TECHNICAL
REPORT

ISO/TR
12391-4

First edition
2002-12-15

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

Reference number
ISO/TR 12391-4:2002(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.

© 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

Copyright International Organization for Standardization
Provided by IHS under license with ISO
No reproduction or networking permitted without license from IHS

Not for Resale

Contents

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 (= $n \times t_\mathrm{d}$);
n	represents multiples of t_d (= $l_\mathrm{o}/t_\mathrm{d}$);
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;
$R_\mathrm{g,\,max}$	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.

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.	$750\ \text{MPa} < R_m \leqslant 950\ \text{MPa}$
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.	$950\ \text{MPa} < R_m \leqslant 1\,080\ \text{MPa}$
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.	$1\,080\ \text{MPa} < R_m \leqslant 1\,210\ \text{MPa}$
E	Experimental cylinders; extra high strength; not currently authorized for use.	$R_m > 1\,210\ \text{MPa}$

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 $\leqslant$ 0,25 mm ± 0,025 mm;
- for cylinders $\leqslant$ 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).

The “standard surface flaw” geometry is shown in Figure 1. The flaw length, l_o, is normally expressed in multiples, n, of the cylinder design minimum wall thickness, t_d, ($l_o = n \times t_d$). The flaw depth is expressed as a percentage of the cylinder design minimum wall thickness, t_d, i.e. flaw depth = $d/t_d \times 100$.

Pressurization is carried out hydrostatically. The requirements of ISO 9809-2 are that the maximum cyclical pressure be equal to at least the design test pressure, P_h, and that the minimum cyclical pressures be 10 % of the maximum cyclical pressure.

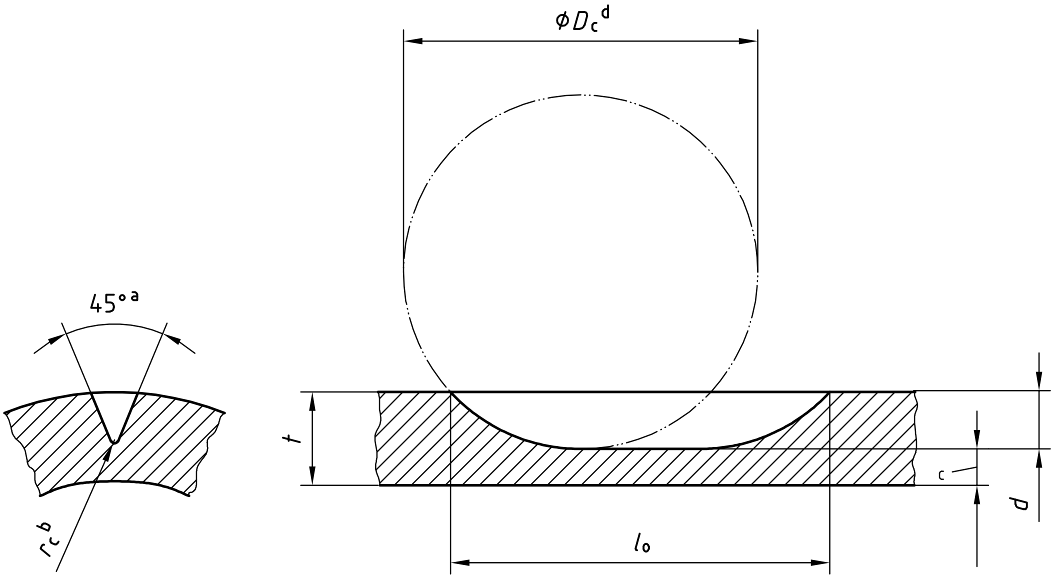
NOTE 2 Some of the tests conducted in this study used slightly different pressure ranges than specified by ISO 9809-2.

During the test, each cylinder is filled with water at room temperature and the pressure is cycled continuously until the cylinder reaches the required number of cycles or fails by leaking or fracturing. The minimum and maximum cyclical pressure, the number of cycles and the failure mode (if the cylinder fails during the test) are reported in the test results.

The acceptance criterion for the flawed-cylinder cycle test specified by ISO 9809-2 is that the cylinder shall have passed the test if the number of cycles attained without failure exceeds 3 500 as a mean value of the two cylinders tested but with an absolute minimum of 3 000;

If the test is continued to failure, then the mode of failure shall be reported (i.e. leak or fracture).

9.2.4 of ISO 9809-2:2000 specifies a “pressure cycling test”. The pressure cycling test is conducted in the same manner as the flawed-cylinder cycle test except that a cylinder without an external flawed is tested. The acceptance test for the pressure cycling test is that the cylinder shall withstand 12 000 pressurization cycles without failure. If the flawed-cylinder cycle test withstands a minimum of 12 000 cycles without failure (by leaking or fracturing) then the pressure cycling test does not have to be carried out. Many of the tests conducted in this programme satisfied this requirement.



[a] Cutter angle

[b] Cutter profile radius

[c] Ligament

[d] Cutter diameter

Figure 1 — Standard flaw geometry for the flawed-cylinder cycle test

7 Flawed-cylinder cycle test results

7.1 Flawed-cylinder cycle test procedure

The results of all of the flawed-cylinder cycle tests that were conducted are shown in Tables 5 to 8. For each cylinder tested, the nominal flaw length, l_o, in terms of a multiple of the actual measured cylinder wall thickness, t_a, is given as $l_o = n \times t_a$ (e.g. $l_o = 10\ t_a$). In a few cases, the actual measured wall thickness, t_a, was not given and the design wall thickness, t_d, was used (e.g. $l_o = 10\ t_d$) to calculate the nominal flaw length. The nominal flaw length was 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. $100 \times d/t_d = 10\ \%$).

A flaw of the required size, generally $10 \times t_a$ long and 10 % t_d deep is machined in the cylinder wall and the cylinder is cyclically pressurized to a maximum pressure equal to the test pressure for the required number of cycles (usually 3 500 cycles). The test results reported in Tables 5 to 8 show the flaw length, the flaw depth, the minimum and maximum cycling pressure, the total number of cycles and the failure mode. If the test was continued until failure occurred, the failure mode was either leaking or fracture (defined as an extension of the original flaw by at least 10 %). For some tests, no failure occurred after a large number of pressurization cycles. These tests are considered to be “run-outs” and the failure mode is shown in Tables 5 to 8 as “none”.

7.2 Flawed-cylinder cycle test results for group F-B materials

The cylinders made from group F-B materials have the lowest tensile strength of the cylinders tested in this programme. These cylinders have measured tensile strengths of less than 950 MPa and are representative of a number of cylinders that have been in worldwide use for about 60 years. Cylinders of this type normally have a service pressure rating of less than 200 bar.

All of the cylinders tested had an initial flaw depth of at least 10 % t_d and a nominal flaw length of $10 \times t_a$. As shown in Table 5, the fatigue cycle life for the all of the cylinders in material group F-B exceeded 3 500 cycles at a maximum cyclical pressure equal to the cylinder test pressure that is required by ISO 9809-2. All of the cylinders in material subgroups F-B-1 and F-B-2 failed by leaking after at least 20 000 cycles. The cylinders in material subgroups F-B-3 and F-B-4 failed by both leaking and fracture after at least 7 500 cycles.

The fatigue cycle life of all but one of the cylinders in material group F-B exceeded 12 000 cycles and therefore satisfied the requirements given in 9.4.2 of ISO 9809-2:2002 for the “Pressure cycling test” for an unflawed-cylinder.

7.3 Flawed-cylinder cycle test results for group F-C materials

The cylinders made from group F-C materials have measured tensile strengths ranging from 950 MPa to about 980 MPa. Cylinders of this type have a normal service pressure rating ranging from about 200 bar to about 300 bar. These cylinders are manufactured according to the requirements of ISO 9809-1.

All cylinders had an initial flaw depth of at least 10 % t_d and a nominal length of $10 \times t_a$. As shown in Table 6, the fatigue cycle life for the all of the cylinders in material subgroups F-C-1, F-C-2 and F-C-4 had an average of 3 500 cycles when the maximum cyclical pressure was equal to the cylinder test pressure and the minimum cyclical pressure was 10 % of the maximum cyclical pressure. Therefore, all of these cylinders satisfied the requirements of ISO 9809-2. All of these cylinders failed by leaking after at least 6 000 cycles.

As shown in Table 6, the cylinders in material subgroup F-C-3 were tested with the maximum cyclical pressure approximately equal to the design service pressure of the cylinders instead of equal to the test pressure of the cylinders. Therefore, these tests were not conducted in full compliance with the requirements of ISO 9809-2 which requires that the maximum cyclical pressure to be equal to the test pressure rather than the design service pressure. However, because the fatigue cycle life of these cylinders exceeded 14 000 cycles when the maximum cyclical pressure was equal to the design service pressure, it is likely that they would have exceeded the requirement of 3 500 cycles when tested at a maximum cyclical pressure equal to the test pressure which is 3/2 times the design service pressure.

The fatigue cycle life of cylinders in material subgroups F-C-1 and F-C-4 exceeded 12 000 cycles when tested at a maximum cyclical pressure equal to the test pressure and therefore satisfied the requirements given in 9.4.2 of ISO 9809-2:2000. The fatigue cycle life of cylinders in material subgroup F-C-2 did not satisfy the 12 000 cycles required by 9.4.2 of ISO 9809-2:2000. The cylinders in material subgroup F-C-3 were tested at a maximum cyclical pressure equal to the design service pressure rather than the test pressure. Although the fatigue cycle life of cylinders in material subgroup F-C-3 exceeded 12 000 cycles when tested to maximum cyclical pressure equal to design service pressure, it is unlikely that the fatigue cycle lift would have exceeded 12 000 cycles if the tests had been conducted at the test pressure and therefore, these cylinders would have to be tested with no flaw in order to determine if they meet the requirements given in 9.4.2 of ISO 9809-2:2000.

7.4 Flawed-cylinder cycle test results for group F-D materials

The cylinders made from group F-D materials are the highest strength steel cylinders currently being manufactured. These cylinders are manufactured to ISO 9809-2 requirements. They are restricted to use for shipping non-corrosive (non-hydrogen bearing) gases. These cylinders are generally made from modified chromium-molybdenum alloy steels that have a good combination of tensile strength and fracture toughness. These cylinders normally have a design service pressures at or above 300 bar.

Most of the cylinders used in these flawed-cylinder cycle tests had an initial flaw depth of at least 10 % t_d and a nominal flaw length of 10 × t_a as required by ISO 9809-2. However, a few of the cylinders had initial flaw depths greater than the required 10 % t_d (e.g. 12 %, 14 %, 15 %, 50 % and 60 %) and a few had initial flaw depths less than the required 10 % t_d (e.g. 5 % and 6 %). When tested at the same pressure range, the effect of the deeper initial flaws is to reduce the total number of cycles to failure and the effect of the shallower flaws is to increase the number of cycles to failure. Most of the cylinders used in these flawed-cylinder cycle tests were tested to a pressure cycle range with the maximum pressure equal to the design test pressure of the cylinder and the minimum pressure equal to 10 % of the maximum pressure as required by ISO 9809-2. However, a few tests were conducted with the maximum pressure equal to the design service pressure (e.g. material groups F-D-4 and F-D-6) or to a maximum pressure of twice the design service pressure (e.g. material group F-D-5). Although most of the tests were conducted with the minimum cyclical pressure equal to 10 % of the maximum cyclical pressure, a few were conducted with the minimum cyclical pressures set at about 1 % of the maximum cyclical pressure or at zero pressure (e.g. material groups F-D-3, F-D-7, F-D-8, F-D-9, F-D-10, F-D-11 and F-D-18). The effect of this larger pressure cycling range, in which the minimum cyclical pressure range is less than 10 % of the maximum cyclical pressure, is to reduce the number of cycles to failure.

As shown in Table 7, the fatigue cycle life for the all of the cylinders in material group F-D had an average of 3 500 cycles when the maximum cyclical pressure equal to the cylinder test pressure and the minimum cyclical pressure was 10 % of the maximum cyclical pressure and the initial flaw depth was 10 % t_d. Therefore, all of the cylinders tested satisfied the requirements of ISO 9809-2.

For the tests conducted according to the requirements of ISO 9809-2, most of the cylinders failed by leaking after exceeding the required 3 500 pressurization cycles. The exceptions were some cylinders in material groups F-D-3, F-D-4, F-D-12, F-D-18 and F-D-20 that failed by fracture.

The cylinders that were tested under conditions that differed from those required by ISO 9809-2 did not meet the requirement that the fatigue cycle life exceed 3 500 cycles without failure. The cylinders in material group F-D-4 that had initial flaw depths of 50 % and 60 % of the wall thickness failed by leaking at less than 700 pressurization cycles. The cylinders in material group F-D-5 that were tested at a maximum cyclical pressure equal to more than twice the design service pressure failed by fracturing at 2 217 and 4 200 pressurization cycles. Two of the cylinders in material subgroup F-D-6 were tested with the maximum cyclical pressure at the design service pressure instead of the design test pressure. The fatigue cycle life of these cylinders greatly exceeded the cycle life of 3 500 cycles required by ISO 9809-2. However, the one cylinder from material subgroup F-D-6 that was tested with the maximum cyclical pressure at the design test pressure had a fatigue cycle life of 7 589 cycles and therefore fully satisfied the requirements of ISO 9809-2 for the flawed-cylinder cycle test.

For the tests conducted according to the requirements of ISO 9809-2, most of the cylinders in material groups F-D-1, F-D-3, F-D-14, F-D-15, F-D-17, F-D-18 and F-D-20 had a fatigue cycle life of greater than 12 000 cycles and therefore satisfied the requirements given in 9.4.2 of ISO 9809-2:2000. Cylinders in material groups F-D-2, F-D-4, F-D-7, F-D-8, F-D-9, F-D-10, F-D-11, F-D-12, F-D-13 and F-D-19 had a fatigue cycle life of less than 12 000 cycles and therefore did not satisfy the requirements given in 9.4.2 of ISO 9809-2:2000. Therefore, additional tests using unflawed-cylinders would need to be conducted in order to fully satisfy the fatigue requirements of ISO 9809-2.

7.5 Flawed-cylinder cycle test results for group F-E materials

The cylinders made from group F-E materials have the highest strengths of any cylinders tested in this programme. These cylinders have measured tensile strengths of greater than 1 300 MPa. This is higher than currently permitted by any safety regulations in the world. These cylinders are experimental cylinders for evaluating the feasibility of using higher strength steels in cylinders without risking failure by fatigue or fracture in service.

All cylinders had an initial flaw depth of at least 10 % t_d and a nominal length of 10 × t_a.

As shown in Table 8, the fatigue cycle life for the all of the cylinders in material group F-E had an average of 3 500 cycles at a maximum cyclical pressure equal to the cylinder test pressure that is required by ISO 9809-2. All of the cylinders in material group E failed by fracture after at least 3 300 cycles.

None of the cylinders from material group F-E that were tested had a fatigue cycle life of greater than 12 000 cycles and therefore did not satisfy the requirements given in 9.4.2 of ISO 9809-2:2000. Therefore, additional tests using unflawed-cylinders would need to be conducted in order to fully satisfy the fatigue requirements of ISO 9809-2.

8 Discussion

8.1 Background

The objective of this part of ISO/TR 12391 was to compile the results of the flawed-cylinder cycle tests that were conducted during the development of the flawed-cylinder cycle test method. The tests results reported here were obtained by the members of the ISO/TC 58/SC 3/WG 14. These test results were used to demonstrate that the flawed-cylinder cycle test adequately evaluates the fatigue resistance of seamless steel cylinders of all strength levels currently used for cylinder construction. The results of these tests were used to establish the procedure for conducting the flawed-cylinder cycle test and for defining the acceptance criteria for passing the test. The flawed-cylinder cycle test procedure and acceptance criteria developed by WG 14 are included in 9.6 of ISO 9809-2:2000. No extensive discussion or analysis of the test data will be presented in this part of ISO/TR 12391.

8.2 Flawed-cylinder cycle test procedures and acceptance criteria (ISO 9809-2)

ISO 9809-2 requires that the fatigue properties of new cylinder designs be evaluated as part of the design approval procedure. Based on the tests reported here, the “flawed-cylinder cycle test” was developed to demonstrate that any new cylinder design has adequate fatigue cycle life to avoid failure during normal service.

In the tests conducted during the development of the flawed-cylinder cycle test and reported here, the flaw length was defined in terms of the design minimum thickness, t_d, of the cylinder alone. In these tests, a common flaw length was $l_o = 10 \times t_d$. However, the single flaw length used in the tests conducted in accordance with ISO 9809-2 is defined differently than the way the flaw lengths is defined in the tests results reported here. In ISO 9809-2 the flaw length is defined in terms of both the cylinder design minimum wall thickness, t_d, and the cylinder diameter, D. For tests conducted in accordance with ISO 9809-2, the single flaw length is defined as: $l_o = 1{,}6\ (D \times t_d)^{0{,}5}$. This has the effect of normalizing the flaw length in terms of both the cylinder diameter and the cylinder wall thickness and therefore makes the test equivalent for cylinders of all sizes and wall thickness. The basis for this choice of flaw length is that the fatigue strength of a flawed-cylinder is a known function of the cylinder diameter, D, the cylinder wall thickness, t_d and the flaw length, l_o. Because many of the test results reported here used cylinders of about 230 mm in diameter and about 6 mm thick, the flaw length calculated by ISO 9809-2 is about the same (i.e. 10 × t_d) as that used in any of the tests.

8.3 Pressure cycling tests (ISO 9809-2)

ISO 9809-2 requires a pressure cycling test as well as a flawed-cylinder cycle test in order to fully evaluate the fatigue performance of new cylinder designs. The pressure cycling test is carried out on an unflawed-cylinder in a manner similar to the flawed-cylinder cycle test. The pressure cycling test requires the cylinder to withstand 12 000 pressure cycles without failure, by leaking or fracture, at a maximum cyclic pressure which is at least equal to the hydraulic test pressure, P_h. The value of the lower cyclic pressure should not exceed 10 % of the upper cyclic pressure, but shall have an absolute maximum of 30 bar. If the number of cycles for the flawed-cylinder cycle test exceeds 12 000 without failure, it is not necessary to conduct the pressure cycling test and the results of the flawed-cylinder cycle test will also satisfy the acceptance criteria for the pressure cycling test.

9 Conclusions

Extensive test results of flawed-cylinder cycle tests and mechanical properties tests that were conducted on seamless steel cylinders are compiled.

The results of these tests were used to demonstrate the capability of the flawed-cylinder cycle to reliably evaluate the fatigue performance of steel cylinders that have tensile strengths covering the full range of steel cylinders currently being produced according to the requirements of ISO 9809-1 and ISO 9809-2.

The results of these tests were used by ISO/TC 58/SC 3 to define the testing procedures and acceptance criteria for the flawed-cylinder cycle test required by ISO 9809-2.

Table 1 — Cylinder description and mechanical properties for group B materials

Test No.	**Cylinder No.**	**Cylinder description**						**Mechanical properties test results**				
		Vol.	**Dia.**	**Design test pressure**	**Design service pressure**	**Wall thickness**		**Tensile test results**		**Charpy-V-notch test results**		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	P_h	P_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-B-1												
F-1	F-B-1-1	50	229	200	133	–	6,60	–	899	–	42	–
F-2	F-B-1-2	50	229	200	133	–	6,50	–	897	–	40	–
F-3	F-B-1-3	50	229	200	133	–	6,80	–	897	–	40	–
Material group F-B-2												
F-4	F-B-2-1	–	238	278	185	–	6,50	–	793	–	–	–
F-5	F-B-2-2	–	238	278	185	–	6,60	–	793	–	–	–
F-6	F-B-2-3	–	238	278	185	–	6,60	–	793	–	–	–
Material group F-B-3												
F-7	F-B-3-1	50	229	300	200	–	6,80	868	950	39	–	21
F-8	F-B-3-2	50	229	300	200	–	7,10	680	805	33	–	23
F-9	F-B-3-3	50	229	300	200	–	7,00	852	963	31	–	18
F-10	F-B-3-3	50	229	300	200	–	6,10	882	944	36	–	31
F-11	F-B-3-5	50	229	300	200	–	6,10	885	949	34	–	37
Material group F-B-4												
F-12	F-B-4-1	–	229	300	200	5,8	6,70	909	992	137	–	70
F-13	F-B-4-2	–	229	300	200	5,8	6,70	859	963	118	–	61
F-14	F-B-4-3	–	229	300	200	5,8	6,30	849	962	141	–	129
F-15	F-B-4-4	–	229	300	200	5,8	6,20	768	924	53	–	20
F-16	F-B-4-5	–	229	300	200	5,8	6,20	776	895	58		24
F-17	F-B-4-6	–	229	300	200	5,8	6,10	759	923	72	–	33

NOTE Values of design service pressure shown in *italics* were not given as part of the test reports and are estimated as 2/3 the maximum cyclical test pressure.

Table 2 — Cylinder description and mechanical properties for group C materials

		Cylinder description						Mechanical properties test results				
Test No.	**Cylinder No.**	**Vol.**	**Dia.**	**Design test pressure**	**Design service pressure**	**Wall thickness**		**Tensile test results**		**Charpy-V-notch test results**		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	p_h	p_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-C-1												
F-18	F-18	–	238	345	230	–	6,60	–	1 000	–	–	–
F-19	F-19	–	238	345	230	–	6,40	–	1 000	–	–	–
F-20	F-20	–	238	345	230	–	6,90	–	1 000	–	–	–
Material group F-C-2												
F-21	F-21	50	229	450	300	6,7	6,70	1 020	1 085	132	–	117
F-22	F-22	50	229	450	300	6,7	6,70	1 015	1 077	127	–	98
F-23	F-23	50	229	450	300	6,7	7,00	1 028	1 094	115	–	104
F-24	F-24	50	229	450	300	6,7	6,80	1 010	1 068	115	–	101
Material group F-C-3												
F-25	F-25	–	238	459	306	–	7,45	–	1 058	–	–	–
F-26	F-26	–	238	459	306	–	7,45	–	1 058	–	–	–
Material group F-C-4												
F-27	F-27	–	229	300	200	–	6,07	–	958	141	–	138
F-28	F-28	–	229	300	200	–	6,01	–	958	141	–	138
F-29	F-29	–	229	300	200	–	6,04	–	958	141	–	138

NOTE Values of design service pressure shown in *italics* were not given as part of the test reports and are estimated as 2/3 the maximum cyclical test pressure.

Table 3 — Cylinder description and mechanical properties for group D materials

Test No.	Cylinder No.	Cylinder description						Mechanical properties test results				
		Vol.	Dia.	Design test pressure	Design service pressure	Wall thickness		Tensile test results		Charpy-V-notch test results		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	P_h	P_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-D-1												
F-30	F-D-1-1	50	229	300	200	–	6,90	–	1 259	–	63	–
F-31	F-D-1-2	50	229	300	200	–	6,80	–	1 189	–	69	–
F-32	F-D-1-3	50	229	300	200	–	6,90	–	1 183	–	71	–
F-33	F-D-1-4	50	229	300	200	–	7,00	–	1 150	–	75	–
F-34	F-D-1-5	50	229	300	200	–	6,80	–	1 150	–	75	–
F-35	F-D-1-6	50	229	300	200	–	6,90	–	1 150	–	75	–
Material group F-D-2												
F-36	F-D-2-1	–	229	375	*250*	5,9	–	–	1 185	–	–	–
Material group F-D-3												
F-37	F-D-3-1	45	239	450	300	6,9	7,20	998	1 080	–	–	96
F-38	F-D-3-2	45	239	450	300	6,9	7,50	989	1 077	109	–	102
F-39	F-D-3-3	45	239	450	300	6,9	7,30	1 050	1 134	102	–	92
F-40	F-D-3-4	45	239	450	300	6,9	7,30	1 025	1 109	95	–	86
F-41	F-D-3-5	45	239	450	300	6,9	7,20	992	1 077	86	–	81
F-42	F-D-3-6	45	239	450	300	6,9	7,30	960	1 060	90	–	82
Material group F-D-4												
F-43	F-D-4-1	45	236	450	300	6,6	7,40	1 103	1 172	–	–	50
F-44	F-D-4-2	45	236	450	300	6,6	7,40	1 075	1 142	–	–	46
F-45	F-D-4-3	45	236	450	300	6,6	6,63	1 066	1 140	54	–	25
F-46	F-D-4-4	45	236	450	300	6,6	6,83	1 052	1 106	65	–	27
F-47	F-D-5-5	45	236	450	300	6,6	7,19	1 052	1 125	55	–	25
Material group F-D-5												
F-48	F-D-5-1	43	235	450	300	8,61	9,12	1 045	1 146	53	–	24
F-49	F-D-5-2	43	235	450	300	8,61	9,07	989	1 067	105	–	34
Material group F-D-6												
F-50	F-D-6-1	50	230	450	300	6,8	7,10	1 022	1 100	–	91	
F-51	F-D-6-2	50	230	450	300	6,8	7,10	1 022	1 100	–	91	–
F-52	F-D-6-3	50	230	450	300	6,8	7,10	1 022	1 100	–	91	–
Material group F-D-7												
F-53	F-D-7-1	50	229	450	300	6,5	6,90	1 073	1 137	84	–	44
F-54	F-D-7-2	50	229	450	300	6,5	7,00	1 079	1 143	81	–	48
F-55	F-D-7-3	50	229	450	300	6,5	7,10	1 022	1 080	95	–	59
F-56	F-D-7-4	50	229	450	300	6,5	6,90	1 070	1 139	79	–	44

Table 3 (*continued*)

Test No.	Cylinder No.	Cylinder description						Mechanical properties test results				
		Vol.	Dia.	Design test pressure	Design service pressure	Wall thickness		Tensile test results		Charpy-V-notch test results		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	P_h	P_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-D-8												
F-57	F-D-8-1	50	230	450	300	6,35	6,80	1 122	1 198	90	–	78
F-58	F-D-8-2	50	230	450	300	6,35	7,00	1 127	1 201	95	–	79
F-59	F-D-8-3	50	230	450	300	6,35	6,90	1 069	1 139	107	–	104
F-60	F-D-8-4	50	230	450	300	6,35	7,00	1 068	1 139	104	–	92
F-61	F-D-8-5	50	230	450	300	6,35	6,80	1 059	1 137	105	–	104
F-62	F-D-8-6	50	230	450	300	6,35	6,80	1 097	1 167	97	–	89
Material group F-D-9												
F-63	F-D-9-1	50	229	450	300	6,4	7,40	1 067	1 144	127	–	69
F-64	F-D-9-2	50	229	450	300	6,4	7,40	1 092	1 155	134	–	71
F-65	F-D-9-3	50	229	450	300	6,4	7,30	1 096	1 160	124	–	74
F-66	F-D-9-4	50	229	450	300	6,4	7,00	1 086	1 152	129	–	70
Material group F-D-10												
F-67	F-D-10-1	50	229	450	300	7,4	7,60	1 032	1 100	93	–	–
F-68	F-D-10-2	50	229	450	300	7,4	7,90	1 028	1 114	88	–	–
F-69	F-D-10-3	50	229	450	300	7,4	7,90	1 061	1 127	79	–	–
F-70	F-D-10-4	50	229	450	300	7,4	7,70	1 039	1 125	88	–	–
Material group F-D-11												
F-71	F-D-11-1	6	140	450	300	4,1	4,30	1 068	1 164	106	–	79
F-72	F-D-11-2	6	140	450	300	4,1	4,20	1 031	1 131	85	–	74
F-73	F-D-11-3	6	140	450	300	4,1	4,30	1 052	1 152	94	–	82
F-74	F-D-11-4	6	140	450	300	4,1	4,20	1 073	1 173	91	–	65
Material group F-D-12												
F-75	F-D-12-1	50	229	450	300	7,2	–	–	1 125	84	–	43
F-76	F-D-12-2	50	229	450	300	7,2	–	–	1 133	92	–	50
F-77	F-D-12-3	50	229	450	300	7,2	–	–	1 139	82	–	46
F-78	F-D-12-4	50	229	450	300	7,2	–	–	1 151	89	–	50
Material group F-D-13												
F-79	F-D-13-1	50	229	450	300	9	–	–	1 131	–	–	F-79
F-80	F-D-13-2	50	229	450	300	9	–	–	1 114	–	–	F-80
F-81	F-D-13-4	50	229	450	300	10	–	–	1 128	–	–	F-81

Table 3 (*continued*)

		Cylinder description						Mechanical properties test results				
Test No.	**Cylinder No.**	**Vol.**	**Dia.**	**Design test pressure**	**Design service pressure**	**Wall thickness**		**Tensile test results**		**Charpy-V-notch test results**		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	P_h	P_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-D-14												
F-82	F-D-14-1	50	229	450	300	9	–	–	1 139	–	–	F-82
F-83	F-D-14-2	50	229	450	300	9	–	–	1 131	–	–	F-83
F-84	F-D-14-3	50	229	450	300	9	–	–	1 139	–	–	F-84
Material group F-D-15												
F-85	F-D-15-1	6	140	450	300	5,1	–	–	1 127	–	–	F-85
F-86	F-D-15-2	6	140	450	300	5,1	–	–	1 121	–	53	F-86
F-87	F-D-15-3	6	140	450	300	5,1	–	–	1 138	–	–	F-87
F-88	F-D-15-4	6	140	450	300	5,1	–	–	1 100	–	–	F-88
F-89	F-D-15-5	6	140	450	300	5,1	–	–	1 118	–	–	F-89
F-90	F-D-15-6	6	140	450	300	5,1	–	–	1 114	–	–	F-90
Material group F-D-16												
F-91	F-D-16-1	–	229	450	300	7,8	–	–	1 140	–	–	–
F-92	F-D-16-2	–	229	450	300	7,8	–	–	1 150	–	–	–
F-93	F-D-16-3	–	229	450	300	7,8	–	–	1 130	–	–	–
Material group F-D-17												
F-94	F-D-17-1	–	229	450	300	7,3	–	–	1 092	120	–	84
F-95	F-D-17-2	–	229	450	300	7,3	–	–	1 092	120	–	84
F-96	F-D-17-3	–	229	450	300	7,3	–	–	1 092	120	–	84
F-97	F-D-17-4	–	229	450	300	7,3	–	–	1 092	120	–	84
F-98	F-D-17-5	–	229	450	300	7,3	–	–	1 092	120	–	84
F-99	F-D-17-6	–	229	450	300	7,3	–	–	1 092	120	–	84
Material group F-D-18												
F-100	F-D-18-1	10	176	450	300	5	5,10	987	1 079	72	–	74
F-101	F-D-18-2	10	176	450	300	5	5,00	1 102	1 178	66	–	75
F-102	F-D-18-3	10	176	450	300	5	5,30	1 069	1 141	80	–	79
F-103	F-D-18-4	10	176	450	300	5	5,10	1 097	1 175	69	–	78
F-104	F-D-18-5	10	176	450	300	5	5,30	1 078	1 163	79	–	75
Material group F-D-19												
F-105	F-D-19-1	–	229	525	350	9,1	–	–	–	–	–	–
Material group F-D-20												
F-106	F-D-20	50	229	300	200	–	6,10	1 036	1 110	25	–	31

NOTE Values of design service pressure shown in *italics* were not given as part of the test reports and are estimated as 2/3 the maximum cyclical test pressure.

Table 4 — Cylinder description and mechanical properties for group E materials

Test No.	Cylinder No.	Cylinder description						Mechanical properties test results				
		Vol.	Dia.	Design test pressure	Design service pressure	Wall thickness		Tensile test results		Charpy-V-notch test results		
						Design thickness	Actual thickness	Yield strength	Tensile strength	Transverse orientation		
			D	p_h	p_s	t_d	t_a	R_{ea}	R_m	at + 20 °C	at − 20 °C	at − 50 °C
		l	mm	bar	bar	mm	mm	MPa	MPa	J/cm^2	J/cm^2	J/cm^2
Material group F-E-1												
F-107	F-E-1-1	6	140	450	300	3,4	3,7	1 281	1 368	55	–	F-107
F-108	F-E-1-2	6	140	450	300	3,4	3,6	1 271	1 345	53	–	F-108
F-109	F-E-1-3	6	140	450	300	3,4	3,6	1 273	1 346	59	–	F-109
F-110	F-E-1-4	6	140	450	300	3,4	3,6	1 244	1 335	54	–	F-110

Table 5 — Fatigue cycle test results for group B materials

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		10 × t_a	10 × t_d		min.	max.		
		mm	mm	% of t_d	bar	bar		
Material group F-B-1								
F-1	F-B-1-1	66,0	–	10,0	–	200	71 928	Leak
F-2	F-B-1-2	65,0	–	10,0	–	200	67 248	Leak
F-3	F-B-1-3	68,0	–	10,0	–	200	163 597	Leak
Material group F-B-2								
F-4	F-B-2-1	65,0	–	10,0	–	278	27 912	Leak
F-5	F-B-2-2	66,0	–	10,0	–	278	27 448	Leak
F-6	F-B-2-3	66,0	–	10,0	–	278	20 650	Leak
Material group F-B-3								
F-7	F-B-3-1	68,0	–	10,0	30	300	24 024	Leak
F-8	F-B-3-2	71,0	–	10,0	30	300	28 240	Fracture
F-9	F-B-3-3	70,0	–	10,0	30	300	17 338	Leak
F-10	F-B-3-3	61,0	–	10,0	30	300	15 132	Fracture
F-11	F-B-3-5	61,0	–	10,0	30	300	12 390	Fracture
Material group F-B-4								
F-12	F-B-4-1	67,0	–	10,0	30	300	16 557	Leak
F-13	F-B-4-2	67,0	–	10,0	30	300	13 440	Leak
F-14	F-B-4-3	63,0	–	10,0	30	300	7 503	Leak
F-15	F-B-4-4	62,0	–	10,0	30	300	17 858	Fracture
F-16	F-B-4-4	62,0	–	10,0	30	300	12 061	Fracture
F-17	F-B-4-6	61,0	–	10,0	30	300	19 470	Fracture

Table 6 — Fatigue cycle test results for group C materials

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		10 × t_a mm	10 × t_d mm	% of t_d	min. bar	max. bar		
Material group F-C-1								
F-18	F-C-1-1	66,0	–	10,0	–	345	26 747	Leak
F-19	F-C-1-2	64,0	–	10,0	–	345	17 050	Leak
F-20	F-C-1-3	69,0	–	10,0	–	345	12 433	Leak
Material group F-C-2								
F-21	F-C-2-1	67,0	–	10,4	45	450	9 121	Leak
F-22	F-C-2-2	67,0	–	10,1	45	450	7 118	Leak
F-23	F-C-2-3	70,0	–	10,1	5	450	6 604	Leak
F-24	F-C-2-4	68,0	–	10,4	5	450	11 261	Leak
Material group F-C-3								
F-25	F-C-3-1	75,0	–	10,0	–	337	18 665	Leak
F-26	F-C-3-2	74,5	–	10,0	–	337	14 628	Leak
Material group F-C-4								
F-27	F-C-4-1	60,7	–	14,0	–	300	19 290	Leak
F-28	F-C-4-2	60,1	–	13,0	–	300	40 780	Leak
F-29	F-C-4-4	60,4	–	12,0	–	300	47 900	Leak

Table 7 — Fatigue cycle test results for group D materials

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		10 × t_a	10 × t_d		min.	max.		
		mm	mm	% of t_d	bar	bar		
Material group F-D-1								
F-30	F-D-1-1	69,0	–	10,0	–	300	31 815	Leak
F-31	F-D-1-2	68,0	–	10,0	–	300	46 405	Leak
F-32	F-D-1-3	69,0	–	10,0	–	300	55 270	Leak
F-33	F-D-1-4	70,0	–	15,0	–	300	16 541	Leak
F-34	F-D-1-5	68,0	–	12,0	–	300	42 319	Leak
F-35	F-D-1-6	68,0	–	10,0	–	300	135 475	Leak
Material group F-D-2								
F-36	F-D-2-1	–	59,0	10,8	–	375	8 602	Leak
Material group F-D-3								
F-37	F-D-3-1	72.0	–	11,9	45	450	34 124	Fracture
F-38	F-D-3-2	75.0	–	10,9	45	450	68 024	Leak
F-39	F-D-3-3	73.0	–	9,7	5	450	4 041	Leak and fracture
F-40	F-D-3-4	73.0	–	11,2	5	450	8 715	Fracture
F-41	F-D-3-5	72.0	–	9,9	45	450	31 989	Leak and fracture
F-42	F-D-3-6	73.0	–	11,2	5	450	3 260	Leak
Material group F-D-4								
F-43	F-D-4-1	74,0	–	50,0	30	310	633	Leak
F-44	F-D-4-2	74,0	–	60,0	30	310	279	Leak
F-45	F-D-4-3	66,3	–	10,0	45	465	5 704	Fracture
F-46	F-D-4-4	68,3	–	10,0	45	465	7 475	Fracture
F-47	F-D-5-5	71,9	–	10,0	45	465	6 151	Fracture
Material group F-D-5								
F-48	F-D-5-1	91,2	–	10,0	–	620	2 217	Fracture
F-49	F-D-5-2	91,0	–	10,0	–	620	4 200	Fracture
Material group F-D-6								
F-50	F-D-6-1	71,0	–	10,0	30	300	54 183	Leak
F-51	F-D-6-2	71,0	–	10,0	30	300	31 110	Leak
F-52	F-D-6-3	71,0	–	10,0	45	450	7 589	Leak

Table 7 (*continued*)

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		10 × t_a	10 × t_d		min.	max.		
		mm	mm	% of t_d	bar	bar		
Material group F-D-7								
F-53	F-D-7-1	69,0	–	10,3	45	450	13 626	Leak
F-54	F-D-7-2	70,0	–	10,9	45	450	4 385	Leak
F-55	F-D-7-3	71,0	–	10,3	5	450	7 450	Leak
F-56	F-D-7-4	69,0	–	9,7	5	450	4 708	Leak
Material group F-D-8								
F-57	F-D-8-1	68,0	–	8,6	45	450	7 604	Leak
F-58	F-D-8-2	70,0	–	9,7	45	450	5 224	Leak
F-59	F-D-8-3	69,0	–	10,9	45	450	4 147	Leak
F-60	F-D-8-4	70,0	–	8,1	0	450	15 404	Leak
F-61	F-D-8-5	68,0	–	9,6	0	450	14 640	Leak
F-62	F-D-8-6	68,0	–	10,1	0	450	10 784	Leak
Material group F-D-9								
F-63	F-D-9-1	74,0	–	10,3	45	450	6 167	Leak
F-64	F-D-9-2	74,0	–	10,5	45	450	4 976	Leak
F-65	F-D-9-3	73,0	–	9,9	5	450	5 610	Leak
F-66	F-D-9-4	70,0	–	10,9	5	450	8 650	Leak
Material group F-D-10								
F-67	F-D-10-1	76,0	–	9,9	45	450	5 698	Leak
F-68	F-D-10-2	79,0	–	9,9	45	450	10 733	Leak
F-69	F-D-10-3	79,0	–	10,0	5	450	6 986	Leak
F-70	F-D-10-4	77,0	–	9,9	5	450	5 320	Leak
Material group F-D-11								
F-71	F-D-11-1	43,0	–	12,6	45	450	4 150	Leak
F-72	F-D-11-2	42,0	–	11,2	45	450	3 610	Leak
F-73	F-D-11-3	43,0	–	11,9	5	450	4 140	Leak
F-74	F-D-11-4	42,0	–	12,4	5	450	4 450	Leak
Material group F-D-12								
F-75	F-D-12-1	–	72,0	9,7	–	450	5 131	Fracture
F-76	F-D-12-2	–	72,0	10,0	–	450	3 356	Fracture
F-77	F-D-12-3	–	72,0	5,5	–	450	16 476	Leak
F-78	F-D-12-4	–	72,0	6,9	–	450	6 566	Leak

Table 7 (*continued*)

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		$10 \times t_a$ mm	$10 \times t_d$ mm	% of t_d	min. bar	max. bar		
Material group F-D-13								
F-79	F-D-13-1	–	90,0	9,8	–	450	7 220	Leak
F-80	F-D-13-2	–	90,0	9,4	–	450	5 500	Leak
F-81	F-D-13-4	–	100,0	9,0	–	450	13 000	Leak
Material group F-D-14								
F-82	F-D-14-1	–	90	9,6	–	450	7 850	Leak
F-83	F-D-14-2	–	90	5,0	–	450	18 000	None
F-84	F-D-14-3	–	90	4,9	–	450	18 000	None
Material group F-D-15								
F-85	F-D-15-1	–	51,0	5,0	–	450	36 169	None
F-86	F-D-15-2	–	51,0	5,5	–	450	40 212	None
F-87	F-D-15-3	–	51,0	5,5	–	450	31 023	None
F-88	F-D-15-4	–	51,0	12,7	–	450	8 554	None
F-89	F-D-15-5	–	51,0	11,8	–	450	22 463	None
F-90	F-D-15-6	–	51,0	12,7	–	450	7 204	None
Material group F-D-16								
F-91	F-D-16-1	–	78,0	10,8	–	450	18 968	Leak
F-92	F-D-16-2	–	78,0	10,6	–	450	8 498	Leak
F-93	F-D-16-3	–	78,0	11,4	–	450	6 034	Leak
Material group F-D-17								
F-94	F-D-17-1	–	73,0	14,0	–	450	6 130	Leak
F-95	F-D-17-2	–	73,0	14,0	–	450	15 180	Leak
F-96	F-D-17-3	–	73,0	12,0	–	450	22 000	None
F-97	F-D-17-4	–	73,0	6,0	–	450	30 000	None
F-98	F-D-17-5	–	73,0	5,0	–	450	30 000	None
F-99	F-D-17-6	–	73,0	6,0	–	450	30 000	None
Material group F-D-18								
F-100	F-D-18-1	51,0	–	10,2	5	450	11 416	Fracture
F-101	F-D-18-2	50,0	–	10,2	5	450	9 557	Fracture
F-102	F-D-18-3	53,0	–	10,2	5	450	11 831	Leak
F-103	F-D-18-4	51,0	–	9,8	5	450	14 607	Leak
F-104	F-D-18-5	53,0	–	9,4	5	450	19 029	Leak
Material group F-D-19								
F-105	F-D-19-1	91,0	–	11,0	–	525	3 919	Leak
Material group F-D-20								
F-106	F-D-20	61,0	–	10,0	30	300	13 939	Fracture

Table 8 — Fatigue cycle test results for group E materials

Test No.	Cylinder No.	Fatigue cycle test results						
		Nominal flaw length		Actual flaw depth	Cycle pressure range		Number of cycles	Failure mode
		10 × t_a mm	10 × t_d mm	% of t_d	min. bar	max. bar		
Material group F-E-1								
F-107	F-E-1-1	37	–	9,7	45	450	3 348	Fracture
F-108	F-E-1-2	36	–	9,7	45	450	8 568	Fracture
F-109	F-E-1-3	36	–	10,0	5	450	5 537	Fracture
F-110	F-E-1-4	36	–	10,0	5	450	5 831	Fracture

ICS 23.020.30

Price based on 22 pages