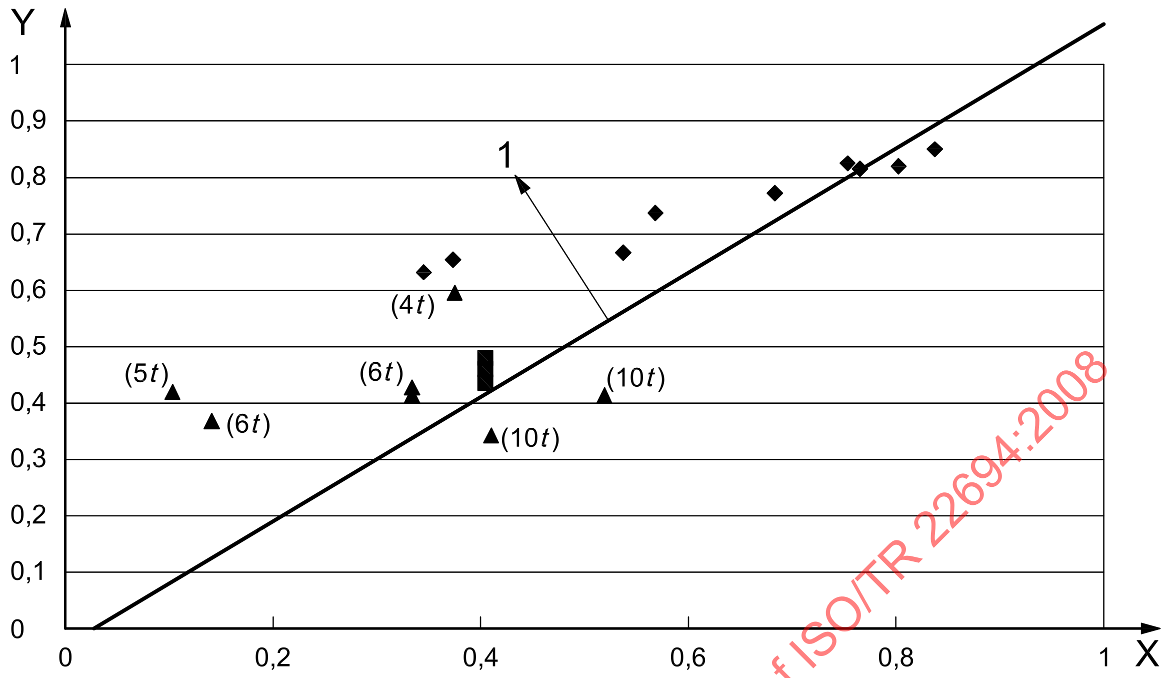
Elongation = 12 %

K_{IC} (J) ⩾ 38 MNm – 3/2

t = 5,08 mm

p_s = 207 bar

p_h = 345 bar



Key

X calculated RSF (p_f/p_b)

Y measured RSF (p_f/p_b)

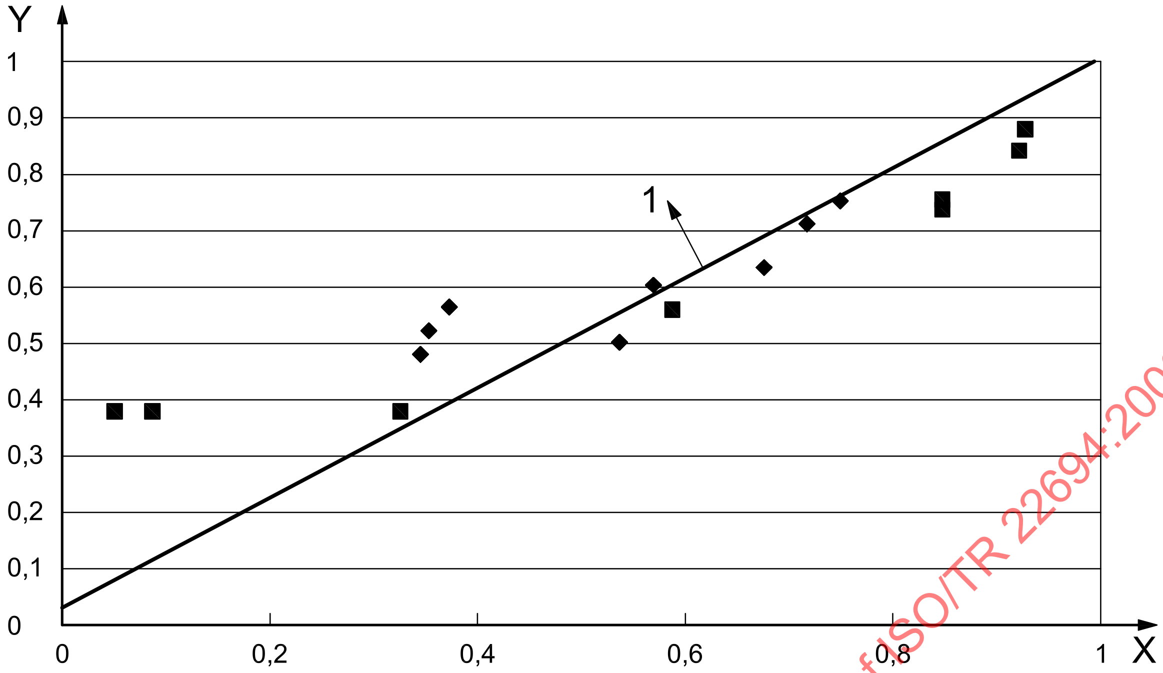
◆ 111 mm (6*t* to 8*t*) 152,7 bar

■ 184 mm (10*t*) 206,8 bar

▲ 203 mm (x*t*) 220,6 bar

1 conservative prediction

Figure 4 — Verification of API 579 analysis for aluminium alloy AA6061 cylinders



Key

X calculated RSF (p_f/p_b)

Y measured RSF (p_f/p_b)

◆ notch

■ fatigue crack

1 conservative prediction

NOTE Flaw lengths up to 10*t*.

Figure 5 — Verification of API 579 analysis for aluminium alloy AA7032 cylinders, 207 bar

8.3 Critical flaw size analysis and verification

The development of CFS requirements that can be used for the inspection of cylinders requires that the length or area and the depth of flaws that will cause the cylinder to fail at a designated pressure be established. These requirements are most conveniently shown as curves of the flaw depth (defined as a/t ratio) versus the length or area of the flaw for designated failure pressures.

As previously shown, the API 579 method of analysis can reliably be used to calculate the failure pressure of seamless steel cylinders containing various types and sizes of flaws. These methods can be used to predict, by analysis, the effect of various sizes of LTAs, cluster of pits, notches, and cracks on the failure pressure of selected sizes and strength levels of cylinders.

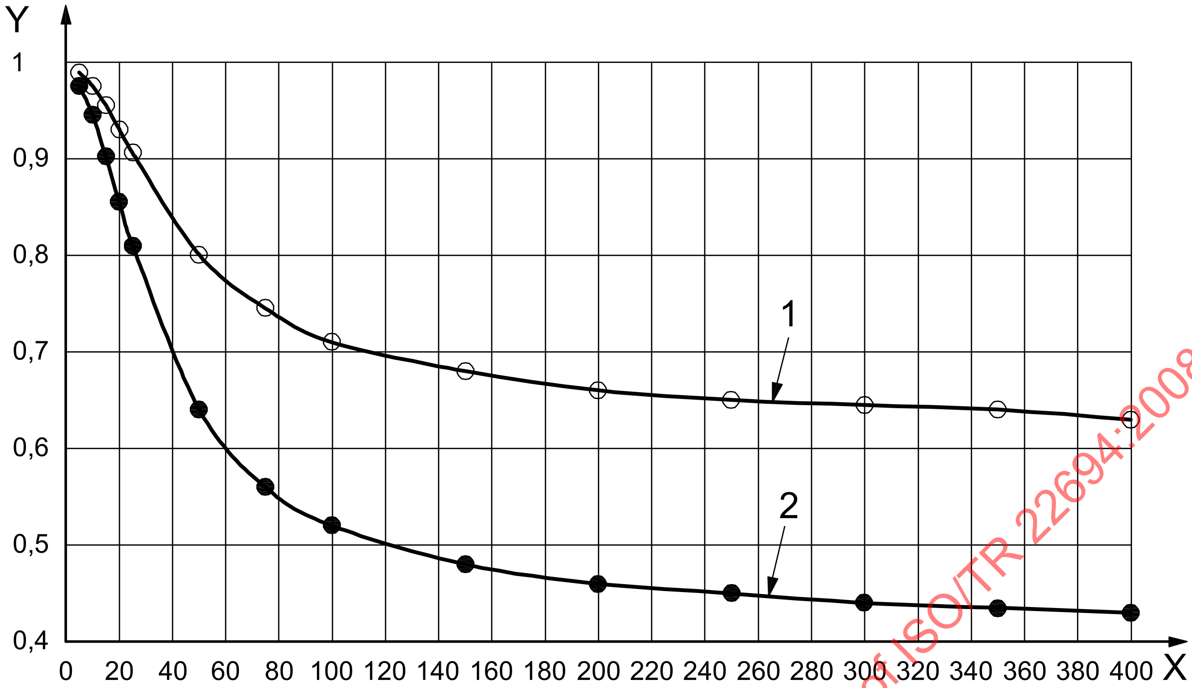
However, the API 579 method has not previously been used to develop CFS requirements for cylinders. The basis for using the API 579 to establish the CFS for seamless steel cylinders has been described in detail [13]. The RSF, which is defined by API 579, may also be defined for the purposes of this document as the failure pressure ratio of (p_f/p_b) where p_f is the failure pressure of the cylinder containing the flaw and p_b is the failure pressure of the same type and size of cylinder that does not contain a flaw.

To establish CFS requirements for cylinders, the failure (burst) pressure (p_f) of the cylinders containing a flaw is determined. The ratio (p_f/p_b) is then calculated. This ratio (p_f/p_b) is now defined as the RSF as shown in Equation (1). An inverted form of Equation (1) is then used to back calculate the flaw depth and length or area that is expected to cause the cylinder to fail at the designated pressure. In the preparation of this Technical Report, the failure pressure (p_f) of the cylinder was specified as either (1) the designated working pressure or (2) the hydrostatic test pressure of the cylinder. The CFS curve (depth versus area or length) for each type of flaw in any cylinder was then calculated. The CFS curves for failure at the designated working pressure of the cylinder shows the size of the flaws that would cause the cylinder to fail in service. The CFS curves for failure at the hydrostatic test pressure of the cylinder show the size of flaws that would cause the cylinder to fail during the traditional hydrostatic pressure test. The CFS curves show the maximum size of flaws that could be expected to have been left in the cylinder after successfully passing the traditional hydrostatic pressure test.

The analysis was carried out for each size of flaw at two values of p_f/p_b or RSF. The values of RSF used in the analysis were 0,67 and 0,44. The p_f/p_b equal to 0,67 is used to calculate the size of the flaws that would be expected to reduce the burst pressure of a cylinder with a flaw to 67 % of the burst pressure of a cylinder without a flaw. This value was chosen because the U.S. DOT specifications for the type of cylinders tested in this study require that the test pressure used in the hydrostatic test must be approximately 67 % of the minimum burst pressure of a cylinder without a flaw. The size of flaws calculated at this pressure represents the size of flaws that could be expected to cause the cylinder to fail (burst) at the test pressure in the hydrostatic test. It should be noted that the ISO cylinder design uses a pressure ratio of 0,625 and 0,417 respectively for the designated RSF values. To evaluate the difference between the DOT pressure ratios and the ISO pressure ratios, both the ISO and DOT values were used and indicated that the difference was less than 1 %. These differences do not change the conclusions of this Technical Report.

Similarly the p_f/p_b equal to 0,44 is used to calculate the size of the flaws that would be expected to reduce the burst pressure of a cylinder with a flaw to 44 % of the burst pressure of a cylinder without a flaw. This value was chosen because the U.S. DOT specifications for the type of cylinders tested require that the working pressure (p) must not be greater than 44 % of the minimum burst pressure of a cylinder without a flaw. The size of flaws calculated at this pressure represents the size of flaws that could be expected to cause the cylinder to fail (burst) in service. An example of these calculations is shown in Figure 6 for a cylinder that was used in this test programme which is 300 bar working pressure, 235 mm outer diameter and 6,6 mm minimum design wall thickness. This analysis method can be used to determine CFS at a specified p_f/p_b ratio for any specific cylinder size.

To demonstrate that the API method of analysis reliably predicts the CFS for a cylinder, a comparison was made between the analytical predictions and experimental test results obtained from the ISO/TC 58/SC 4/WG 1 on rejection criteria for metal cylinders and from the preparation of ISO/TR 12391-2 [5]. Selected results from the WG 1 test programme are shown in Figures 7 and 8. Figure 7 shows that the measured flaw sizes for a LTA-type flaw are all equal to, or larger than, the calculated CFS for a failure pressure of 99 % of the failure pressure of an unflawed cylinder. Figure 8 shows that for a longitudinal notch type of flaw that is 10 times the cylinder wall thickness in length (a 10t flaw), the measured and calculated flaw depth are in good agreement for flawed cylinders that failed at pressures of 66 % to 91 % of the failure pressure of an unflawed cylinder.



Key

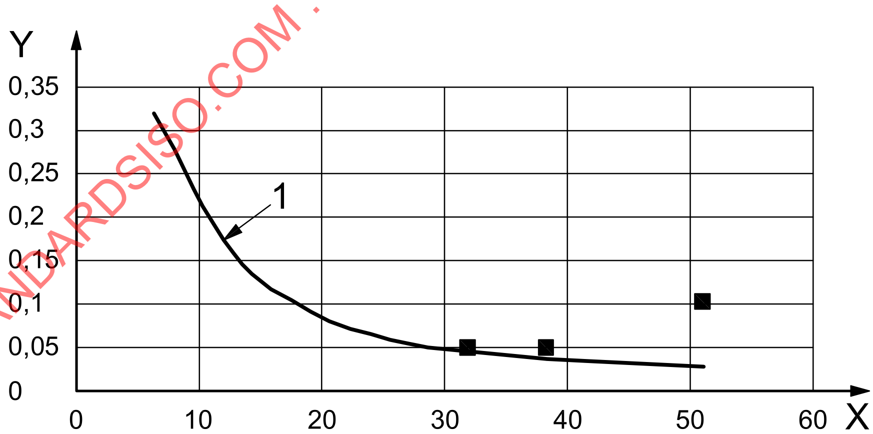
X LTA diameter, mm

Y flaw depth ratio, (a/t)

1 failure at working pressure

2 failure at test pressure

Figure 6 — Flaw depth and area for $p_f = p_h$ or p_s for a range of steel compositions



Key

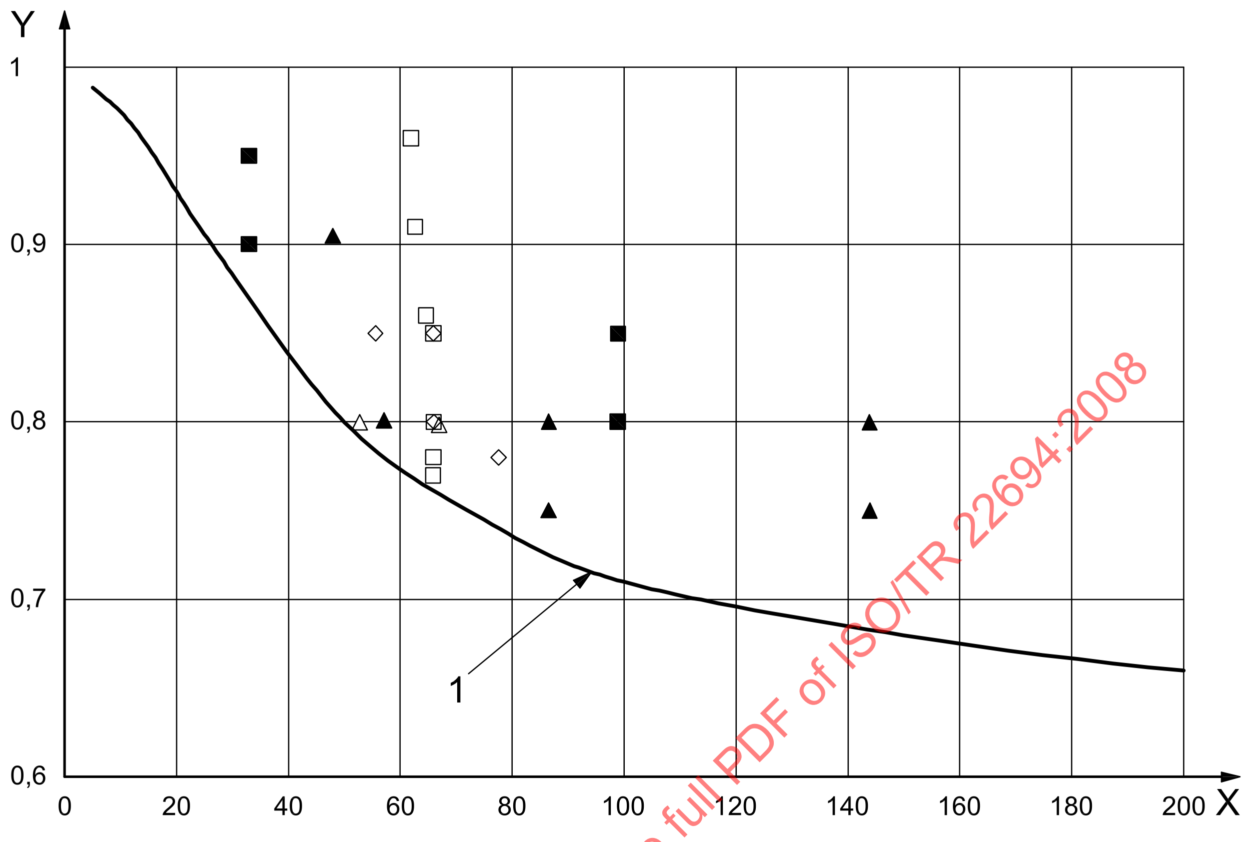
X local thin area diameter, mm

Y flaw depth ratio, (a/t)

1 calculated critical flaw size

■ WG-1 data D hole (pit)

Figure 7 — Flaw depth versus LTA diameter for various steels



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

p_f / p_s Calculated:

■ A-MATL

▲ B-MATL

◇ C-MATL

□ D-MATL

△ E-MATL

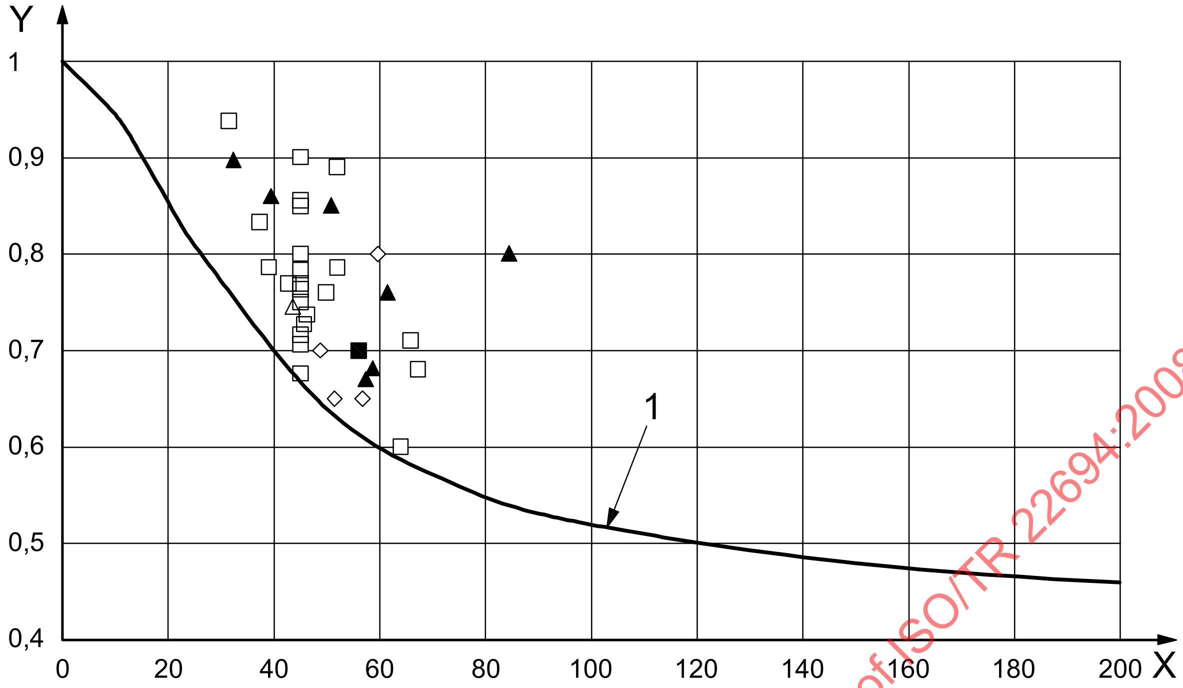
1 calculated flaw size for failure at working pressure

NOTE Material properties for steels A to E are given in Table A.5.

Figure 8 — Critical flaw depth and length for $p_t = p_s$ in steel cylinders of various compositions

The test data from the WG 14 test programme in which the measured failure pressure was near the cylinder working pressure were selected. The measured flaw sizes from these tests that caused failure at the working pressure were compared with the calculated CFS for failure at the working pressure as shown in Figure 8.

In addition, the test data from the WG 14 test programme in which the measured failure pressure was near the cylinder test pressure were selected. The measured flaw sizes from these tests that caused failure at the test pressure were compared with the calculated CFS for failure at the test pressure as shown in Figure 9.



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

p_f/p_h Calcukated:

■ A-MATL

▲ B-MATL

◇ C-MATL

□ D-MATL

△ E-MATL

1 calculated flaw size for failure at test pressure

NOTE Material properties for steels A to E are given in Table A.5.

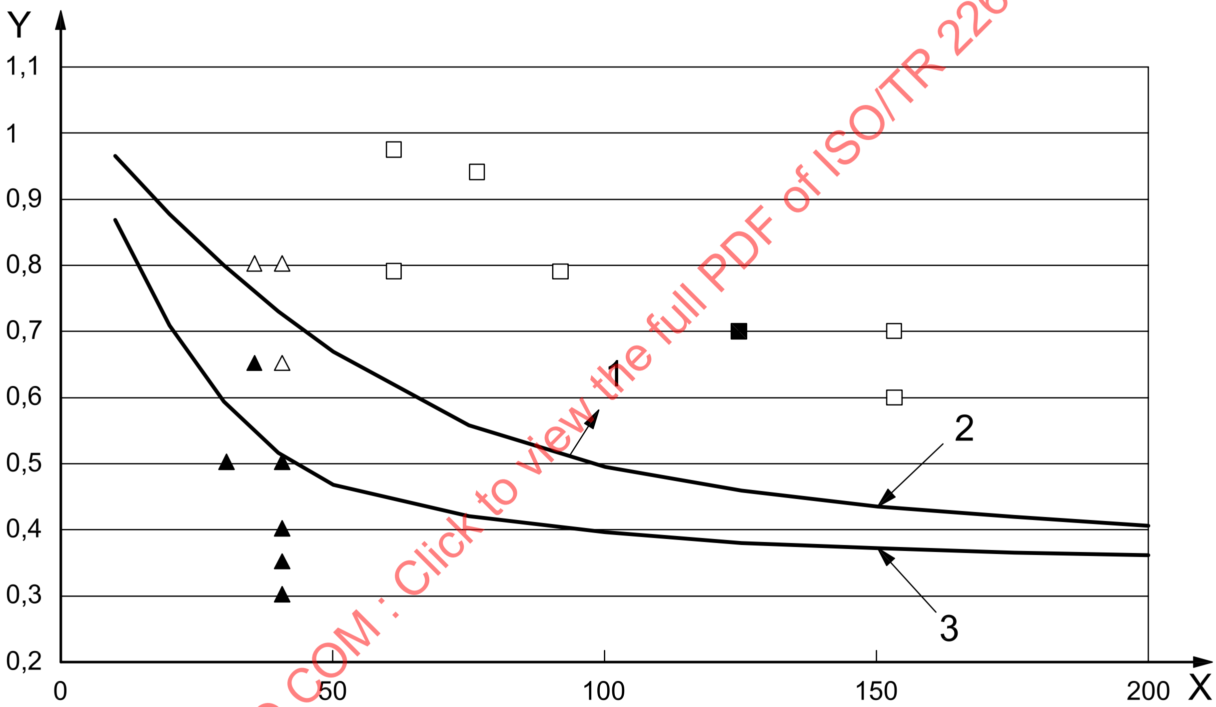
Figure 9 — Critical flaw depth and length for $p_f = p_h$ in steel cylinders of various compositions

These results show that for failure at both the working pressure and the test pressure, the measured flaw sizes were larger than the calculated CFS. Therefore, CFS can be reliably calculated using the API 579 assessment procedure and used to establish CFS for all cylinders currently in use.

The same analysis procedure was used to calculate and verify the CFS for aluminium alloy cylinders. In the preparation of this Technical Report, the failure pressure (p_f) of the aluminium cylinder was specified as the hydrostatic test pressure of the cylinder. The CFS curve (depth versus area or length) for the flaws in any (e.g. ISO 9809-1, ISO 7866) cylinder can then be calculated. The CFS curves for failure at the hydrostatic test pressure of the cylinder show the size of flaws that would cause the cylinder to fail during the traditional hydrostatic pressure test. The CFS curves show the size of flaws that could be expected to have been left in the cylinder after successfully performing the traditional hydrostatic pressure test.

For the aluminium cylinders, the analysis was carried out for each size of flaw at a value of p_f/p_b or RSF equal to 0,67. The p_f/p_b equal to 0,67 is used to calculate the size of the flaws that would be expected to reduce the burst pressure of a cylinder with a flaw to 67 % of the burst pressure of a cylinder without a flaw. This value was chosen because the U.S. DOT specifications for the type of cylinders tested (see Reference [6]) require that the test pressure used in the hydrostatic test must be approximately 67 % of the minimum burst pressure of a cylinder without a flaw. The size of flaws calculated at this pressure represents the size of flaws that could be expected to cause the cylinder to fail (burst) at the test pressure of the hydrostatic test.

To demonstrate that the API 579 method of analysis reliably predicts the CFS for aluminium cylinders, a comparison was made between the analytical predictions and experimental test results obtained from the ISO/TC 58/SC 4/WG 1 on work rejection criteria for metal cylinders. Selected results from the WG 1 test programme are shown in Figures 10 and 11. Figure 10 and Figure 11 show that the measured flaw sizes for a notch type of flaw in aluminium alloys AA6061 and AA7032 cylinders respectively are all equal to, or larger than, the calculated CFS for a failure pressure at the test pressure. Figure 12 shows the maximum size of flaws that may remain and still allow the cylinder to pass the hydrostatic pressure test.



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

■ 184 mm (< TP)

▲ 111 mm (> TP)

□ 203 mm (< TP)

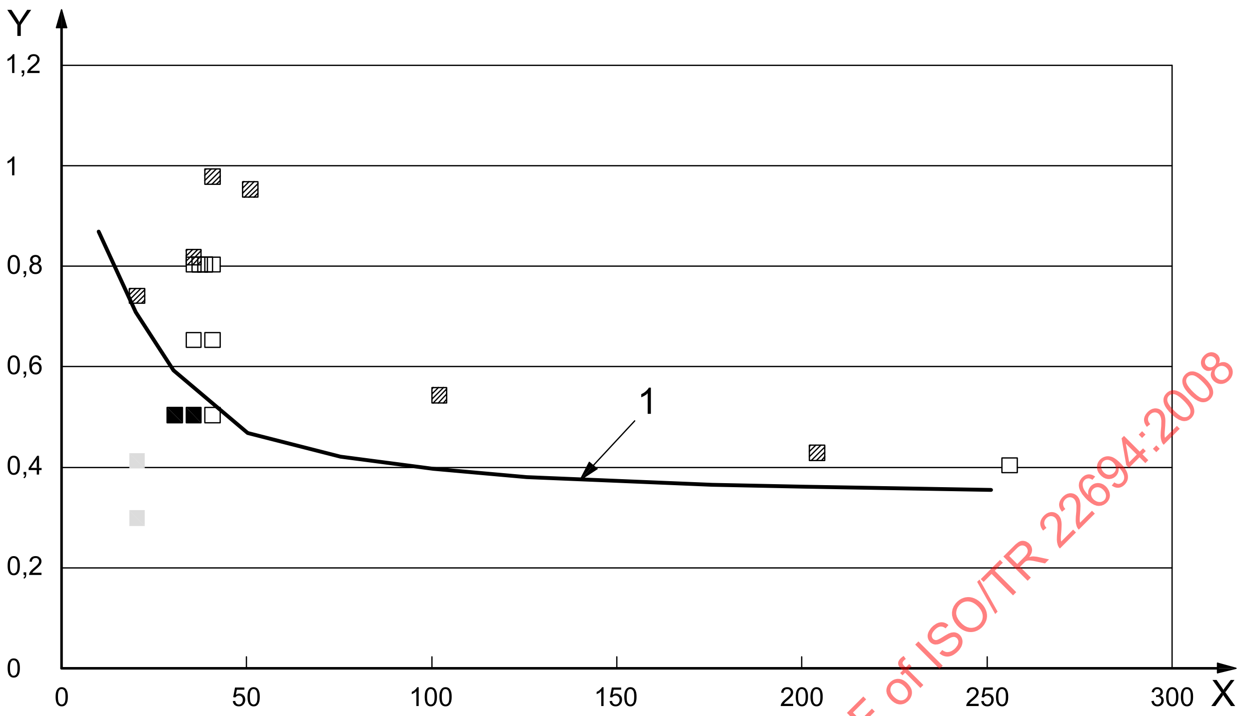
△ 111 mm (< TP)

1 RSF = 0,67 (111 mm)

2 RSF = 0,67 (203 mm)

3 failure pressure below TP

Figure 10 — Flaw depth versus length values for DOT-3AL AA6061 gas cylinders with working pressures of 153 bar to 221 bar



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

Measured final pressure

■ notch (> TP)

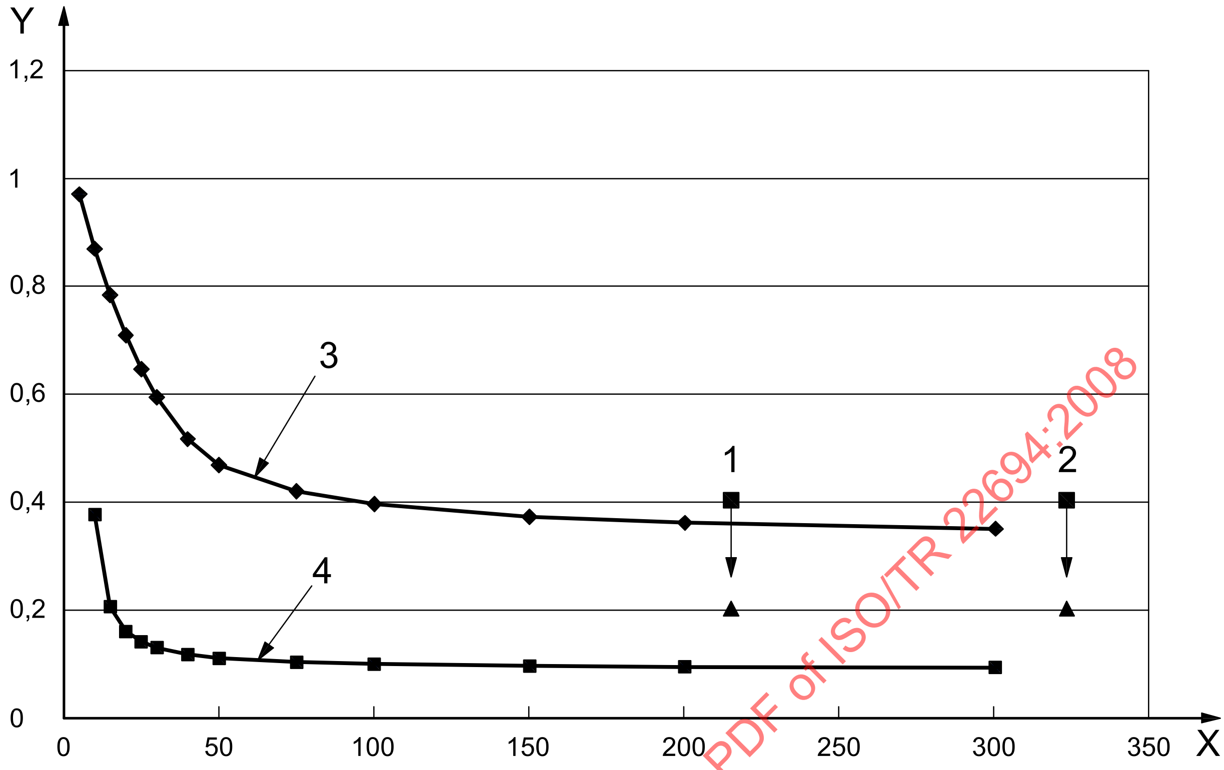
□ notch (< TP)

fatigue crack (> TP)

fatigue (< TP)

1 RSF (TP) = 0,67 (calc.)

Figure 11 — Flaw depth and length values for AA7032 gas cylinders (111 mm diameter with working pressure of 207 bar)



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

▲ before cycle = monotonic burst of flawed cylinder (actual)

■ final after TP cycle = monotonic burst of flawed cylinder after TP cycling (actual)

1 cylinder failure after cycle (386 bar)

2 cylinder failure after cycle (365 bar)

3 RSF = 0,67 (calculated)

4 before TP cycle = monotonic burst of flawed cylinder (calculated)

Figure 12 — LTA analysis for AA6061 cylinders (111 mm diameter with working pressure of 153 bar)

9 Allowable flaw size analysis and verification

The CFS requirements define the size of flaws that will cause the cylinder to fail immediately when the cylinder is pressurized to the specified pressure. Flaws in cylinders are known to grow during service by fatigue, corrosion and by stress corrosion. A variety of corrosion mechanisms can operate given the appropriate conditions such as adequate time and chemical environment. For this study, only fatigue crack growth in air is considered because it is assumed that the internal condition of the cylinder is dry, and consequently no internal corrosion is expected. To develop allowable flaw sizes for cylinders, the fatigue life cycle is defined as 3 500 pressure cycles from zero to the working pressure (though a cylinder will normally see a slightly higher pressure during filling). This fatigue life cycle was chosen to represent an extreme case of the cylinder use, which is approximately a daily filling of the cylinder to the working pressure for 10 years, which is the maximum period between retests.

To develop the allowable flaw size requirements, the CFSs that are expected to cause failure at both the working pressure and the test pressure are then carried out to determine the “initial” flaw sizes that will grow to the CFS after 3 500 pressure cycles to a maximum pressure equal to the working pressure. These initial flaw sizes are then defined as the allowable flaw sizes for the cylinder.

The following example shows the procedure used to calculate the allowable flaw sizes for a typical steel cylinder. The fatigue crack growth rate analysis used in this study is based on the Paris fatigue crack growth rate equation. This analysis assumes crack growth from the very first cycle and does not take into account any crack incubation period. Consequently, this analysis may underestimate the allowable flaw size.

The crack growth rate is calculated as:

$$da/dN \quad C\,(\Delta K)^{m}$$

where

C 0,79 × 10 $^{-12}$

m 0,8

da/dN is the crack growth per unit cycle, m/cycle

ΔK is the cyclic stress-intensity range, MPa $M_{RN}^{1/2}$

The values of the above-referred constants C and m were established by fatigue-crack-growth-rate tests on modern, high-strength (1 034 MPa to 1 206 MPa range) cylinder steel.

For a surface crack in a cylinder, the stress-intensity is defined as:

$$\Delta K = M_{f} M_{RN} \Delta\sigma \sqrt{\Pi \alpha / Q}$$

where

M_f is the Folias stress-intensity magnification factor

M_{RN} is the Raju-Newman factor

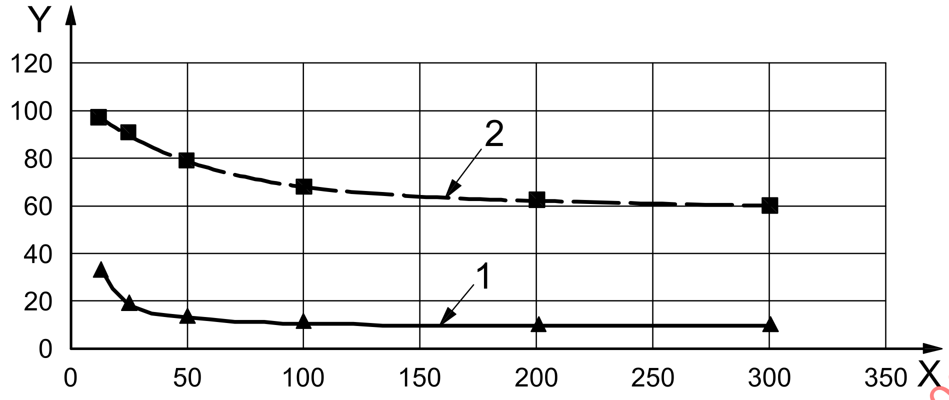
$\Delta\sigma$ is the cyclic stress, MPa

a is the crack depth, m

Q is the crack shape factor, a function of the crack depth and crack length

The example cylinder had a working pressure (p_s) of 310 bar and a test pressure (p_h) of 465 bar. CFSs were first calculated using the API 579 Level 1 method of analysis. The allowable flaw sizes were then calculated using the fatigue crack analysis equations described above. For this analysis the computer software program “Crackwise”® was used [15].

For this example, the cyclical stress used was 483 MPa. This represents a nominal hoop stress at the 310 bar working pressure calculated using the mean diameter formula $pD/2t$. The final flaw dimensions are known from the calculation of the CFS at each of the specified failure pressures. The fatigue crack growth analysis programme is then used to calculate the initial flaw sizes that will grow to these critical sizes after 3 500 cycles. The results of the allowable flaw size calculations are shown in Figures 13 and 14 and Tables 4 and 5. Table 4 shows the allowable flaw sizes that will become the critical sizes at the working pressure. Similarly, Table 5 shows the allowable flaw size that will become of a critical size in nature at the test pressure. The difference in the allowable flaw size for the analysed two cases (i.e. allowable flaw size for failure at working pressure and at test pressure) is very small.



Key

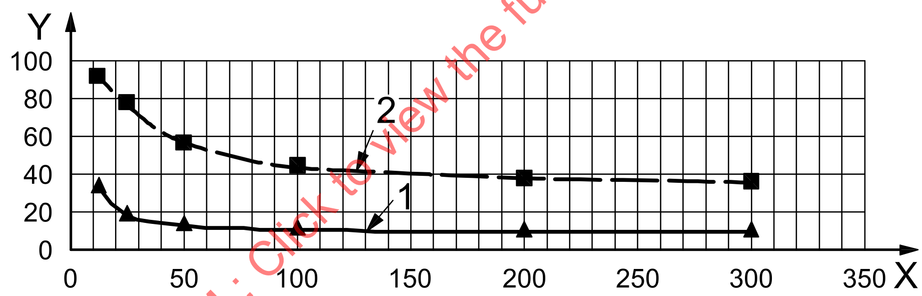
X flaw length, mm

Y flaw depth ratio, (a/t)

1 initial flaw before 3 500 cycles at 310 bar

2 critical flaw at working pressure (p_s)

Figure 13 — LTA analysis of steel cylinders 310 bar, 235 mm outside diameter, 6,6 mm wall cylinder



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

1 initial flaw before 3 500 cycles at 310 bar

2 critical flaw at test pressure (p_s)

Figure 14 — LTA analysis of steel cylinders 310 bar, 235 mm outside diameter, 6,6 mm wall cylinder

Table 4 — Calculated initial flaw size in steel cylinders of various compositions to become critical size at p_s subjected to 3 500 cycles at zero to 300 bar working pressure, p_s

Flaw length L mm	Critical flaw depth at working pressure, p_s a mm	Initial flaw depth a_i mm	Flaw depth ratio a_i/t
12,5	6,4	2,24	0,34
25,0	6,0	1,22	0,18
50,0	5,2	0,86	0,13
100,0	4,5	0,71	0,11
200,0	4,1	0,64	0,10
300,0	3,9	0,62	0,09

Table 5 — Calculated initial flaw size in steel cylinders of various compositions to become critical size at p_h subjected to 3 500 cycles at zero to 300 bar working pressure, p_s

Flaw length L mm	Critical flaw depth at working pressure, p_h a mm	Initial flaw depth a_i mm	Flaw depth ratio a_i/t
12,5	6,1	2,19	0,33
25,0	5,2	1,18	0,18
50,0	3,8	0,83	0,13
100,0	3,0	0,69	0,10
200,0	2,5	0,63	0,09
300,0	2,4	0,60	0,09
NOTE See Table 1 for cylinder data used in the analysis.			

A parametric study was conducted to assess the effect of thickness and diameter on the critical and allowable flaw sizes using the above-described analysis procedure. The three sizes of cylinders analysed had the following dimensions:

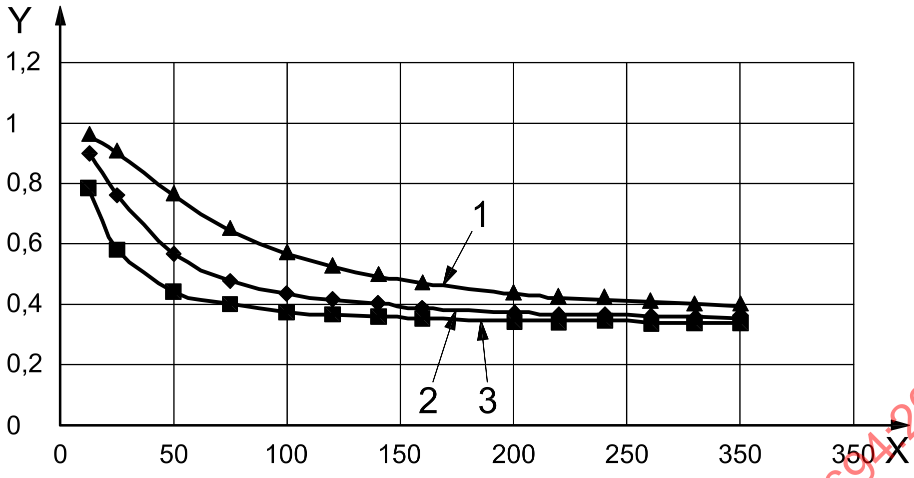
135 mm D X 3 mm wall

230 mm D X 6,6 mm wall

559 mm D X 10,7 mm wall

The working pressure of the above cylinder is 300 bar, and the test pressure is 450 bar.

Figure 15 shows the CFS for failure pressure equal to test pressure (i.e. RSF = 0,67) for all three sizes of cylinder. As shown in Figure 15, the CFS of a large diameter (and thickness) cylinder is larger compared to that of the small diameter cylinder.



Key

X LTA length, mm

Y flaw depth ratio, (a/t)

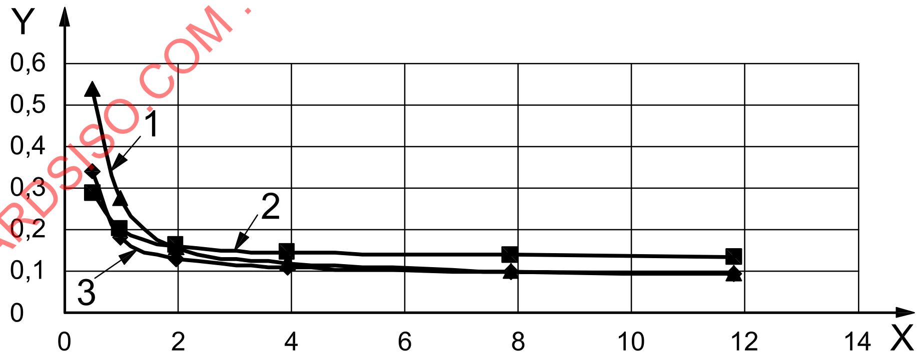
1 559 mm DIA

2 230 mm DIA

3 135 mm DIA

Figure 15 — Effect of diameter and thickness on critical flaw size for failure pressure equal to 450 bar test pressure, RSF of 0,67 for cylinders of various steel compositions

Figure 16 shows the allowable flaw sizes that include the effect of fatigue. As can be seen from Figure 16, the effect of the diameter (and thickness) is not consistent. However, the data on 230 mm diameter cylinders appear to provide the near lower bound curve. This lower bound curve is shown in Figure 17, which can be used as a master curve to develop the acceptance criteria for LTA. One can also specify the allowable flaw size in step function as shown in Figure 18. Figure 19 shows the recommended acceptance/rejection criteria for steel cylinders to be used in the periodic inspection procedures of the cylinders.



Key

X flaw length, mm

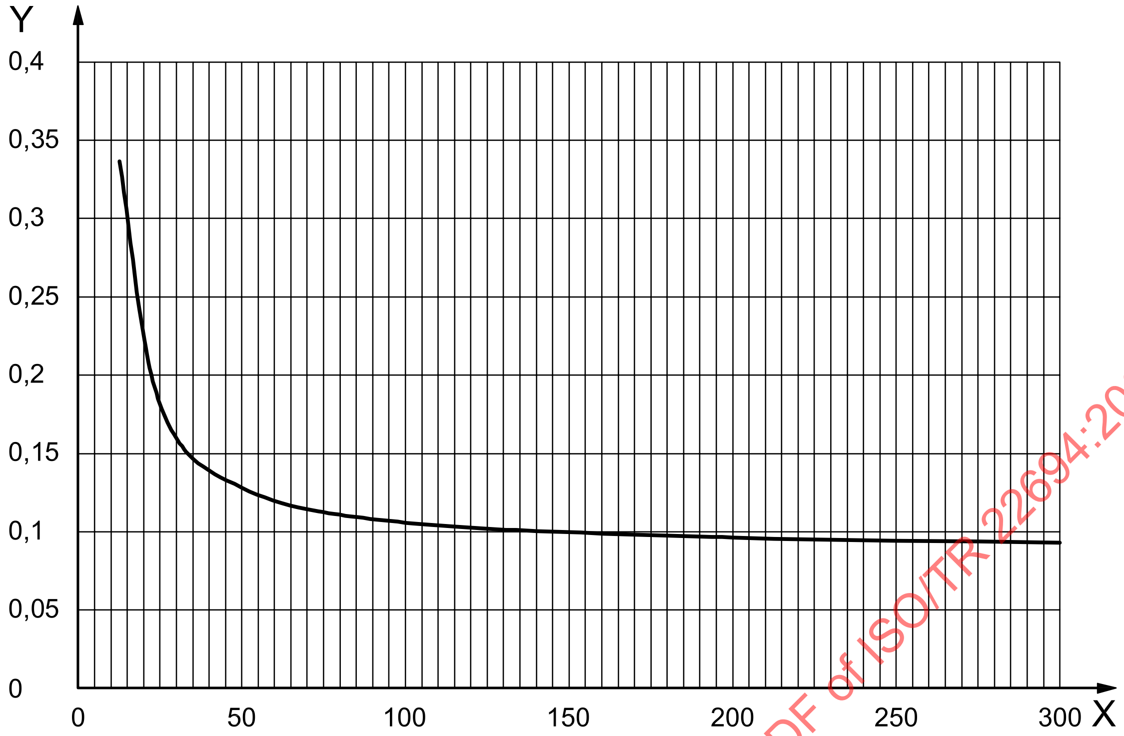
Y initial flaw depth ratio, (a_i/t)

1 559 mm DIA

2 135 mm DIA

3 230 mm DIA

Figure 16 — Effect of diameter and thickness on allowable flaw size for failure pressure equal to 450 bar test pressure and 3 500 cycles at 300 bar working pressure for various steel compositions

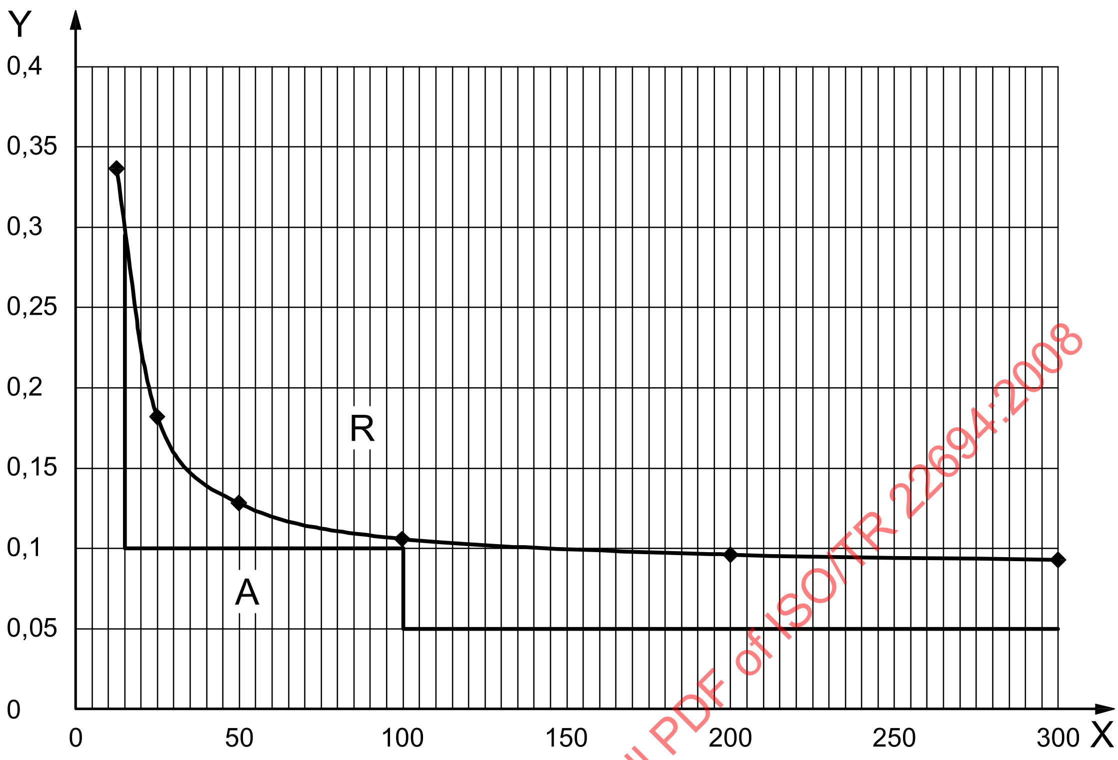


Key

X LTA length, mm

Y LTA depth/design thickness ratio

Figure 17 — Master curve for allowable flaw size for seamless steel cylinders of various compositions



Key

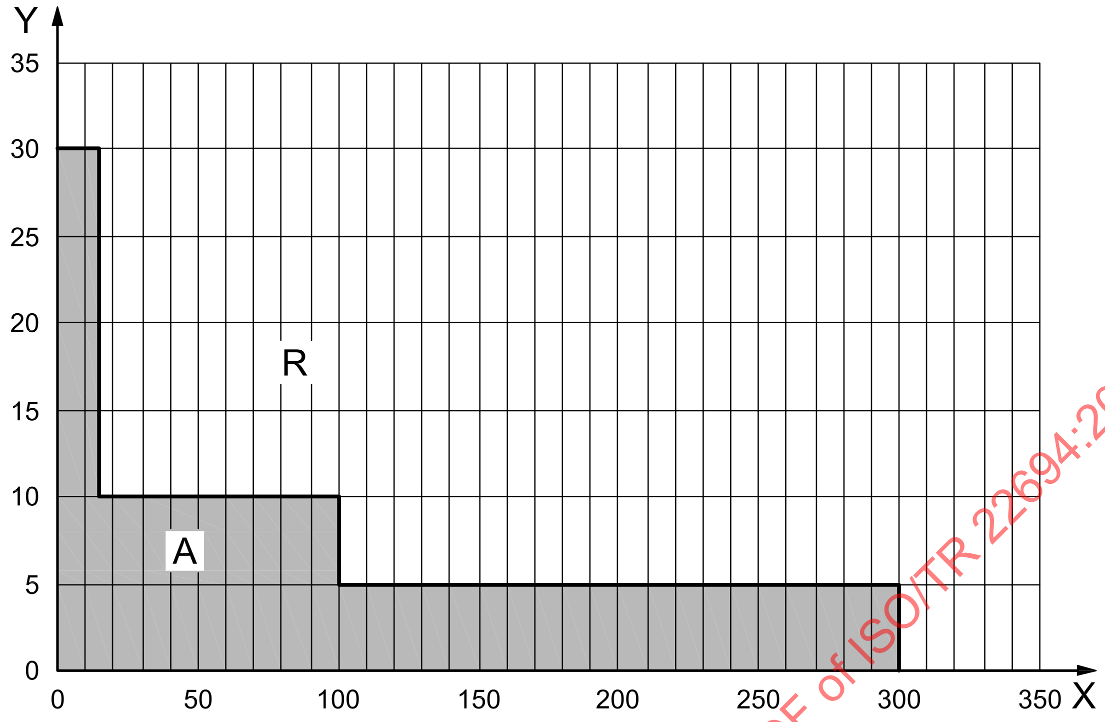
X LTA length, mm

Y LTA depth/design thickness ratio

A accept

R reject

Figure 18 — Flaw acceptance/rejection criteria from master curve on allowable flaw size for seamless steel cylinders of various compositions



Key

X flaw length, mm

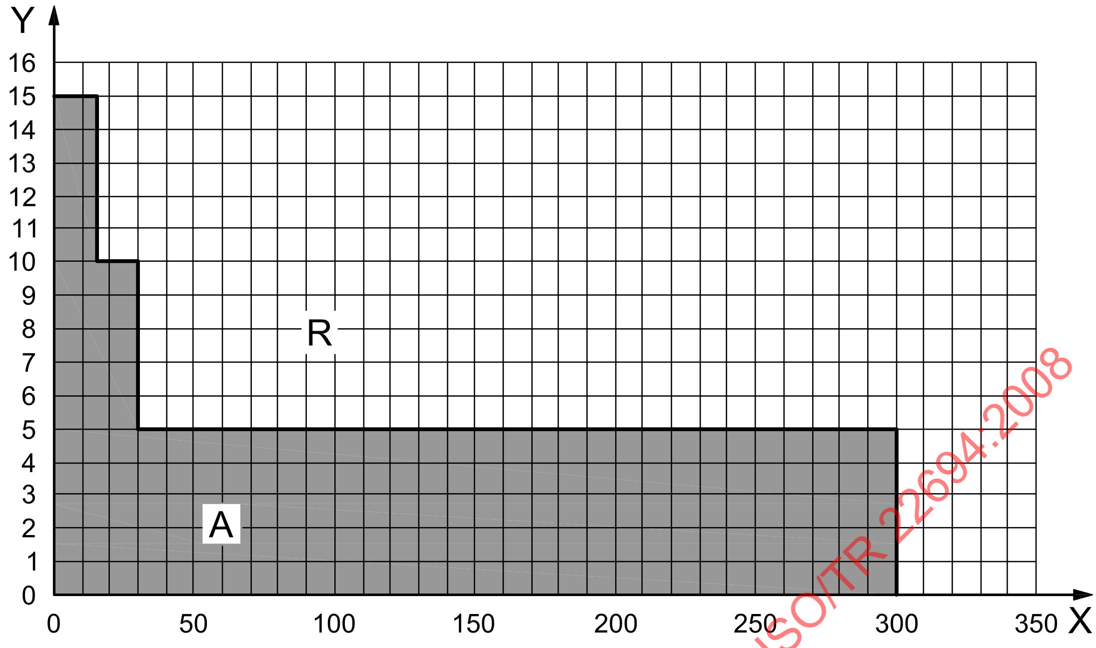
Y flaw depth ratio, (a/t)

A accept

R reject

Figure 19 — LTA acceptance/rejection criteria curve for seamless steel cylinders of various compositions

For aluminium-alloy cylinders constructed from AA6061 and AA7032 aluminium alloys, the same approach as was used to calculate allowable flaw-size curves and accept/reject curves was used. The allowable flaw sizes for the aluminium cylinders were calculated by allowing for fatigue crack growth of 3 500 fatigue cycles at the designated working pressure. The results of the analysis for two AA6061 aluminium-alloy cylinders sizes are shown in Tables 6 and 7. The allowable flaw-size curve for AA6061 aluminium-alloy cylinders is shown in Figure 20, and a similar curve for cylinders made from AA7032 aluminium alloy is shown in Figure 21.



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

A accept

R reject

Figure 20 — LTA acceptance/rejection curve for AA6061 aluminium-alloy cylinders

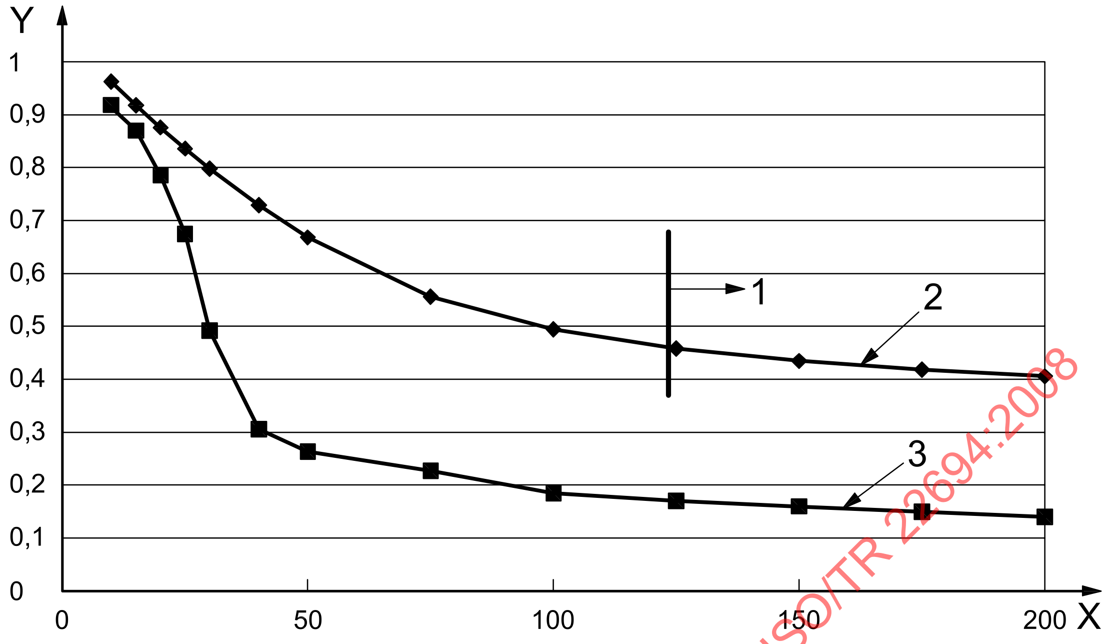
Table 6 — Calculated initial flaw size in AA6061 (111 mm diameter) cylinders to become critical size at p_h after being subject to 3 500 cycles at zero to 153 bar working pressure, p_s

Flaw length mm	Critical flaw depth at p_h mm	Initial flaw depth before cycling at p_s mm	Flaw depth ratio before cycling at p_s (a/t)
5	4,293	—	—
10	4,409	1,910	0,376
15	3,973	1,045	0,206
20	3,597	0,815	0,160
25	3,277	0,718	0,141
30	3,012	0,662	0,130
40	2,621	0,598	0,118
50	2,377	0,563	0,111
60	2,240	0,540	0,106
75	2,134	0,526	0,103
100	2,012	0,508	0,100
150	1,890	0,491	0,097
200	1,834	0,483	0,095
300	1,778	0,475	0,094
NOTE Cylinder diameter: D = 111 mm.			

Table 7 — Calculated initial flaw size in AA6061 (203 mm diameter) cylinders to become critical size at p_h after being subject to 3 500 cycles at zero to 221 bar working pressure, p_s

Flaw length mm	Critical flaw depth at p_h mm	Initial flaw depth before cycling at p_s mm	Flaw depth ratio before cycling at p_s (a/t)
5	15,300	—	—
10	14,749	—	—
15	14,051	13,330	0,871
20	13,418	12,035	0,787
25	13,112	10,340	0,676
30	12,225	7,540	0,493
40	11,169	4,679	0,306
50	10,236	4,036	0,264
75	8,522	3,475	0,227
100	7,574	2,832	0,185
125	7,023	Fracture	Control
150	6,656	—	—
175	6,411	—	—
200	6,212	—	—
250	5,952	—	—
300	5,783	—	—

NOTE Cylinder diameter: D = 203 mm.



Key

X flaw length, mm

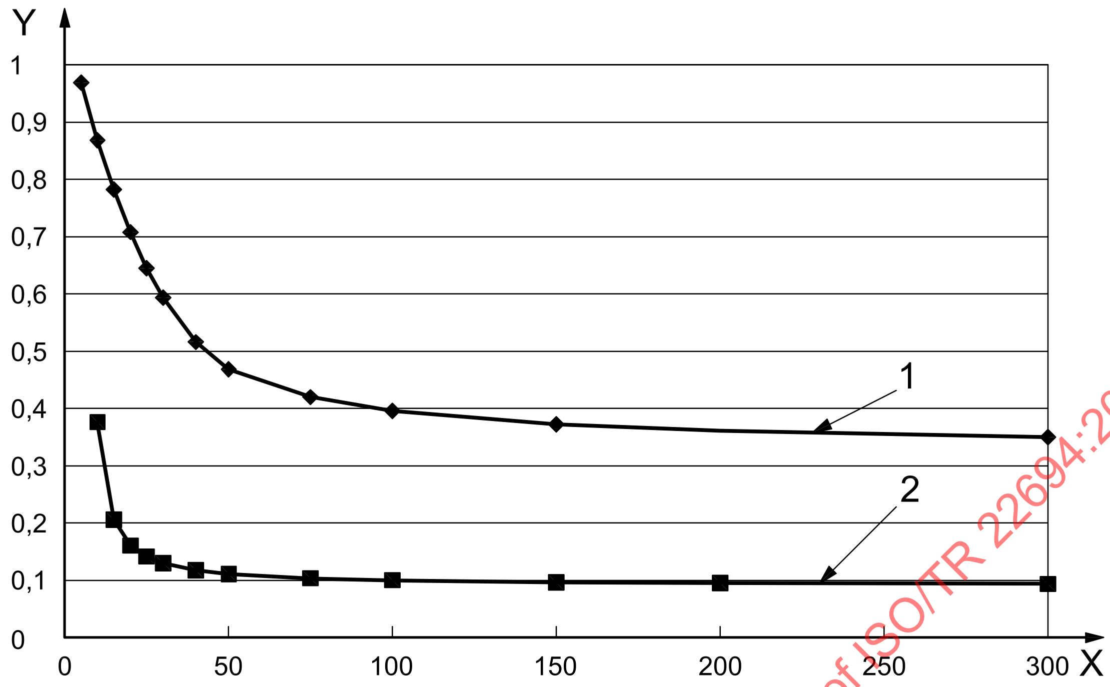
Y flaw depth ratio, (a/t)

1 fracture control burst

2 RSF = 0,67

3 before TP cycles

Figure 21 — LTA analysis of AA6061 cylinder, 203 mm diameter, 221 bar



Key

X flaw length, mm

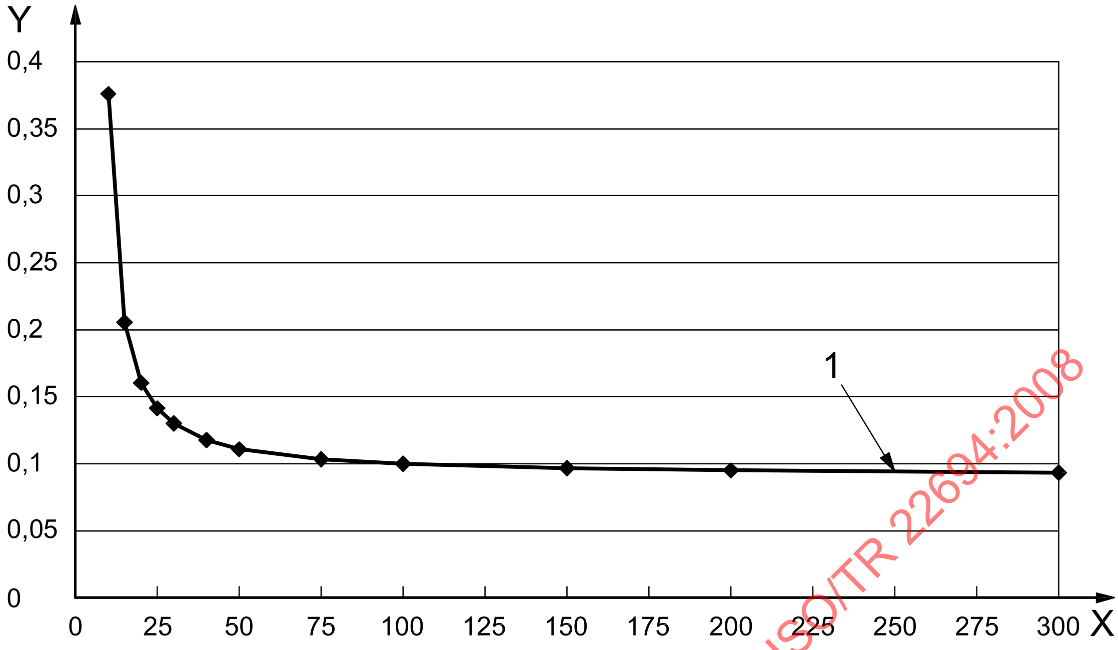
Y flaw depth ratio, (a/t)

1 RSF = 0,67

2 before TP cycles

Figure 22 — LTA analysis of AA7032 cylinder, 111 mm diameter, 207 bar

After the allowable flaw-size curves were developed for the aluminium-alloy cylinders, a master curve for the allowable flaw sizes was developed similar to the master curve that was developed for the steel cylinder. This master curve is shown in Figure 23.



Key

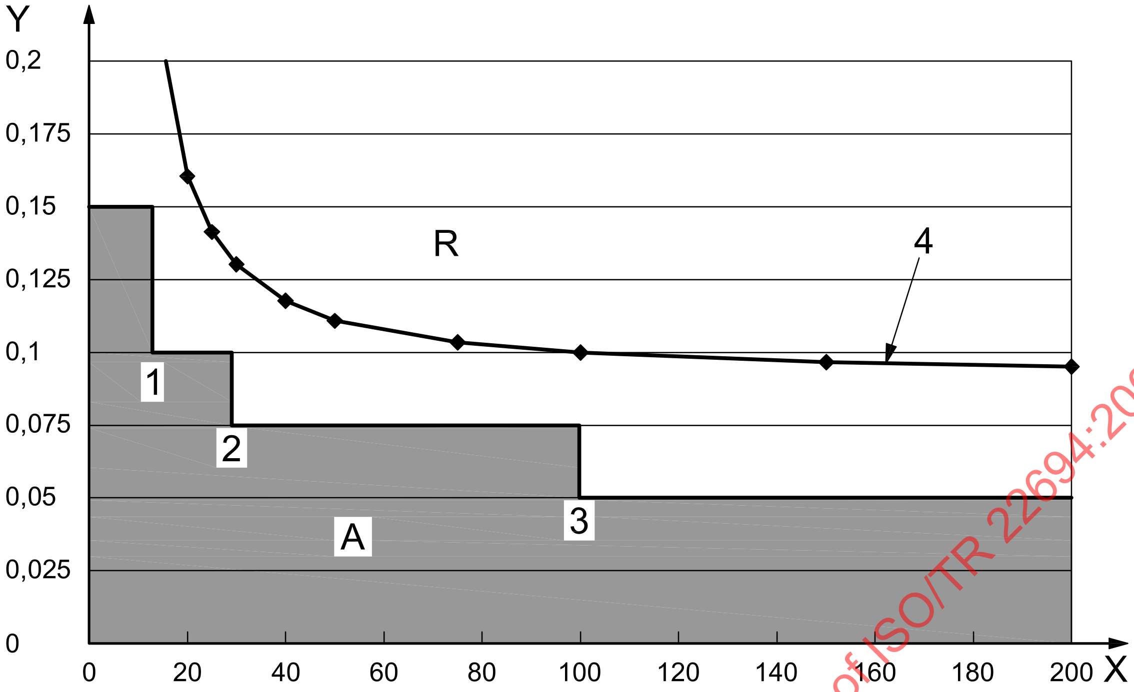
X flaw length, mm

Y flaw depth ratio, (*a*/*t*)

1 master curve

Figure 23 — Master curve for all aluminium-alloy cylinders

From the master curve for the allowable flaw sizes shown in Figure 23, the acceptance/rejection limits as shown in Figures 24 and 25 were developed for the aluminium-alloy cylinders.



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

A accept

R reject

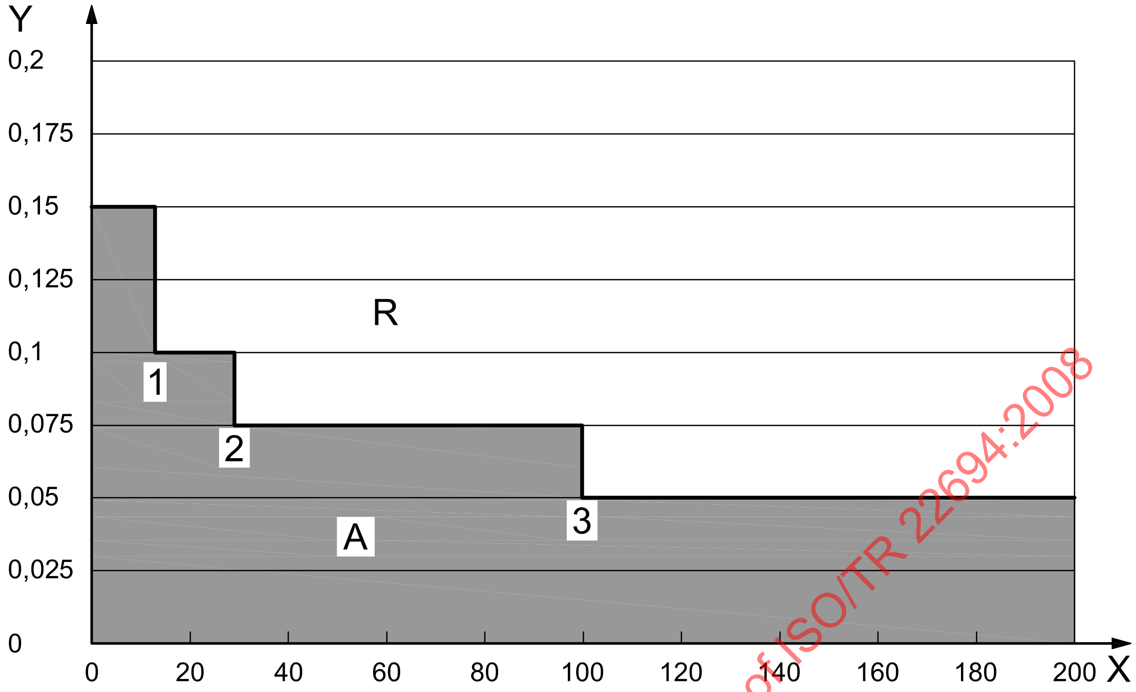
1 15 mm

2 30 mm

3 100 mm

4 master curve

Figure 24 — Accept/reject master curve for all aluminium-alloy cylinders



Key

X flaw length, mm

Y flaw depth ratio, (a/t)

R reject

A accept

1 15 mm

2 30 mm

3 100 mm

Figure 25 — Accept/reject master curve for all aluminium-alloy cylinders

10 Discussion

10.1 Significance of analysis

For steel cylinders and aluminium-alloy cylinders at all strength levels, the API 579 method of analysis has been shown to be reliable for calculating CFS for failure of the cylinders at all pressures. The flaw types analysed were LTAs, pits, clusters of pits, notches and crack-like flaws. The predicted failure pressures and the predicted flaw sizes that were obtained by the analyses agreed with extensive experimental test results.

For the steel cylinders that were evaluated, it was shown that the failure mode due to the internal pressure in the cylinder was by bursting due to ductile, plastic collapse of the cylinder wall in the region of the flaw. Other failure modes that could result from the pressure in the cylinder, such as fracture, were shown not to be significant for the steel cylinders evaluated in this study. It was found to be sufficient to analyse the flaws in the cylinders using only a two-dimensional model. That is, the circumferential dimension of the flaws did not significantly affect the predicted failure pressure of the cylinder.

The flaw-size analysis conducted in this study and the experimental verification of the analysis shows that, for cylinders, the CFS and the allowable flaw sizes can be reliably determined by the analytical modelling alone. The verification of the analysis is sufficient so that it should not be necessary to conduct additional experimental tests to determine maximum allowable flaw sizes. The calculated critical and allowable flaw sizes may be used as a basis for the acceptance/rejection criteria for use at the time of retesting.

For steel cylinders tested in this study, the ductility and fracture toughness are sufficiently high that the flow strength of the steel is the appropriate material parameter that controls in the failure of the cylinder. By this flow strength criterion, failure occurs when the local stress in the presence of a flaw reaches the material's flow strength, and failure by burst occurs at the flaw. The extensive testing that was done as part of the WG 14 programme showed that the flow strength criterion was appropriate for all presently used steel cylinders and that fracture analysis is not required to evaluate such cylinders.

10.2 Significance of critical flaw size (CFS)

The CFS evaluation is the starting point to be used for developing acceptance/rejection criteria for use at the time of retesting. The CFSs are the flaw sizes expected to actually cause failure at the specified pressure. The CFSs at the working pressure show the flaw size that would be expected to cause a failure of the cylinder whilst in service. Once this flaw size is established, allowable flaw sizes can be determined to ensure that no flaw actually reaches the critical size whilst the cylinder is in service between retesting dates.

The CFS at test pressure determines the flaw size that is expected to cause failure of the cylinder during the traditionally used hydrostatic pressure test. The significance of the CFS at test pressure is that flaws of these sizes could have been left in the cylinder at the end of hydrostatic testing. Because cylinders that have been in service after only being retested by hydrostatic testing have not been found to fail in service in significant numbers, it can be concluded that cylinders that contain flaws that are as large as the CFS at test pressure have an adequate safety margin.

10.3 Significance of allowable flaw sizes

The allowable flaw size is established by reducing the size of the CFS to account for flaw growth during service due to such phenomena as fatigue, corrosion or stress-corrosion. Accelerated crack growth due to the effects of hydrogen was not taken into account for steel cylinders in this Technical Report. The analysis and experimental verification conducted in this study was limited to an evaluation of fatigue crack growth. The allowable flaw sizes are used to establish the size of flaws that causes the cylinder to be rejected at the time of retesting. The analysis of the allowable flaw sizes may also be used to define the required retesting interval.

10.4 Significance of other failure modes

In this study only failure by bursting due to the internal pressure in the cylinder was evaluated. However, other failure modes may occur in cylinders and may need to be evaluated before establishing final acceptance/rejection criteria. Some cylinder applications may require an evaluation of stress-corrosion or corrosion.

In this study, only fatigue crack growth was considered in establishing allowable flaw sizes. Crack growth due to stress corrosion cracking is not considered in this Technical Report.

Evaluation of corrosion pitting found that cylinders can fail when the gas environment permits pitting corrosion either (1) by bursting or (2) by leaking. Although pitting may occur as an isolated individual pit, generally, when pitting corrosion occurs, it will result in a failure due to a cluster or line of corrosion pits. Isolated through-wall pits were not considered in this Technical Report.

When pitting corrosion is significant enough for failure to occur by bursting, the API 579 analysis can be used to calculate the CFS. However, for failure to occur by bursting from an LTA, the LTA must be sufficiently large in diameter and depth, i.e. with a diameter equal to approximately twice the wall thickness of the cylinder and a depth of approximately 80 % through the cylinder wall. Smaller or shallower LTAs would not be expected to fail by bursting but could fail by leaking if the corrosion continues for a sufficient period of time.

10.5 Considerations for establishing acceptance/rejection criteria

Although a sound technical basis has been established for developing allowable flaw sizes that takes into account fatigue cracking, other factors may be taken into account before establishing the final acceptance/rejection criteria for retesting cylinders. It may be necessary to consider all the expected operating conditions that the cylinder will see. In addition, it may be necessary to take into account the reliability and detect ability of the specific inspection equipment and to adjust the "allowable flaw sizes" to provide an additional margin of safety.

Having taken all of the above information into account, final assessment curves are given in Figures 19 and 25. These figures give the limits for steel and aluminium alloys, respectively, to be used as acceptance/rejection criteria. Figure 19 provides limits only for steel cylinders. Figure 25 provides limits only for aluminium-alloy cylinders. These final assessment curves are based on the master curves for the individual materials and are the recommendation from the experts of the working group. The output of this Technical Report may form the basis for inclusion in the periodic inspection and tests standards for seamless steel and seamless aluminium-alloy cylinders (ISO 6406 and ISO 10461).

11 Summary and conclusions

— The API 579 fitness-for-service method of analysis has been shown to reliably define the CFS for flaws in seamless steel and seamless aluminium-alloy cylinders.

— Extensive hydrostatic, flawed-cylinder burst test data were used to verify the use of the API 579 methods of analysis for defining CFS in seamless cylinders.

— For the cylinders tested in the ISO/TC 58/SC 4/WG 1 and ISO/TC 58/SC 3/WG 14 projects, the ductility and fracture toughness are sufficiently high that the flow stress criterion is the appropriate failure criterion to predict the burst pressure and therefore to develop CFS requirements for seamless steel cylinders for all strength ranges.

— For aluminium-alloy cylinders tested in the ISO/TC 58/SC 4/WG 1 and ISO/TC 58/SC 3/WG 19 projects, results show that, for flaw sizes up to a/t 0,5, the flow stress criterion is the appropriate failure mechanism to predict the burst pressure and thus to develop CFS requirements.

— Allowable flaw sizes can be established by calculating the amount of fatigue crack growth during the use of the cylinder using established fatigue crack growth rate data and analysis.

— The allowable flaw sizes are then used as the basis to develop acceptance levels for flaws at the time of retesting of the cylinders.

Recommendations have been made in this Technical Report for suitable acceptance/rejection criteria of defects to be used at the time of periodic inspection and testing.

Annex A
(informative)

Tests conducted on seamless steel cylinders for fitness-for-service analysis

Table A.1 — Burst tests on DOT 3F/9809-1 steel cylinders for fitness-for-service analysis

Wall thickness				Flaw at	Flaw type	Flaw description	Flaw size						Burst pressure	Failure at flaw	Cycles to fail
Minimum wall	Average wall	Wall under flaw	Wall at flaw				Depth	Length	Length	Width	Diameter	Area			
mm	mm	mm	mm				% X t_d	n X t_d	mm	mm	mm	mm²	bar		
5,69	—		—	—	design	—	—	—	—	—	—	—	—	—	—
6,05	6,76	—	—	—	none	—	—	—	—	—	—	—	570	—	—
5,92	6,58	—	—	—	none	—	—	—	—	—	—	—	570	—	—
5,92	6,73	—	—	—	none	—	—	—	—	—	—	—	565	—	—
6,22	6,65	—	—	—	none	—	—	—	—	—	—	—	577	—	—
5,89	6,63	5,12	—	avg.	OD-LTA-round	LTA 38,1 mm Ø (1 140 mm²) @ 0,90 t	10	—	—	—	25,4	1 140	557	yes	—
5,84	6,58	5,12	—	avg.	OD-LTA-round	LTA 38,1 mm Ø (1 140 mm²) @ 0,90 t	10	—	—	—	25,4	1 140	530	no	—
6,05	6,73	5,41	—	avg.	OD-LTA-round	LTA 38,1 mm Ø (1 140 mm²) @ 0,95 t	5	—	—	—	25,4	1 140	547	yes	—
5,82	6,63	5,41	—	avg.	OD-LTA-round	LTA 38,1 mm Ø (1 140 mm²) @ 0,95 t	5	—	—	—	25,4	1 140	533	no	—
6,10	6,68	4,55	—	min.	OD-LTA-round	LTA 31,8 mm Ø @ 0,80 t	20	—	—	—	25,4	1 140	550	no	—
5,99	6,78	5,12	—	min.	OD-LTA-round	LTA 31,8 mm Ø @ 0,90 t	10	—	—	—	25,4	1 140	543	no	—
5,82	6,50	5,12	—	avg.	OD-LTA-round	LTA 31,8 mm Ø (792 mm²) @ 0,90 t	10	—	—	—	25,4	792	530	no	—
6,07	6,60	5,12	—	avg.	OD-LTA-round	LTA 31,8 mm Ø (792 mm²) @ 0,90 t	10	—	—	—	25,4	792	533	no	—
5,97	6,65	5,41	—	avg.	OD-LTA-round	LTA 31,8 mm Ø (792 mm²) @ 0,95 t	5	—	—	—	25,4	792	550	yes	—
5,79	6,60	5,41	—	avg.	OD-LTA-round	LTA 31,8 mm Ø (792 mm²) @ 0,95 t	5	—	—	—	25,4	792	523	no	—
6,35	6,91	5,12	—	avg.	OD-LTA-round	LTA 25,4 mm Ø (506 mm²) @ 0,90 t	10	—	—	—	25,4	507	583	no	—
5,94	6,68	5,12	—	avg.	OD-LTA-round	LTA 25,4 mm Ø (506 mm²) @ 0,90 t	10	—	—	—	25,4	507	550	no	—

Table A.1 *(continued)*

Wall thickness				Flaw at	Flaw type	Flaw description	Flaw size						Burst pressure	Failure at flaw	Cycles to fail
Minimum wall	Average wall	Wall under flaw	Wall at flaw				Depth	Length	Length	Width	Diameter	Area			
mm	mm	mm	mm				% X t_d	n X t_d	mm	mm	mm	mm²	bar		
6,10	6,68	5,41	—	avg.	OD-LTA-round	LTA 25,4 mm Ø (506 mm²) @ 0,95 *t*	5	—	—	—	25,4	507	563	no	—
5,82	6,65	5,41	—	avg.	OD-LTA-round	LTA 25,4 mm Ø (506 mm²) @ 0,95 *t*	5	—	—	—	25,4	507	537	no	—
5,99	6,65	4,55	—	min.	OD-LTA-round	LTA 25,4 mm Ø @ 0,80 *t*	20	—	—	—	25,4	507	543	no	—
6,05	6,73	5,12	—	min.	OD-LTA-round	LTA 25,4 mm Ø @ 0,90 *t*	10	—	—	—	25,4	507	543	no	—
5,97	6,68	4,55	—	min.	OD-LTA-round	LTA 50,8 mm Ø @ 0,80 *t*	20	—	—	—	25,4	2 027	580	no	—
6,15	6,71	5,12	—	min.	OD-LTA-round	LTA 50,8 mm Ø @ 0,90 *t*	10	—	—	—	25,4	2 027	563	yes	—
5,79	6.55	3,81	—	avg.	OD-LTA-round	LTA 19,05 mm Ø (285 mm²) @ 0,67 *t*	33	—	—	—	25,4	285	543	yes	—
5,97	6,58	5,12	—	avg.	OD-LTA-round	LTA 19,05 mm Ø (285 mm²) @ 0,90 *t*	10	—	—	—	25,4	285	533	no	—
5,99	6,71	5,12	—	avg.	OD-LTA-round	LTA 19,05 mm Ø (285 mm²) @ 0,90 *t*	10	—	—	—	25,4	285	570	no	—
6,07	6,63	5,41	—	avg.	OD-LTA-round	LTA 19,05 mm Ø (285 mm²) @ 0,95 *t*	5	—	—	—	25,4	285	547	no	—
5,94	6,73	5,12	—	avg.	OD-LTA-round	LTA 19,05 mm Ø (285 mm²) @ 0,95 *t*	5	—	—	—	25,4	285	547	no	—
5,94	6,50	5,37	—	min.	OD-LTA-rectangular	LTA 57,15 mm (10 *t*) long × 44,45 mm × 10 % *t* deep	10	—	57,2	44,5	—	2 540	550	no	—
6,05	6,83	4,91	—	min.	OD-LTA-rectangular	LTA 57,15 mm (10 *t*) long × 44,45 mm × 20 % *t* deep	20	—	57,2	44,5	—	2 540	513	yes	—
5,84	6,40	4,14	—	min.	OD-LTA-rectangular	LTA 57,15 mm (10 *t*) long × 44,45 mm × 30 % *t* deep	30	—	57,2	44,5	—	2 540	487	yes	—

Table A.1 *(continued)*

Wall thickness							Flaw size								
Minimum wall mm	Average wall mm	Wall under flaw mm	Wall at flaw mm	Flaw at	Flaw type	Flaw description	Depth % X t_d	Length n X t_d	Length mm	Width mm	Diameter mm	Area mm²	Burst pressure bar	Failure at flaw	Cycles to fail
5,89	6,71	3,62	—	min.	OD-LTA-rectangular	LTA 57,15 mm (10 *t*) long × 44,45 mm × 40 % *t* deep	40	—	57,2	44,5	—	2 540	493	yes	—
6,12	6,71	3,28	—	min.	OD-LTA-rectangular	LTA 57,15 mm (10 *t*) long × 44,45 mm × 50 % *t* deep	50	—	57,2	44,5	—	2 540	473	yes	—
5,97	6,73	5,40	—	min.	OD-notch	longitudinal notch 10 % *t* deep × 10 *t* long	10	10	57,2	—	—	—	550	yes	—
5,72	6,60	6,04	—	avg.	OD-notch	longitudinal notch 10 % *t* deep × 5 *t* long	10	5	28,6	—	—	—	563	no	—
5,72	6,48	5,92	—	avg.	OD-notch	longitudinal notch 10 % *t* deep × 5 *t* long	10	5	28,6	—	—	—	537	no	—
5,92	6,68	5,05	—	min.	OD-notch	longitudinal notch 15 % *t* deep × 5 *t* long	15	5	28,6	—	—	—	530	no	—
6,12	6,71	5,84	—	avg.	OD-notch	longitudinal notch 15 % *t* deep × 5 *t* long	15	5	28,6	—	—	—	573	yes	—
5,89	6,63	5,77	—	avg.	OD-notch	longitudinal notch 15 % *t* deep × 5 *t* long	15	5	28,6	—	—	—	533	yes	—
5,99	6,58	4,86	—	min.	OD-notch	longitudinal notch 20 % *t* deep × 10 *t* long	15	10	57,2	—	—	—	503	yes	—
5,99	6,81	5,66	—	avg.	OD-notch	longitudinal notch 20 % *t* deep × 5 *t* long	20	5	28,6	—	—	—	563	no	—
5,92	6,63	4,77	—	min.	OD-notch	longitudinal notch 20 % *t* deep × 5 *t* long	20	5	28,6	—	—	—	533	yes	—
6,17	6,73	5,59	—	avg.	OD-notch	longitudinal notch 20 % *t* deep × 5 *t* long	20	5	28,6	—	—	—	560	no	—
6,30	6,73	4,88	—	min.	OD-notch	longitudinal notch 25 % *t* deep × 5 *t* long	25	5	28,6	—	—	—	543	yes	—
5,77	6,63	4,06	—	min.	OD-notch	longitudinal notch 30 % *t* deep × 10 *t* long	30	10	57,2	—	—	—	483	yes	—