TECHNICAL REPORT

ISO/TR 12391-2

First edition
2002-12-15

Gas cylinders — Refillable seamless steel — Performance tests —

Part 2:
Fracture performance tests — Monotonic burst tests

Bouteilles à gaz — Rechargeables en acier sans soudure — Essais de performance —

Partie 2: Essais de mode de rupture — Essais de rupture monotonique

Reference number
ISO/TR 12391-2:2002(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

iTeh STANDARD PREVIEW
(standards.iteh.ai)
ISO/TR 12391-2:2002
https://standards.iteh.ai/catalog/standards/sist/9a7961e7-523a-464e-8aff-995031b78be9/iso-tr-12391-2-2002

© ISO 2002

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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

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

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

ISO/TR 12391-2 was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 3, *Cylinder design*.

ISO/TR 12391 consists of the following parts, under the general title *Gas cylinders — Refillable seamless steel — Performance tests*:

- *Part 1: Philosophy, background and conclusions*
- *Part 2: Fracture performance tests — Monotonic burst tests*
- *Part 3: Fracture performance tests — Cyclical burst tests*
- *Part 4: Flawed-cylinder cycle test*

Introduction

Gas cylinders as specified in ISO 9809-1 have been constructed of steel with a maximum tensile strength of less than 1 100 MPa. With the technical changes in steel-making using a two-stage process, referred to as ladle metallurgy or secondary refining, significant improvement in mechanical properties have been achieved. These improved mechanical properties provide the opportunity of producing gas cylinders with higher tensile strength and which achieve a lower ratio of steel weight to gas weight. The major concern in using steels of higher tensile strength with correspondingly higher design wall stress is safety throughout the life of the gas cylinder.

When ISO/TC 58/SC 3 began drafting ISO 9809-2, Working Group 14 was formed to study the need for additional controls for the manufacture of steel gas cylinders having a tensile strength greater than 1 100 MPa.

This part of ISO/TR 12391 presents all of the specific test results of the monotonic, flawed-cylinder burst tests that were conducted in order to evaluate the fracture performance of cylinders ranging in tensile strength from less 750 MPa to greater than 1 210 MPa.

Gas cylinders — Refillable seamless steel — Performance tests —

Part 2:
Fracture performance tests — Monotonic burst tests

1 Scope

This part of ISO/TR 12391 is a summary and compilation of the test results obtained during the development of the “Flawed-Cylinder Burst Test”. The concept and development of the flawed cylinder burst test is described in ISO/TR 12391-1. The test is a method for evaluating the fracture performance of steel cylinders that are used to transport high pressure, compressed gases. In this part of ISO/TR 12391, test results are reported for several hundred flawed cylinder burst tests that were conducted on seamless steel cylinders ranging in tensile strength from less than 750 MPa up to about 1 400 MPa.

This test method has been shown to reliably predict the fracture performance of seamless steel cylinders. The test method is intended to be used both for the selection of materials and design parameters in the development of new cylinder designs as well as for an efficient quality control test to be used during the production of cylinders.

2 References

ISO 148:1983, *Steel — Charpy impact test (V-notch)*

ISO 6892:1998, *Metallic materials — Tensile testing at ambient temperature*

ISO 9809-1:1999, *Gas cylinders — Refillable seamless steel gas cylinders — Design, construction and testing — Part 1: Quenched and tempered steel cylinders with tensile strength less than 1 100 MPa*

ISO 9809-2:2000, *Gas cylinders — Refillable seamless steel gas cylinders — Design, construction and testing — Part 2: Quenched and tempered steel cylinders with tensile strength greater than or equal to 1 100 MPa*

ISO/TR 12391-1, *Gas cylinders — Refillable seamless steel — Performance tests — Part 1: Philosophy, background and conclusions*

ISO/TR 12391-3, *Gas cylinders — Refillable seamless steel — Performance tests — Part 3: Fracture performance tests — Cyclical burst tests*

3 Symbols

A	is the elongation expressed as a percentage (= d/t_{d});
d	is the flaw depth, expressed in millimetres (= $A \times t_{\mathrm{d}}$);
D	is the outside diameter of the cylinder, expressed in millimetres;
l_{o}	is the flaw length, expressed in millimetres (= $n \times t_{\mathrm{d}}$);
n	represents multiples of t_{d} (= $l_{\mathrm{o}}/t_{\mathrm{d}}$);
P_{f}	is the failure pressure measured in the flawed-cylinder burst test expressed in bar.
P_{h}	is the calculated design test pressure for the cylinder, expressed in bar;
P_{s}	is the calculated design service pressure for the cylinder, expressed in bar;
R_{ea}	is the actual measured value of yield strength, expressed in megapascals;
$R_{\mathrm{g,\ max}}$	is the maximum value of tensile strength guaranteed by the manufacturer, expressed in megapascals;
$R_{\mathrm{g,\ min}}$	is the minimum value of tensile strength guaranteed by the manufacturer, expressed in megapascals;
R_{m}	is the actual measured value of tensile strength expressed in megapascals;
t_{a}	is the actual measured wall thickness at the location of the flaw, expressed in millimetres;
t_{d}	is the calculated minimum design wall thickness, expressed in millimetres.

4 Background information

High-pressure industrial gases (such as oxygen, nitrogen, argon, hydrogen, helium) are stored and transported in portable steel cylinders. These cylinders are designed, manufactured and maintained in accordance with ISO 9809-1, ISO 9809-2, or national specifications such as those of the U.S. Department of Transportation (DOT) 49 CFR Part 178 [1]. The cylinders are constructed from specified alloy steels that are generally modified versions of steels such as AISI 4130 and AISI 4140 [2] or equivalent steels made to other national specifications. The cylinders are of seamless construction and are manufactured by either a forging process, a tube drawing process or a plate drawing process. The required mechanical properties are obtained by using an austenitizing, quenching and tempering heat treatment. Typical sizes of these cylinders are 100 mm to 250 mm in diameter, 500 mm to 2 000 mm in length, and 3 mm to 20 mm in wall thickness. Typical working pressure ranges are 100 bar to 400 bar.

Until recently, the tensile strength of the steels used in the construction of such cylinders has been limited to a maximum of about 1 100 MPa. This limitation for the maximum tensile strength occurs because the fracture toughness of the steels decreases with increase in the tensile strength, and above a tensile strength of about 1 100 MPa the fracture toughness was not adequate to prevent fracture of the cylinders. Recently developed new alloy steels that are modifications of the AISI 4130 and AISI 4140, and which have both high tensile strength and high fracture toughness make it possible to construct lighter cylinders with higher tensile strength steels. This permits the use of cylinder designs in which the stress in the cylinder wall is increased for a constant wall thickness. The use of higher strength steels will therefore achieve a lower ratio of steel weight to gas weight that reduces shipping and handling costs.

A major concern in using higher strength steels for cylinder construction and correspondingly higher design wall stress is the ability to maintain the same level of safety throughout the life of the cylinder. In particular, increasing the tensile strength of the steels and increasing the stress in the wall of the cylinders could make the cylinders less fracture resistant than cylinders made from steels with the traditionally-used lower tensile strength levels. In order to use steels with strength levels higher than 1 100 MPa, it was determined that new requirements were needed to assure adequate fracture resistance of the cylinders.

To develop these requirements, a Working Group on Cylinder Fracture (WG14) was formed under ISO/TC 58/SC 3. WG 14 was assigned the task of “developing a suitable test method and specifications to assure adequate fracture resistance for gas cylinders made from steels with tensile strengths greater than 1 100 MPa”. WG14 decided that the test method and specifications that were developed should demonstrate that the overall “fracture resistance” of cylinders made from higher strength steels was equivalent to that of cylinders made from lower strength steels. Fracture resistance of the cylinder is defined as the adequate fracture initiation strength in the presence of a crack-like flaw to assure leak rather than fracture performance of the cylinder at a specified failure pressure (usually the marked service pressure of the cylinder).

The test methods and procedures that have previously been used to evaluate the fracture performance of high pressure cylinders have been based either on fracture mechanics tests and analysis [3] or have been based on empirical correlations with the Charpy-V-notch (CVN) test impact energy [4]. The objectives of these tests and analyses are to predict the fracture initiation stress (or pressure) and fracture mode (leak or unstable fracture).

The fracture mechanics tests and analysis showed that to provide adequate fracture resistance, the cylinder wall should be in the plane-stress fracture state and that the fracture should occur under elastic-plastic conditions. To reliably evaluate the fracture performance of cylinders in the plane-stress fracture state requires that an elastic-plastic fracture mechanics analysis (i.e. J_{Ic}, J_R) be conducted. Using the fracture mechanics analysis approach to evaluate fracture performance may require that a complex and expensive finite-element analysis be done for each specific type of flaw on each specific cylinder design to establish the J_{Ic} or J_R requirements for adequate fracture resistance. Also, the J_{Ic} materials property test required to evaluate the cylinder material is expensive and time-consuming. Such costly and time-consuming tests, have not proven to be practical for use with the high volume cylinder production.

Empirical correlations have been used to predict the fracture performance of cylinders. These empirical correlations relate the fracture initiation stress level for specific flaw types to the Charpy-V-notch (CVN) test impact energy. Although the Charpy-V-notch (CVN) test is useful for evaluating the quality of cylinders during production, the Charpy-V-notch (CVN) test alone may not be a reliable means to evaluate the fracture resistance of new designs of steel cylinders or to evaluate new alloy steels for cylinder construction.

As a result of these limitations with fracture mechanics analysis and with empirical correlations based on CVN tests, it was concluded that an alternate approach was required to evaluate the fracture resistance of high strength steel cylinders. It was decided that the test method that was developed should measure the total fracture resistance of the cylinder and not just the fracture toughness. Therefore, WG 14 decided to use a direct approach to evaluate the fracture resistance of cylinders and this led to the development of the “Flawed-Cylinder Burst Test”.

In this test method, the fracture test is performed on an actual, full size, cylinder rather than by measuring the fracture properties of the material alone by taking small scale test specimens from the cylinder, such as for J_{Ic} tests. This test method consists of testing cylinders in which flaws of specified sizes are machined into the external surface of the cylinders. The cylinders are pressurized until failure, and the failure pressure and failure mode (leak or fracture) is determined. This approach is only possible because the cylinders are required by the existing safety regulations to be produced in large, controlled groups of uniform cylinders and therefore a single sample cylinder from the group will adequately represent the behaviour of all cylinders in the production group.

The concept of the flawed-cylinder burst test and the development conducted under WG 14 is described in ISO/TR 12391-1. The technical basis for the flawed-cylinder burst test is described in detail in reference [5].

In the development of the test method and acceptance criteria for the flawed-cylinder burst test, it was decided that the fracture resistance of newer, higher-strength steel cylinders should essentially be the same as that of the lower strength, existing cylinders because the existing cylinders have provided fracture-safe performance during their many years of service. Therefore, flawed-cylinder burst tests were conducted on cylinders with strength levels covering the full range of strength levels currently being produced in the world. Tests were conducted on cylinders made from steels ranging in tensile strength from 620 MPa to 1 400 MPa. During the development of the flawed-cylinder burst test, several hundred flawed-cylinder burst tests were conducted by the members of WG 14. Flawed-cylinder burst tests were conducted by 10 different companies in seven different countries (Austria, France, Germany, Japan, Sweden, the United Kingdom and the United States).

This part of ISO/TR 12391 is limited to a summary and compilation of the results of the flawed-cylinder burst tests that were conducted by WG 14 during the development of the flawed-cylinder burst test method. Results of flawed-cylinder cycle burst tests that assess the fracture performance of the cylinders due to pressure cycling were also carried out by WG 14 and are given in ISO/TR 12391-3. This part of ISO/TR 12391 is in the form of a data base of the test results intended to be used for further analysis of the fracture performance of steel cylinders.

5 Experimental test programme

5.1 Types of cylinder tested

Flawed-cylinder burst tests were conducted on cylinders that represented all of the currently used and proposed new types of seamless steel cylinders. A brief description of all the cylinders that were tested is shown in Tables 1 to 5. For this study, the cylinders were classified into material groups (designated groups A to E) based on the actual measured tensile strength (R_m) of the cylinders that were tested. The actual measured tensile strength for each group of cylinders that was tested is shown in Tables 6 to 10. The general description of the cylinders in each material group is shown below. Cylinders made from materials in groups A to D are currently being produced and used throughout the world. Cylinders made from materials in group E, are experimental and are not currently authorized for use.

Material group	Description of cylinder	Tensile strength R_m
A	Cylinders made from carbon steel and which may be heat treated by normalizing, normalizing and tempering, or quenching and tempering	$R_m < 750$ MPa
B	Cylinders made from alloy steel (Cr-Mo steels) heat treated by quenching and tempering; these cylinders may generally be used for all gases	750 MPa $\leqslant R_m \leqslant$ 950 MPa
C	Cylinders made from alloy steel (Cr-Mo steels) heat treated by quenching and tempering; these cylinders are restricted to use with non-corrosive gases and are made in accordance with ISO 9809-1	950 MPa $\leqslant R_m \leqslant$ 1 080 MPa
D	Cylinders made from alloy steel (Cr-Mo steels) heat treated by quenching and tempering; high strength and high toughness steel cylinders restricted to use with non corrosive gases and made in accordance with ISO 9809-2	1 080 MPa $\leqslant R_m \leqslant$ 1 210 MPa
E	Experimental cylinders; extra high strength; not currently authorized for use	$R_m >$ 1 210 MPa

Within each main material group (A to E) material subgroups are designated, e.g., material subgroup A-1, A-2. All the cylinders within a given subgroup were made to the same specification, of the same size (diameter, thickness, and volume), the same material, the same specified tensile strength range, the same designated service pressure and test pressure and were made by the same manufacturing process. The cylinders in a specific material subgroup (e.g. subgroup B-2) may be of a different alloy, size, design specification or manufacturing process than cylinders in a different materials subgroup (for example B-3) in the same main material group (e.g. group B). However, the actual measured tensile strength for all cylinders in a material group will be in the same range (e.g., 750 MPa to 950 MPa for all cylinders in group B).

In Tables 1 to 5, it should be noted that the code numbers for some material subgroups (e.g. B-1, C-1 and C-2) are missing. The cylinders in these missing material subgroups were tested using the flawed-cylinder burst test with cyclical pressurization and the results are given in ISO/TR 12391-3.

In Tables 1 to 5, each flawed-cylinder burst test is assigned a number in sequence, as shown in the first column, for purposes of tracking each test. The same number is then used to identify the cylinders in the tables for the results of the mechanical properties tests (Tables 6 to 10) and in the tables for the results of the burst test (Tables 12 to 16). In addition, each individual cylinder tested is assigned a number, such as A-1-1, as shown in the second column of the tables.

The specified tensile strength range given in Tables 1 to 5 is the range of “guaranteed” minimum, $R_{\mathrm{g,\ min}}$, and maximum, $R_{\mathrm{g,\ max}}$, tensile strength designated by the cylinder manufacturer or the cylinder specification used for the design of the cylinder. These values are used to calculate the cylinder wall thickness when designing the cylinder. These are specified values rather than actual measured values of the tensile strength, R_{m}. In a few cases, the manufacturer did not provide a specified minimum or maximum tensile strength values.

The information required to calculate the wall thickness of the cylinder, the test pressure of the cylinder and the service pressure of the cylinder is listed in Tables 1 to 5. This information includes the outside diameter of the cylinder, D, and the particular national or international design specification used by the manufacturer to design the cylinder. These specifications are used to calculate the stress in the cylinder wall, the minimum design wall thickness of the cylinder, t_{d}, the maximum design test pressure, P_{h}, and the maximum design service pressure, P_{s}. Each of the national or international cylinder specifications has a different formula for calculating the stress in the wall of the cylinder and therefore the design wall thickness for a specified cylinder diameter and service pressure. In some cases the cylinders tested were not designed to an existing design specification so these cylinders are designated as experimental cylinders.

The other items listed in Tables 1 to 5, for information purposes only, are the type of manufacturing process used to make the cylinder, the cylinder volume (in litres) and the specific material used, when given. This information is shown only to better identify the cylinders that were tested and is not used for any analysis of the test results.

In Tables 1 to 5, the results show that in some cases the same cylinder was tested several times. This was achieved by welding the cylinder shut after it had leaked and re-testing it until it failed by fracturing. In this case the cylinder numbering sequence is shown repeatedly as the same cylinder number, e.g. as A-1-1, but the burst test number is shown sequentially as number 1, 2, 3 and 4. In other cases, a different cylinder was used for each burst test in the material subgroup series and each cylinder was tested only once. In these cases, each cylinder will have the same material subgroup number but will have a different cylinder number. An example of this is shown for material subgroup B-3 where the cylinders tested are numbered as B-3-1, B-3-2, etc.

In Tables 1 to 5, there are a few cases, such as material subgroup B-2, where the specified tensile strength range (e.g., 1 069 MPa to 1 207 MPa) does not agree with the tensile strength range for that particular material groups (e.g., 750 MPa to 950 MPa). In these cases, the cylinders were manufactured to a particular strength range (e.g., 1 069 MPa to 1 207 MPa) but were then re-tempered to change their actual strength for use in the studies reported here. For these studies, the test results for these cylinders were put into the material group represented by the actual measured tensile strength range and not the tensile strength range represented by the specified range.

It should be noted that in a few cases, the actual measured tensile strength (R_{m}) for one or more cylinders in a particular material subgroup is slightly outside the designated range for the tensile strength of the particular material subgroup in which the cylinder is included. However, the measured tensile strength of the rest of the cylinders from that material subgroup that were tested are within the appropriate tensile strength range for that material subgroup. Examples of this occur in material subgroups A-1, B-9, C-5, D-9 and D-10.

5.2 Material properties tests

Conventional mechanical properties tests, such as tensile tests and Charpy-V-notch tests, were conducted on each set of cylinders on which flawed-cylinder burst tests were performed. The results of these tests are shown in Tables 6 to 10 for each group of materials.

The tensile test results shown in Tables 6 to 10 are the actual measured yield strength, R_{ea}, the actual measured tensile strength, R_m, and the total elongation, A. These material properties are required to be measured by all of the existing national or international cylinder design specifications. The actual measured tensile strength, R_m value is used to determine that the cylinder meets the specification to which it is manufactured and is used in this test programme to determine in which material group the tested cylinder should be placed. The actual measured yield strength, R_{ea} is used to determine that the cylinder meets the requirement for the yield strength to tensile strength ratio when this ratio is a part of the specification. The actual measured tensile strength, R_m value may also be used for additional analysis of the cylinder design parameters permitted in some of the specifications. The total elongation, A is used to determine that the requirement for minimum elongation is met when that is part of the specification to which the cylinder is manufactured. The elongation value is not used for any calculations in the design of cylinder.

For cylinders manufactured in the United States (such as those designated as DOT type 3A or 3AA) the tensile tests used to measure the properties of the cylinders were of the type specified by the 49 CFR part 178 [1]. These test specimens have a fixed gauge length of 50 mm, a fixed width of 38 mm and a thickness equal to the actual wall thickness of the finished cylinder from which the specimens were taken. For other cylinders the tensile tests of the type specified by ISO 6892:1998 were used. The ISO test specimens have a gauge length of 5,65 × the square root of the cross section of the specimen, a width of 4 × the specimen thickness and a thickness equal to the actual wall thickness of the finished cylinder from which the specimens were taken. The ultimate tensile strength and the yield strength values should be essentially the same when measured with either the DOT or the ISO type of specimen. The measured elongation values will be different depending on the specific type of tensile specimen used.

The Charpy-V-notch tests were conducted in accordance with test method ASTM E-23 [6] for cylinders manufactured in the United States. For other cylinders, the Charpy-V-notch tests were conducted in accordance with test method ISO 148:1983. The Charpy-V-notch impact test energy values should be essentially the same when measured with either the ASTM or the ISO test method. The Charpy-V-notch test specimens had cross sectional dimensions of either 10 mm deep by 5 mm thick or 10 mm deep by 4 mm thick depending on the available wall thickness of the cylinder and the orientation of the Charpy-V-notch test specimen. The exact dimension of each Charpy-V-notch test specimen used is listed in Tables 6 to 10. The Charpy-V-notch tests were conducted either at ambient temperature (20 °C) or at low temperature (– 50 °C), as listed in Tables 6 to 10.

NOTE An exception is for material subgroup D-14 in which the low temperature tests were conducted at – 20 °C instead of at – 50 °C.

The Charpy-V-notch test specimens were either oriented with the longitudinal axis of the specimen parallel to the longitudinal axis of the cylinder (designated longitudinal specimens) or with the longitudinal axis of the specimen perpendicular to the longitudinal axis of the cylinder (designated transverse specimens). As shown in Tables 6 to 10, not all combinations of test temperatures and specimen orientation were used on each cylinder that was tested. The total energy absorbed in breaking the Charpy-V-notch test specimens was measured in Joules (J). All Charpy-V-notch test results are reported in J/cm^2, where the total energy absorbed is divided by the area of the specimen ligament below the specimen notch.

In the specifications for certain cylinder designs, particularly for material group C and D type cylinders, minimum Charpy-V-notch energy levels are required. The Charpy-V-notch tests were conducted on all cylinders to determine that these requirements were met. The Charpy-V-notch energy test results are not used to evaluate the results of the flawed-cylinder burst test. However, the Charpy-V-notch energy test results are reported here because these results may be used to evaluate the fracture performance of the cylinders using alternative analysis procedures to the flawed-cylinder burst test.

For certain material subgroups on which flawed-cylinder burst tests were conducted, mechanical properties test specimens were taken from each cylinder in the material subgroup after the burst test was completed. In this case, the test results are listed in the tables of results for each of the individual cylinders. Material subgroups in which each cylinder was tested are subgroups A-1, B-6 (tensile tests only), B-9 (tensile tests only), B-11, C-3 (tensile tests only), C-10 (tensile tests only), C-12, C-13, D-2, D-3 and D-10.

For other material subgroups on which flawed-cylinder burst tests were conducted, a single cylinder was tested multiple times by welding the flaw shut after a flawed-cylinder burst resulted in a leak and then repeating the test. In this case, mechanical properties test specimens were taken after all of the burst tests had been completed and the test results shown in the tables are the same for each cylinder in the material subgroup. Material subgroups in which only one cylinder was tested are subgroups B-2, C-3, C-4, C-11 and D-4.

For some material subgroups on which flawed-cylinder burst tests were conducted, mechanical property test specimens were taken only from selected cylinders in that particular material subgroup after the burst test was completed. In these case, results are shown in the tables of results for the cylinders for which mechanical property tests were conducted and blank spaces are shown for the other cylinders on which flawed-cylinder burst tests were conducted but mechanical property tests were not conducted. Because the cylinders in a particular material subgroup are all of the same type and from the same production batch, the mechanical property test results for the cylinders that were tested are considered to adequately represent the properties of all cylinders in that material subgroup. Material subgroups in which selected cylinders were tested are subgroups A-2, B-4, B-5, B-7, B-8, C-5, C-6, C-14, D-5, D-6, D-9, D-11, D-14, E-1 and E-2.

In a few cases, no mechanical property tests were taken from cylinders on which flawed-cylinder burst tests were conducted. In these cases, the mechanical property test results that are shown in the tables are considered to be typical of cylinders of the type in the material subgroup. Generally, these test results are taken from the production records for cylinders of the type that are represented by the material subgroup. These results are marked in Tables 6 to 10 with (T) for typical only attached to the test result value. Material subgroups in which only typical properties are reported are subgroups C-7, C-8 and C-10.

The fracture toughness of the steel cylinders was measured on a limited number of the cylinders on which flawed-cylinder burst tests were conducted. All test were conducted in accordance with ASTM 813-89 [7]. All fracture toughness tests were conducted at ambient temperature (+ 20 °C). Fracture toughness tests were conducted on materials subgroups B-3, D-5, D-6 and D-11. The results of all fracture toughness tests are shown in Table 11.

5.3 Description of the flawed-cylinder burst test

The flawed-cylinder burst test is used to evaluate the overall fracture performance of the entire cylinder and not just the “fracture toughness” of the material as determined with conventional fracture toughness test specimens. The flawed-cylinder burst test is intended to be both a “design qualification approval test” and a “production lot test”. The full details of the test and the criteria for acceptable fracture performance of steel cylinders are given in 8.2.3 of ISO 9809-2:2000.

In the flawed-cylinder burst test, the fracture performance of the cylinder is evaluated by pressurizing a cylinder with a designated type (shape and sharpness) and size (length and depth) of surface flaw to failure. Failure occurs either by leaking or by fracturing.

The cylinder to be tested has a flaw machined into the exterior surface of the cylinder wall. The flaw is machined in the location of probable maximum stress under pressurized loading, i.e. a longitudinal surface flaw at mid-length and at thinnest place in the cylinder wall. To make the tests adequately uniform and reproducible, a surface flaw with a standard geometry is required. A standard Charpy-V-notch milling cutter is used to machine the flaw to the designated length and depth. The milling cutter is required to meet the following specification:

— Thickness of the cutter = 12,5 mm ± 0,2 mm;

— Angle of the cutter = 45° ± 1°;

— Tip radius $\leqslant$ 0,2 mm;

— For cylinders $\leqslant$ 140 mm in diameter, cutter diameter = 50 mm ± 0,5 mm;

— For cylinders $>$ 140 mm in diameter, cutter diameter = 60 mm to 80 mm.

This results in a "surface flaw" geometry of the type shown in Figure 1. The flaw length, l_o, and the flaw depth, d, are adjusted for each test as described below. The flaw length is normally expressed in multiples, n, of the cylinder design minimum wall thickness, t_d, ($l_o = n \times t_d$) and the flaw depth is expressed as a percentage of the cylinder design minimum wall thickness, i.e. flaw depth = $d/t_d \times 100$.

Pressurization is carried out hydrostatically. In conducting the test, each cylinder is filled with water at room temperature and the pressure is increased continuously until the cylinder fails at a pressure designated as the failure pressure P_f. Failure occurs when the ligament of metal below the surface flaw fails.

The stress required to fracture the ligament of metal below the surface flaw and to cause failure of the cylinder does not change with the type of pressurizing medium (i.e. whether it is pneumatic using gas or hydraulic using water). Because this test method is intended only to evaluate fracture initiation and not fracture propagation, water can be used as the pressurizing medium to evaluate the fracture initiation of the cylinder. This simplifies the testing and is safer than testing using a gas as the pressurizing medium. A few tests were conducted using gaseous nitrogen to confirm that the behaviour of the flawed-cylinder burst test is the same for a pneumatic test as for a hydrostatic test. These results of these tests are described in 6.7.2.

After the ligament fails, the cylinder will either leak or fracture. The length of the flaw is measured after the test has been completed in order to determine if fracture has occurred. For this test, the definition of fracture is: "an extension of at least 10 % in the length of the machined flaw in the longitudinal direction". The failure pressure and failure mode, either "leak" or "fracture", are reported as the test results.

Although, for cylinders in service, flaws are normally expected to develop on the interior surface of the cylinder wall, it was determined that production of a standard internal flaw for testing purposes was not practical. However, the external flaw in "thin walled" cylinders should be reliable to evaluate the fracture performance of the cylinders.

For a specified flaw length, conducting the flawed-cylinder burst test requires that a series of cylinders be tested, in which the depth, d, of the machined flaw is varied until failure occurs by leaking in at least one cylinder and by fracturing in at least one cylinder; e.g, if the first cylinder tested with a certain specified flaw length leaks, similar cylinders with the same flaw length but with progressively smaller flaw depths will be tested until a sufficiently high failure pressure is reached to cause at least one cylinder to fail by fracturing. For a specified flaw length, the depth of the flaw determines the pressure at which the cylinder fails, P_f. This pressure determines the stress in the wall at the time of failure. For the specified flaw size and failure pressure, P_f, whether the cylinder fails by leaking or by fracturing depends on the fracture resistance of the cylinder. This testing sequence necessarily results in several redundant (and unused) test results at each specified flaw length because only the test results with highest pressure at which a leak occurs and the lowest pressure at which a fracture occurs are used to define the leak-fracture boundary. This is illustrated in Figure 2.

The fracture performance of the cylinder is determined with the flawed-cylinder burst test by empirically determining the "leak-fracture boundary" for the specified flaw length. The "leak-fracture boundary" for a specified flaw length is defined as the average of the highest pressure at which a leak occurs and the lowest pressure at which a fracture occurs.

During the development of the flawed-cylinder burst test, tests were conducted on series of cylinders over a range of flaw lengths to define the "leak-fracture boundary" for each particular type of cylinder and material. This was done to evaluate the overall fracture performance of the cylinder type. An example of these test results is shown in Figure 3. It is expected that this procedure to determine the full "leak-fracture boundary" over a range of flaw lengths will be used only for the "design qualification" evaluation of new cylinders (i.e. for new materials and production processes) to demonstrate that the cylinder type has adequate fracture resistance.

Once the full fracture performance is determined for a particular cylinder type from the flawed-cylinder burst tests conducted during the "design qualification" procedure, the testing procedure used to evaluate cylinders during large scale production can be simplified and made much more efficient. For production testing, a single specified flaw length, often 10 × the cylinder wall thickness, can be used and the criteria for a successful test is that cylinder failure occurs by leaking at a pressure in excess of the defined service pressure of the cylinder. In this case, if a cylinder fails by leaking at a pressure less than the defined service pressure, retest on the same cylinder may be allowed. The cylinder may be welded shut and a new flaw of the same length but with a smaller flaw depth can be machined into the cylinder and retesting to a higher failure pressure can be conducted.

To determine if the fracture resistance of the cylinders, as determined by the flawed-cylinder burst test is adequate, the failure pressure, P_f, at the leak-fracture boundary for a specified flaw length is compared with the designated service pressure, P_s, of the cylinder; e.g., for a specified flaw length such as 10 × the cylinder wall thickness it may be required that the measured failure pressure, P_f, exceed the defined service pressure, P_s, for the cylinder design (i.e. $P_f/P_s > 1{,}0$). This will ensure that failure of the cylinder does not occur in service unless a very long and deep flaw occurs in the cylinder.

During the development of the flawed-cylinder burst test, it was decided that the acceptable level of fracture resistance for cylinders of any strength level should be equivalent to the fracture resistance of existing cylinders that have been used for extended periods of time. Therefore, flawed-cylinder burst tests were conducted on cylinders with tensile strength levels ranging from about 640 MPa to 1 400 MPa. The existing cylinders (with tensile strengths levels less than 950 MPa) have provided fracture-safe performance over many years of service. From these results, it was determined that to have fracture resistance equivalent to the fracture resistance of existing cylinders, new, higher strength steel cylinders should have a leak-fracture boundary of P_f/P_s greater than 1,0 when the designated flaw length was about 10 × the cylinder wall thickness (t_d).

6 Flawed-cylinder burst test results

6.1 Flawed-cylinder burst test procedure

The results of all of the flawed-cylinder burst tests that were conducted are listed in Tables 12 to 16. For each cylinder tested, the crack length, l_o, in terms of a multiple of the design minimum cylinder wall thickness, t_d, is given as $l_o = n \times t_d$ (e.g. $l_o = 10\ t_d$). This term is used as a common reference to compare cylinders with different wall thicknesses. The flaw depth, d, is given as a percentage of the design minimum cylinder wall thickness, t_d (e.g. $100 \times d/t_d = 80\ \%$).

For a specified flaw length, the pressure at which the cylinder fails depends on the depth of the flaw and the thickness of the remaining ligament of metal below the flaw. Failure of the cylinder occurs when the ligament of metal below the flaw breaks. The machined flaw depth is varied to control the pressure at which the cylinder fails. Once the failure pressure, P_f, is reached, the cylinder will either leak or fracture depending on whether the combination of stress and flaw length is below or above the critical level for fracture to occur.

The actual cylinder wall thickness, t_a, at the location of the machined flaw is measured after the test. The actual cylinder wall thickness at any location in the cylinder should be greater than the design minimum cylinder wall thickness, t_d. It should be noted that during production of the cylinders, only the average cylinder wall thickness is measured and so it is possible that there may be specific locations in the cylinder where the actual cylinder wall thickness, t_a, at a specific location, may be slightly lower than the design minimum cylinder wall thickness, t_d. The difference between the actual cylinder wall thickness and the design minimum cylinder wall thickness depends on the method of manufacture used to produce the cylinder. The actual measured cylinder wall thickness, t_a, is included in the data to permit additional analysis of the results using this cylinder wall thickness instead of the nominal cylinder wall thickness that is given by the design minimum cylinder wall thickness, t_d. The pressure at the time that the cylinder fails, either by leaking or by fracturing, is given as P_f measured in bar. The failure mode, either leak or fracture, is reported.

The ratio of the failure pressure, P_f, to the marked service pressure of the cylinder, P_s, is given as P_f/P_s. The marked service pressure (bar) is the maximum pressure to which the cylinder may be filled when in service and is specified by the cylinder manufacturer. It should be noted that the marked service pressure for the cylinders of the same size and tensile strength will be slightly different depending on the design specification used by the manufacturer. The cylinders were designed and the marked service pressure was specified