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Gas cylinders — Refillable seamless steel — Performance tests —

Part 3:
Fracture performance tests — Cyclical burst tests

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

Partie 3: Essais de mode de rupture — Essais de rupture cyclique

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Foreword

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

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

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

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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this part of ISO/TR 12391 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 12391-3 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 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 3: Fracture performance tests — Cyclical burst tests

1 Scope

This part of ISO/TR 12391 applies to seamless refillable cylinders of all sizes from 0,5 l up to and including 150 l water capacity produced of steel with tensile strength (R_m) greater than 1 100 MPa.

It can also be applied to cylinders produced from steels used at lower tensile strengths. In particular, it provides the technical rationale and background to guide future alterations of existing ISO standards or for developing advanced design standards.

This part of ISO/TR 12391 is a summary and compilation of the test results obtained during the development of the “flawed-cylinder cyclical burst test”. The test is an alternate test method to the flawed-cylinder burst test with monotonic pressurization and is used to evaluate the fracture performance of steel cylinders which are used to transport high-pressure compressed gases.

The concept and development of the flawed-cylinder cyclical burst test is described in ISO/TR 12391-1. The details of the test method and the criteria for acceptable fracture performance of steel cylinders are given in 9.2.5.3.2 of ISO 9809-2:2000. In this part of ISO/TR 12391, test results are reported for more than one hundred flawed-cylinder cyclical burst tests that were conducted on seamless steel cylinders that ranged in tensile strength from 750 MPa to 1 210 MPa. The test method is intended to be used both for the selection of materials and to establish design parameters in the development of new cylinders 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 12391-2, *Gas cylinders — Refillable seamless steel — Performance tests — Part 2: Fracture performance tests — Monotonic burst tests*

3 Symbols

A is the elongation, expressed as a percentage (= d/t_d);

d is the flaw depth, expressed in millimetres (= $A \times t_d$);

D is the outside diameter of the cylinder, expressed in millimetres;

l_o is the flaw length, expressed in millimetres (= $n \times t_d$);

n represents multiples of t_d (= l_o/t_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_e is the guaranteed minimum yield strength;

R_{ea} is the actual measured value of yield strength, expressed in megapascals;

$R_{g, max}$ is the maximum value of tensile strength guaranteed by the manufacturer, expressed in megapascals;

$R_{g, min}$ 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, etc.) are stored and transported in portable steel cylinders. These cylinders are designed, manufactured, and maintained in accordance with ISO 9809-1 and ISO 9809-2. The cylinders are constructed from specified alloy steels that are generally modified versions of steel alloys such as AISI 4130 or 34 Cr Mo 4 and AISI 4140 [1] 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 by 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 from 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, which are modifications of the AISI 4130 and AISI 4140 steels, 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 out of 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 (WG 14) 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". WG 14 decided that the test method and specifications that were developed should demonstrate that the overall “fracture resistance” of cylinders made out of 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 or have been based on empirical correlations with the Charpy-V-notch (CVN) test impact energy [4]. The objectives of these test methods and procedures 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 steel alloys 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” and the “Flawed-cylinder cyclical burst test”.

In these test methods, 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. The proposed test methods consist 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 flawed-cylinder cyclical burst test and the development conducted under WG 14 are described in ISO/TR 12391-1. The results of the flawed-cylinder burst test conducted with monotonic pressurization are described in ISO/TR 12391-2.

In the development of the test method and acceptance criteria for the flawed-cylinder burst test and the flawed-cylinder cyclical burst test, it was decided that the fracture performance of newer, higher-strength steel cylinders should be essentially 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 and flawed-cylinder cyclical burst tests were conducted on cylinders with strength levels covering the full range of strength levels currently being produced in the world. Flawed-cylinder burst tests were conducted on cylinders made from steels ranging in tensile strength from 620 MPa to 1 400 MPa and flawed-cylinder cyclical burst tests were conducted on cylinders made from steels ranging in tensile strength from 750 MPa to 1 210 MPa. Ten different companies in seven different countries (Austria, France, Germany, Japan, Sweden, the United Kingdom and the United States) conducted flawed-cylinder burst tests and flawed-cylinder cyclical burst tests.

This part of ISO/TR 12391 is limited to a summary and compilation of the results of the flawed-cylinder cyclical burst tests that were conducted by WG 14 during the development of the test method for the flawed-cylinder cyclical burst tests. This part of ISO/TR 12391 is in the form of a database of the test results that is 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 cyclical 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 3. For this study, the cylinders were classified into material groups (designated groups B to D) 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 4 to 6. The general description of the cylinders in each material group is shown below. Cylinders made from materials in groups B to D are currently being produced and used throughout the world.

NOTE Material groups designated A and E were only used for cylinders tested using the flawed-cylinder burst test with monotonic pressurization and the results are reported in ISO/TR-12391-2.

Material group	Description of cylinder	Tensile strength R_m
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 < $R_m \leqslant$ 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 gasesand 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 gasesand and made in accordance with ISO 9809-2	1 080 MPa $\leqslant R_m \leqslant$ 1 210 MPa

Within each main material group (B to D) material subgroups are designated, e.g., material subgroups B-1 and B-10. 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-10) may be of a different alloy, size, design specification or manufacturing process than cylinders in a different materials subgroup (e.g. B-1) 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 3, it should be noted that the code numbers for some material subgroups (e.g. B-2, C-3 and C-4) are missing. The cylinders in these missing material subgroups were tested using the flawed-cylinder cyclical burst test, with monotonic pressurization and were not tested using the flawed-cylinder cyclical burst test procedures. The results of the tests on cylinders made from missing material subgroups using the flawed-cylinder cyclical burst test, with monotonic pressurization are reported in ISO/TR 12391-2.

In Tables 1 to 3, each flawed-cylinder cyclical 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 property tests (Tables 4 to 6) and in the tables for the results of the flawed-cylinder cyclical burst test (Tables 7 to 9). In addition, each individual cylinder tested is assigned a code, such as CB-B-1-1 as shown in the second column of the tables; e.g. this code shows that the test is a cyclical burst test (CB), for material subgroup B-1, and is cylinder number 1 in this material subgroup.

The specified tensile strength range shown in Tables 1 to 3 is the range of "guaranteed" minimum, $R_{g, min}$, and maximum, $R_{g, max}$, 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 are shown in Tables 1 to 3. This information includes the outside diameter or the cylinder, D, and the particular national or international design specification (when provided by the manufacturer) 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 may have 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 shown in Tables 1 to 3, for information purposes only, are:

— the type of manufacturing process used to make the cylinder;

— the cylinder volume (in litres);

— the specific material used (when provided by the manufacturer).

This information is only shown in order to better identify the cylinders that were tested and is not used for any analysis of the test results.

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 the same material subgroup that were tested is within the appropriate tensile strength range for that material subgroup.

5.2 Material properties tests

Conventional mechanical properties tests, such as tensile tests conducted in accordance with ISO 6892 and Charpy-V-notch tests conducted in accordance with ISO 148, were carried out on each set of cylinders on which flawed-cylinder cyclical burst tests were performed. The results of these tests are shown in Tables 4 to 6 for each group of materials.

The tensile test results shown in Tables 4 to 6 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 value is used to determine that the cylinder meets the specification to which it is manufactured and is used in this test programme to classify the cylinder in the appropriate material group tested. The actual measured yield strength 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 value may also be used for additional analysis of the cylinder design parameters permitted in some of the specifications. The total elongation 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 CFR Title 49 Part 178 [2]. 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 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 E23-02 [3] for cylinders manufactured in the United States. For other cylinders, the Charpy-V-notch tests were conducted in accordance with the test method described in ISO 148. 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 dimensions of each Charpy-V-notch test specimen used are shown in Tables 4 to 6. The Charpy-V-notch tests were conducted either at ambient temperature (20 °C) or at low temperature (– 50 °C), as shown in Tables 4 to 6.

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 4 to 6, 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 groups C and D 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 cyclical 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 alternate analysis procedures to the flawed-cylinder cyclical burst test.

For certain material subgroups on which flawed-cylinder cyclical 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 shown in the tables of results for each of the individual cylinders.

For some material subgroups on which flawed-cylinder cyclical burst tests were conducted, mechanical properties test specimens were taken only from selected cylinders in that particular material subgroup after the burst test was completed. In these cases, 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 cyclical burst tests were conducted but mechanical properties 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 properties test results for the cylinders that were tested are considered to adequately represent the properties of all cylinders in that material subgroup.

5.3 Description of the flawed-cylinder cyclical burst test

The flawed-cylinder cyclical 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 cyclical 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 9.2.5 of ISO 9809-2:2000.

In the flawed-cylinder cyclical burst test, the fracture performance of the cylinder is evaluated by cyclically pressurizing a cylinder with a designated type (shape and sharpness) and size (length and depth) of surface flaw until failure occurs. 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 the thinnest place in the cylinder wall. To make the tests adequately uniform and reproducible, a surface flaw with a deep enough standard geometry is required. The geometry of the standard flaw is shown in Figure 1. 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 $\pm$ 0,2 mm;

— angle of the cutter = 45° $\pm$ 1°;

— tip radius $\leqslant$ 0,2 mm;

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

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

This machined flaw is a surface flaw of the type shown in Figure 1. The flaw size is specified as:

— flaw length, $l_o = 1{,}6\,(D \times t_d)^{0{,}5}$

NOTE For the size of cylinders tested here, this flaw length is approximately $l_o = 10 \times t_d$.

— flaw depth, $d > 0{,}60 \times t_d$

Pressurization is carried out hydrostatically. During the test, each cylinder is filled with water at room temperature and the pressure is cycled until the cylinder fails. The maximum cycling pressure is the "adjusted design service pressure" = $P_s \times (t_a/t_d)$. This pressure is also the designated failure pressure, P_f, of the cylinder in the test. The minimum cycling pressure is 10 % of the maximum pressure, but not more than 30 bar. The maximum cycling frequency is 15 cycles/min.

The test is continued until failure occurs. The number of cycles to failure is recorded and the failure mode (either leak or fracture) is recorded. 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. The failure pressure is the maximum cyclical pressure, $P_f = P_s \times (t_a/t_d)$. During the flawed-cylinder cyclical burst test, a single test cylinder may be sufficient if the failure occurs by leaking, and shows that the cylinder has adequate fracture resistance.

The overall fracture performance of the cylinder is determined with the flawed-cylinder cyclical burst test by empirically determining the "leak-fracture boundary" for the specified maximum cycling pressure. This requires that a series of cylinders with different flaw lengths be tested. The "leak-fracture boundary" for a specified maximum cycling pressure is defined as the average of the longest flaw length at which a leak occurs and the shortest flaw length at which a fracture occurs.

During the development of the flawed-cylinder cyclical burst test, some tests were conducted on series of cylinders with 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 such test results is shown in Figure 2. 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 cyclical 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 cylinder with the specified flaw length is tested at the designated maximum cycling pressure and if the failure mode is a ”leak”, the cylinder satisfies the criteria for adequate fracture resistance given in ISO 9809-2.

During the development of the flawed-cylinder cyclical 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 cyclical burst tests were conducted on cylinders with tensile strength levels ranging from about 750 MPa to 1 210 MPa. The existing cylinders (with tensile strengths levels less than 950 MPa) have provided fracture-safe performance during 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, $l_o = 1{,}6\ (D \times t_d)^{0{,}5}$.

6 Flawed-cylinder cyclical burst test results

6.1 Flawed-cylinder burst test procedure

The results of all of the flawed-cylinder cyclical burst tests that were conducted are shown in Tables 7 to 9. 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, at the start of the cycling testing 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 and cycling pressure, the number of cycles at which the cylinder fails depends on the initial depth of the flaw and the thickness of the remaining ligament of metal below the flaw. Failure of the cylinder occurs when the original flaw depth is increased by fatigue due to the pressure cycling so that the ligament of metal below the flaw breaks. Once the ligament of metal below the flaw fails, 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. The actual measured cylinder wall thickness is included in the data in order 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. 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 would be slightly different depending on the design specification used by the manufacturer. The cylinders were designed and the marked service pressure was specified according to the design specification used in the country of manufacture. The use of the parameter P_f/P_s permits the leak-fracture boundary to be defined in terms of the marked service pressure of the cylinder. This allows a comparison of cylinders of different sizes (diameters and wall thickness) to be made on a common basis.

ISO 9809-2 requires that the measured ratio of the failure pressure to the service pressure, P_f/P_s, be adjusted to account for the local thickness of the cylinder wall at the location of the flaw. This adjustment was made to the measured values of the P_f/P_s ratio for all of the flawed-cylinder cyclical burst tests conducted in this study. The adjusted ratio of the failure pressure to the service pressure, $P_{f,\ adjusted}/P_s$, is shown as the last column in Tables 7 to 9.

For completeness of the database, the results of all tests that were conducted are shown in Tables 7 to 9. It should be noted that a range of test parameters (such as flaw length, flaw depth and maximum cycling pressure) were used in the tests conducted here as part of the development of the flawed-cylinder cyclical burst procedure. Therefore, many of the tests were not conducted using the exact flaw length, flaw depth, and maximum cycling pressure specified in ISO 9809-2 and shown above.

For some of the material subgroups, cylinders with a range of flaw lengths were tested to define the full leak-fracture boundary over a range of flaw lengths. The results of flawed-cylinder cyclical burst tests for these material subgroups are shown in Tables 7 to 9 and are plotted in the Figures 3 to 7. To define the leak-fracture boundary, the shortest flaw length for which a failure occurred by fracture and the longest flaw length for which failure occurred by leaking are plotted. An estimate of the leak-fracture boundary is shown in Figures 3 to 7 for each material subgroup. Data for failures over a range of flaw lengths is available for material subgroups B-1, C-5, D-1, D-7 and D-12.

For some of the other material subgroups, all the flawed-cylinder cyclical burst tests were conducted at a single defined flaw length and both leak results and fracture results were obtained. For these tests the leak-fracture boundary can be defined only for the single specified flaw length. These results are not plotted but the test results are summarized and the estimated leak-fracture boundary for these material subgroups is shown in Table 10. Flawed-cylinder cyclical burst tests for material subgroups C-10 and C-11 were conducted at only a single value of flaw length.

For some of the material subgroups, all the flawed-cylinder cyclical burst tests were conducted at a single defined flaw length and only leak results or fracture results were obtained. These test results are summarized in Table 11. An estimate of the leak-fracture boundary is reported as the minimum flaw length at specified pressure at which failure by fracture occurs or the maximum flaw length at a specific pressure at which failure by leaking occurs. These results may be of value if there are similar cylinders in other material subgroups with which they may be combined to estimate the leak-fracture boundary more accurately.

Flawed-cylinder cyclical burst tests for material subgroups B-10, B-11, C-2, C-12, C-13, C-14, D-2 and D-13 were conducted at only a single value of flaw length and each test series resulted in failure only by leaking or by fracture. Because there were failures that did not occur by both leaking and failure, the leak-fracture boundary could not be determined. It could only be estimated that the leak-fracture boundary was greater than the longest flaw at which failure occurred by leaking or less than the shortest flaw where failure occurred by fracture.

6.2 Flawed-cylinder cyclical burst test results for group B materials

The cylinders made from group B materials were cylinders made from chromium-molybdenum alloy steel. These cylinders are representative of the largest number of cylinders that have been in worldwide use for about 60 years. Cylinders of this type normally have a service pressure rating of 150 bar to 200 bar.

Eleven cylinders from material subgroup B-1 were tested. The results of these tests are shown in Table 7. The cylinders in material subgroup B-1 were all tested at a maximum cyclical pressure of 1,5 × the design service pressure, i.e. $P_f/P_s = 1,5$. This is the normal pressure used for hydrostatically retesting these cylinders. The initial flaw length ranged from $l_o = 8,6 \times t_d$ to $l_o = 11,2 \times t_d$. The initial flaw depth ranged from 31,3 % to 78,8 % of the design wall thickness, t_d, of the cylinders. Four of the test cylinders failed by leaking and seven of the cylinders failed by fracturing. As shown in Figure 3, the leak-fracture boundary for material subgroup B-1 cylinders is at a flaw length of $l_o = 8,8 \times t_d$ at a failure pressure of 1,5 × the service pressure, P_s. Therefore, these cylinders should have an adequate level of fracture resistance according to the requirements of ISO 9809-2.

Only one cylinder from material subgroup B-10 was tested by cyclical pressurization. This cylinder was tested at a maximum cyclical pressure of 1,72 × the design service pressure, i.e. $P_f/P_s = 1,72$. This is above the normal pressure used for hydrostatically retesting these cylinders. The initial flaw length was $l_o = 9,9 \times t_d$. The initial flaw depth was 9,8 % of the design wall thickness of the cylinders. The cylinder failed by fracturing. A single cylinder from the B-10 material subgroup was also tested using the flawed-burst testing procedure with monotonic pressurization. This cylinder had an initial flaw depth of 83,3 % of the design wall thickness and failed at a maximum pressure of 0,93 × the design service pressure, i.e. $P_f/P_s = 0,93$. This cylinder failed by leaking. However, because the cylinder that was tested using cyclical pressurization and the cylinder that was tested using monotonic pressurization had significantly different failure pressures and different initial flaw depths, no specific conclusions can be drawn from these tests.