TECHNICAL REPORT

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Gas cylinders — Refillable seamless steel — Performance tests —

Part 4:
Flawed-cylinder cycle test

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

Partie 4: Cycle d'essai pour bouteilles défectueuses

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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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 12391-4 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, 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 fl*awed-cyl*inder cycle tests that were conducted to evaluate the fatigue performance of cylinders ranging in tensile strength from less 800 MPa to greater than 1 350 MPa.

Gas cylinders — Refillable seamless steel — Performance tests —

Part 4: Flawed-cylinder cycle test

1 Scope

This part of ISO/TR 12391 applies to seamless steel 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 cycle test". The "flawed-cylinder cycle test" was developed as part of a co-operative project under the direction of ISO/TC 58/SC 3/WG 14. The "flawed-cylinder cycle test" is a test method to evaluate the fatigue performance of steel cylinders that are used to transport high pressure, compressed gases.

The concept and development of the flawed-cylinder cycle test is described in ISO/TR 12391-1. The details of the test method and the criteria for acceptable fatigue performance of steel cylinders are given in 9.2.6 of ISO 9809-2:2000, "flawed-cylinder cycle test". In this part of ISO/TR 12391, test results are reported for more than a hundred flawed-cylinder cycle tests that were conducted on seamless steel cylinders ranging in measured tensile strength from less than 800 MPa to greater than 1 350 MPa. The test method is intended to be used for the selection of materials and design parameters in the development of new cylinder designs.

2 References

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

ISO 6406:—[1)], *Seamless steel gas cylinders — Periodic inspection and testing*

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*

1) To be published. (Revision of ISO 6406:1992)

ISO/TR 12391-2, *Gas cylinders — Refillable seamless steel — Performance tests — Part 2: Fracture performance test — Monotonic burst tests*

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

3 Terms and definitions

3.1
flawed-cylinder cycle test
test conducted on a finished gas cylinder having a shallow prescribed flaw of 10 % of the cylindrical wall thickness machined into the exterior sidewall and failed by cyclical internal pressurization that is normally hydraulic

3.2
flawed-cylinder burst test
test conducted on a finished gas cylinder having a deep prescribed flaw in the range of 75 % of the cylindrical wall thickness machined into the exterior sidewall and failed by internal pressurization that may be hydraulic, and is applied either monotonically or cyclically

3.3
pressure cycling test
test conducted on a finished gas cylinder that does not have a flaw machined into the exterior sidewall and failed by cyclical internal pressurization that is normally hydraulic

4 Symbols

d is the flaw depth, expressed in millimetres as a percentage of 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_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.

5 Background

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 generally contain chromium and molybdenum as the principal alloying elements. 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 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 and ductility of the steels decreases with increase in the tensile strength and above a tensile strength of about 1 100 MPa the fracture toughness and ductility were not adequate to prevent fracture of the cylinders. Recently developed new steel alloys that have both high tensile strength and high fracture toughness and ductility make it possible to construct lighter cylinders with higher tensile strength steels. This permits the use of cylinder designs with higher permissible stresses in the cylinder wall increased for a constant wall thickness. The use of higher strength steels therefore leads to 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 and more subject to fatigue failure 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 decided that new requirements were needed to assure adequate fracture and fatigue resistance of the cylinders.

To develop these requirements, WG 14 was formed under ISO/TC 58/SC 3. WG 14 was assigned the task: “develop 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”. The results of the test programme to develop suitable test methods and acceptance criteria to ensure adequate fracture performance are described in ISO/TR 12391-1, ISO/TR 12391-2 and ISO/TR 12391-3.

The original scope of the WG 14 work was amended to also include the development of a suitable test method and acceptance criteria to ensure adequate fatigue resistance for gas cylinders made from steels with tensile strengths greater than 1 100 MPa. This was required because the fatigue crack growth rate is controlled by the wall stress in the cylinder, so that by increasing the tensile strength of the steels and increasing the stress in the wall of the cylinders the cylinders may become less fatigue resistant and more subject to fatigue failure than cylinders made from steels with the traditionally used lower tensile strength levels.

WG 14 decided that the test method and acceptance criteria that were developed to evaluate the fatigue performance of the cylinders should demonstrate that the overall “fatigue resistance” of cylinders made from higher strength steels was equivalent to that of cylinders made from lower strength steels. It was decided that the test method that was developed should measure the total fatigue resistance of the cylinder and not just the fatigue crack growth rate of the steel used in the cylinder. Therefore, the test method that was developed to evaluate the total fatigue performance of cylinders was the “flawed-cylinder cycle test”. The concept of the flawed-cylinder cycle test and the development conducted under WG 14 is described in the ISO/TR 12391-1.

In the “flawed-cylinder cycle test”, the fatigue test is performed on an actual, full size, cylinder rather than by measuring the fatigue properties of the material alone by taking small-scale test specimens. This test method requires the testing of cylinders in which flaws of specified sizes are machined into the external surface of the cylinders. The cylinders are cyclically pressurized to a specified maximum pressure until failure occurs either by leaking or by fracturing or for a defined maximum number of pressure cycles without failure. The maximum and minimum cycling pressure and the number of pressurization cycles is recorded. If the cylinder fails either by leaking or by fracture, the failure mode and number of pressurization cycles to failure are recorded as the test results. If the maximum number of pressurization cycles is reached without the cylinder failing, the cylinder is confirmed as having adequate fatigue resistance.

In the development of the test method and acceptance criteria for the flawed-cylinder cycle test, it was decided that the fatigue resistance 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 adequate fatigue performance during their many years of service. Therefore, flawed-cylinder cycle 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 less than 800 MPa to greater than 1 350 MPa. During the development of the flawed-cylinder cycle test, more than one hundred flawed-cylinder cycle tests, were conducted.

The acceptance criteria for the flawed-cylinder cycle test was based on the maximum pressurization cycles and the maximum pressure that a cylinder is likely to experience in service. The maximum number of pressurization cycles was established based on a cylinder being filled rather frequently (e.g. once per day). The cycle life of a cylinder having an acceptable defect at the time of manufacture or at the time of retesting should therefore withstand an average 3 500 cycles within a 10 year re-testing period (i.e. 350 d × 10 years). In addition, for the purpose of testing, it was assumed that the absolute maximum developed pressure in a cylinder could be up to the design test pressure of the cylinder. Therefore, this pressure level was chosen for the flawed-cylinder cycle test.

The size of the standard flaw that was machined in the test cylinders was based on the size of flaws that can occur during manufacturing of the cylinder or that can be developed in service. For cylinders manufactured in accordance with ISO 9809-2, an ultrasonic inspection was required for each cylinder at the time of manufacture. The flaw detection sensitivity for this inspection is limited to 5 % of wall thickness. Therefore, flaws developed by service abuse would not be of concern unless the flaws are deeper than 5 % of the wall thickness. Furthermore, according to ISO 6406, during periodic inspection, flaws such as "cuts and gouges" are acceptable provided the depth of the flaw does not exceed 10 % of the wall thickness. Therefore, WG 14 established that a standard flaw type for the flawed-cylinder cycle test that is similar to the flaw type used in the flawed-cylinder burst test (ISO/TR 12391-2 and ISO/TR 12391-3) but with a smaller depth of 10 % of the wall thickness would be appropriate for evaluation of the effect of service induced flaws on fatigue cycle life. The standard flaw has a length of approximately 10 × wall thickness.

The flawed-cylinder cycle test is included in ISO 9809-2 as a design approval test. The test is used for the design approval of all newly designed cylinders. The details of the test method and the acceptance criteria are given in 9.2.6 of ISO 9809-2:2000.

This part of ISO/TR 12391 is limited to a summary and compilation of the results of the flawed-cylinder cycle tests that were conducted by WG 14 during the development of the flawed-cylinder cycle test method. This part of ISO/TR 12391 is in the form of a data-base of the test results and is intended to be used for further analysis of the fatigue performance of steel cylinders and to define acceptable sizes of flaws for use at the time of periodic inspection.

6 Experimental test programme

6.1 Types of cylinder tested

Flawed-cylinder cycle tests were conducted on cylinders that represented most 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 4.

The cylinders are classified in material groups based on strength level that is consistent with the classification of the cylinder materials used in the WG 14 report on the flawed-cylinder burst test described in ISO/TR 12391-2 and ISO/TR 12391-3. For this study, the cylinders were classified into material groups (designated Group B to E) based on the actual measured tensile strength, R_m, of the cylinders that were tested. No flawed-cylinder tests were conducted on cylinders of material group A strength levels (tensile strength less than 750 MPa). The actual measured tensile strength, R_m, for each group of cylinders that was tested is shown in Tables 1 to 4. 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. Cylinders made from material group E, are experimental and are not currently authorized for use.

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 gases made in accordance with ISO 9809-1.	950 MPa $< R_m \leqslant$ 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: these cylinders are restricted to use with non-corrosive gases made in accordance with ISO 9809-2.	1 080 MPa $< R_m \leqslant$ 1 210 MPa
E	Experimental cylinders; extra high strength; not currently authorized for use.	$R_m >$ 1 210 MPa

Within each main material group (FB to FE) shown in Tables 1 to 4, material subgroups are designated; e.g., material subgroup F-B-1, F-B-2. The material group coding, e.g. F-B-1 indicates that the test was a fatigue cycle test (F) and the material strength was in the B group range (R_m = 750 MPa to 950 MPa). All the cylinders within a given material subgroup were made to the same specification, of the same dimensions (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. material subgroup F-B-2) may be of a different alloy, size, design specification or manufacturing process than cylinders in a different materials subgroup (e.g. F-B-3) in the same main material group (group F-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 F-B).

In Tables 1 to 4, each flawed-cylinder cycle test is assigned a number in sequence, as shown in the first column, for the purpose of tracking each test. The same number is then used to identify the cylinders in the tables for the cycle test results (Tables 5 to 8). In addition, each individual cylinder tested is assigned a number, such as F-B-1, as shown in the second column of the tables.

Additional information to fully describe each cylinder is shown in Tables 1 to 4. This information includes the outside diameter of the cylinder, D, the minimum design wall thickness of the cylinder, t_d, the maximum design test pressure, P_h, the maximum design service pressure, P_s, the actual wall thickness, t_a and the cylinder volume (in litres).

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

6.2 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 cycle tests were performed. The results of these tests are shown in Tables 1 to 4 for each group of materials.

The tensile test results shown in Tables 1 to 4 are the actual measured yield strength, R_{ea}, and the actual measured tensile strength, R_m. These materials properties are required to be measured by all of the existing ISO cylinder design standards. The actual measured tensile strength, R_m value is used to determine whether the cylinder meets the standard 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 whether the cylinder meets the requirement for the yield strength to tensile strength ratio when this ratio is a part of the standard.

The Charpy-V-notch tests were conducted in accordance with the test method described in ISO 148:1983. The Charpy-V-notch tests were conducted either at ambient temperature (20 °C) or at low temperature (– 20 °C or – 50 °C), as shown in Tables 1 to 4. The Charpy-V-notch test specimens were all oriented with the longitudinal axis perpendicular to the longitudinal axis of the cylinder (designated transverse specimens). 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 as J/cm^2, where the total energy absorbed is divided by the area of the specimen ligament below the specimen notch. The Charpy-V-notch energy test results are not used to evaluate the results of the flawed-cylinder cycle test. However, the Charpy-V-notch energy test results are reported here because these results may be used to evaluate the fatigue and fracture performance of the cylinders using alternate analysis procedures to the flawed-cylinder cycle test.

6.3 Description of the flawed-cylinder cycle test

The flawed-cylinder cycle test is used to evaluate the overall fatigue performance of the entire cylinder and is used only as a “design approval test”. The full details of the test and the criteria for acceptable fatigue performance of steel cylinders are given in 9.2.6 of ISO 9809-2:2000.

In the flawed-cylinder cycle test, the fatigue performance of the cylinder is evaluated by cyclically pressurizing a cylinder with a designated type (shape and sharpness) and dimension (length and depth) of surface flaw, until failure. 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.

All tests carried out for this project were conducted in accordance with the requirements specified in ISO 9809-2. These requirements are as follows.

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 specifications:

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

— angle of the cutter = 45° ± 1°;

— tip radius ⩽ 0,25 mm ± 0,025 mm;

— for cylinders ⩽ 140 mm in diameter, cutter diameter = 50 mm ± 0,5 mm;

— for cylinders > 140 mm in diameter, cutter diameter = 65 mm to 80 mm.

The cycling frequency shall not exceed 5 cycles/min.

The flaw length l_o shall be $1{,}6 \times (D \times t_d)^{0{,}5}$

NOTE 1 For the specific test conducted here, the flaw length is approximately expressed as multiples of the design wall thickness, i.e. $n \times t_d$ and is approximately $10 \times t_d$ for all tests.

The depth, d of the flaw shall be not less than 10 % of the wall thickness, t_d.

When measuring the actual flaw depth, a deviation not exceeding 0,1 mm is acceptable (e.g. for an actual wall thickness of 7 mm the flaw depth shall in no case be less than 0,6 mm).

