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Gas cylinders — Refillable seamless steel — Performance tests —

Part 2:
Fracture performance tests — Monotonic burst tests

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

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

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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.

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

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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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

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

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

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

Introduction

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

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

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

TECHNICAL REPORT **ISO/TR 12391-2:2002(E)**

Gas cylinders — Refillable seamless steel — Performance tests —

Part 2:
Fracture performance tests — Monotonic burst tests

1 Scope

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

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

2 References

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

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

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

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

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

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

3 Symbols

A	is the elongation expressed as a percentage (= d/t_d);
d	is the flaw depth, expressed in millimetres (= $A \times t_d$);
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_{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) are stored and transported in portable steel cylinders. These cylinders are designed, manufactured and maintained in accordance with ISO 9809-1, ISO 9809-2, or national specifications such as those of the U.S. Department of Transportation (DOT) 49 CFR Part 178 [1]. The cylinders are constructed from specified alloy steels that are generally modified versions of steels such as AISI 4130 and AISI 4140 [2] or equivalent steels made to other national specifications. The cylinders are of seamless construction and are manufactured by either a forging process, a tube drawing process or a plate drawing process. The required mechanical properties are obtained by using an austenitizing, quenching and tempering heat treatment. Typical sizes of these cylinders are 100 mm to 250 mm in diameter, 500 mm to 2 000 mm in length, and 3 mm to 20 mm in wall thickness. Typical working pressure ranges are 100 bar to 400 bar.

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

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

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

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

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

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

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

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

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

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

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

5 Experimental test programme

5.1 Types of cylinder tested

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

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

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

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

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

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

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

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

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

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

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

5.2 Material properties tests

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

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

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

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

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

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

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

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

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

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

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

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

5.3 Description of the flawed-cylinder burst test

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

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

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

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

— Angle of the cutter = 45° ± 1°;

— Tip radius $\leqslant$ 0,2 mm;

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

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

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

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

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

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

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

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

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

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

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

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

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

6 Flawed-cylinder burst test results

6.1 Flawed-cylinder burst test procedure

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

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

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

The ratio of the failure pressure, P_f, to the marked service pressure of the cylinder, P_s, is given as P_f/P_s. The marked service pressure (bar) is the maximum pressure to which the cylinder may be filled when in service and is specified by the cylinder manufacturer. It should be noted that the marked service pressure for the cylinders of the same size and tensile strength will be slightly different depending on the design specification used by the manufacturer. The cylinders were designed and the marked service pressure was specified 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 in turn permits 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 burst tests conducted in this study. The adjusted ratio of the failure pressure to the service pressure, $P_{f,\ adjusted}/P_s$, is shown in the last column in Tables 12 to 16.

For completeness of the data base, the results of all tests that were conducted are listed in Tables 12 to 16. 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 burst tests for these material subgroups are listed in Tables 12 to 16 and are plotted in Figures 4 to 17. Only the data points necessary to define the leak-fracture boundary are plotted in Figures 4 to 17; i.e., for each flaw length, only the lowest value of P_f/P_s for which a failure occurred by fracture and the highest value of P_f/P_s for which failure occurred by leaking are plotted. An estimate of the leak-fracture boundary is shown in the Figures for each material subgroup. Data for P_f/P_s over a range of flaw lengths is available for material subgroups A-1, A-2, B-3, B-6, B-8, C-3, C-5, C-11, D-3, D-5, D-6, D-11, E-1 and E-2.

For some of the other material subgroups, all the flawed-cylinder 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 tests results are summarized and the estimated leak-fracture boundaries for these material subgroups are shown in Table 17. Flawed-cylinder burst tests for material subgroups B-2, B-4, B-5, B-7, B-13, B-15, C-6, C-7, C-8, C-9, C-10, C-15, C-17, C-18, C-23, D-2, D-4, D-9, D-10 and D-14 were conducted at only a single value of flaw length. In some of these cases (e.g. material subgroup D-14), multiple (repeated) tests were conducted with similar cylinders with a single flaw length. These results are useful for helping to evaluate the uncertainty in the measurements made with the flawed-cylinder burst test.

For some of the material subgroups, all the flawed-cylinder burst tests were conducted at a single defined flaw length and only leak results or fracture results were obtained. These results are not plotted as separate figures. These tests results are summarized in Table 18. An estimate of the leak-fracture boundary is reported as a failure pressure ratio (P_f/P_s) that is at least as high as the highest value of the failure pressure ratio for a cylinder in which failure occurred by leaking or as a failure pressure ratio that is lower that the value of the lowest failure pressure ratio for a cylinder in which failure occurred by fracturing. These results may be of value if there are similar cylinders in other material subgroups with which they may be combined in order to estimate the leak-fracture boundary more accurately. These test results may also be used to determine if this particular type of cylinder is likely to leak (i.e. if $P_f/P_s > 1{,}0$) or fracture (i.e. if $P_f/P_s < 1{,}0$) in service with a flaw of the specified length. Flawed-cylinder burst tests for material subgroups B-8, B-10, B-11, B-12, B-14, C-12, C-13, C-14, C-16, C-19, C-20, C-21, C-22, D-13, D-15, D-16, D-17, D-18 and D-19 were conducted at only a single value of flaw length and each test series resulted in failure only by leaking or by fracture. Because failures 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 highest failure pressure ratio (P_f/P_s) at which leaking occurred or less than the lowest failure pressure ratio (P_f/P_s) at which fracture occurred.

6.2 Flawed-cylinder burst test results for group A materials

The cylinders made from group A materials were older cylinders made from carbon steel to the U.S. Department of Transportation (DOT) type 3A specification. These cylinders represent the lowest strength cylinders tested in this programme. The cylinders were tested to serve as a bench mark for the fracture resistance of seamless steel cylinders. These cylinders have been manufactured and used for many years without any significant incidents of failure by fracture. These cylinders are made from steels that have an inherently low fracture toughness as indicated by the low Charpy-V-notch energy values (12 J/cm^2 to 32 J/cm^2 at ± 20 °C for transverse specimens). However, the stress in the cylinder wall at the service pressure is low enough to prevent fracture. In the flawed-cylinder burst tests, cylinders in both material subgroups A-1 and A-2, had a P_f/P_s ratio greater than 1,0 for flaw lengths, l_o, of at least $12 \times t_d$, as shown by Figures 4 and 5. This represents a high level of fracture resistance for these types of cylinder.

6.3 Flawed-cylinder 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. As shown by Figures 6, 7 and 8, the cylinders in material subgroups B-3, B-6 and B-9 have a leak-fracture boundary of at least P_f/P_s = 1,0 for flaw lengths, l_o, of at least = 12 × t_d. As shown in Tables 17 and 18, the cylinders in the other material group B subgroups had an estimated P_f/P_s ratio equal to at least 1,0 for flaw lengths of at least 10 × t_d. This represents an adequate level of fracture resistance for all cylinders in this group. There has been no adverse service experience with this type of cylinder during their widespread use.

Cylinders in material subgroup B-2 were originally produced to be of the type represented by the cylinders in material group D. The cylinder tested as material subgroup B-2 was tempered to reduce the tensile strength to the Group B range for comparison with the same type of cylinder at the higher strength range (material group D). The marked service pressure (310 bar) is the rating for the cylinder as manufactured at the higher strength range. Using the marked service pressure of 310 bar provided by the manufacturer, the cylinders in this material subgroup had an estimated P_f/P_s ratio equal to at least 1,0 for flaw lengths of 10 × t_d. This represents an adequate level of fracture resistance for the cylinders in this group. It should be noted that to compare these cylinders with others in this material group, the service pressure should be recalculated using the actual measured tensile strength.

Cylinders in subgroups B-7 and B-8 are conventional cylinders made to the strength range of group B cylinders but thicker than normal so that they can be used at higher pressures (276 bar marked service pressure for B-7 cylinders and 460 bar marked service pressure for B-8 cylinders). This series of tests was conducted to demonstrate that the flawed-cylinder burst test adequately evaluates the fracture resistance of the cylinders even when they are unusually thick. Conventional linear-elastic fracture mechanics' theory predicts that the fracture resistance of thick cylinders may be lower than for thin cylinders made from the same steel. The cylinders in these material subgroups had an estimated P_f/P_s ratio equal to at least 1,0 for flaw lengths of 10 × t_d. This represents an adequate level of fracture resistance for the cylinders in these material subgroups.

6.4 Flawed-cylinder burst test results for group C materials

The cylinders made from group C materials are higher strength steel cylinders that have been used worldwide for about 10 years. These cylinders are generally made from chromium-molybdenum alloy steel that is produced to higher levels of cleanliness to improve fracture toughness. This enables the cylinders to be designed to a service pressure of about 300 bar.

As shown in Figures 9 and 10, the cylinders in material subgroups C-3 and C-7 have a leak-fracture boundary of at least P_f/P_s = 1,0 for flaw lengths, l_o, of 10 × t_d. As shown in Figure 11, the cylinders in material subgroup C-11 have a leak-fracture boundary of at least P_f/P_s = 1,2 for flaw lengths of 8 × t_d. By extrapolation, the leak-fracture boundary for cylinders in material subgroup C-11 is estimated to be at least P_f/P_s = 1,0 for flaw lengths of 10 × t_d. As shown in Tables 17 and 18, the cylinders in the other group C material subgroups also had an estimated P_f/P_s ratio equal to at least 1,0 for flaw lengths of at least 10 × t_d. This represents an adequate level of fracture resistance for all cylinders in this group.

6.5 Flawed-cylinder burst test results for group D materials

The cylinders made from group D materials are the highest strength steel cylinders now permitted to be used in any country in the world. 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 are intended to have service pressures at or above 300 bar.

As shown in Figures 12, 13 and 15, the cylinders in material subgroups D-3, D-5 and D-11 have a leak-fracture boundary of at least P_f/P_s = 1,0 for flaw lengths, l_o, of at least = 10 × t_d. This indicates that the fracture resistance of these cylinders is equivalent to the cylinders in materials group C and that these cylinders should have adequate fracture resistance for all normal use. As shown in Figure 14, the cylinders in material subgroup D-6 have a leak-fracture boundary of less than P_f/P_s = 1,0 for flaw lengths of about 7 × t_d. This is less than that of any of the other cylinder groups tested and may indicate that the fracture resistance of these cylinders is less than is desirable.

As shown in Tables 17 and 18, except for material subgroup D-19, all of the cylinders in the other group D material subgroups had an estimated P_f/P_s ratio equal to at least 1,0 for flaw lengths of at least 10 × t_d. This should represent an adequate level of fracture resistance for all cylinders in this group.

6.6 Flawed-cylinder burst test results for group E materials

The cylinders made from group E materials are made from higher strength steels than are 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 fracture in service. As shown in Figure 16, for the cylinders from the material subgroup E-1, the leak-fracture boundary $P_f/P_s > 1{,}3$ at a flaw length, l_o, of 8 × t_d. indicates that these cylinders are likely to have adequate fracture resistance. However, no tests resulted in leaking for the cylinders that were tested at flaw lengths longer than 8 × t_d so it is not possible to make a complete assessment of the fracture resistance of these cylinders.

The cylinders made from the material subgroup E-2 have a tensile strength of about 1 400 MPa. This was the highest strength steel tested in this programme. As shown in Figure 17, for the cylinders from the E-2 material subgroup, the leak-fracture boundary P_f/P_s was slightly less than 1,0 for a flaw length of only 8 × t_d. This indicates that at the high strength levels of the material subgroup E-2 steels, these cylinders will have a lower fracture resistance than that of the currently used lower strength cylinders and that the fracture resistance of these cylinders may not be adequate.

6.7 Flawed-cylinder burst test results for tests conducted under special conditions

6.7.1 Low temperature tests

Cylinders in material subgroups C-8 and C-9 were tested at both room temperature and at – 50 °C to evaluate the low temperature fracture performance of the cylinders. All tests were done with a flaw length, l_o, of 10 × t_d. The results of these tests are shown in Figures 18 and 19. For both sets of test cylinders the fracture resistance was not reduced at low temperature. The P_f/P_s ratio was slightly higher at – 50 °C than at + 20 °C for both sets of test cylinders. However, the number of cylinders tested at both temperatures was too small to determine if this difference is significant. This limited number of tests indicate that cylinders in which the flawed-cylinder burst tests demonstrate that the cylinders have adequate fracture resistance at room temperature should also have adequate fracture resistance at low temperature. This is important because the cylinders may be used at temperatures as low as – 50 °C in service.

6.7.2 Pneumatic tests

Two cylinders in material subgroup D-5 were tested with nitrogen to produce a pneumatic test for comparison with the hydrostatic tests conducted for the rest of the cylinders in this test programme. As shown in Figure 20, both of the pneumatic tests failed by leaking at about the same P_f/P_s ratio as cylinders with the same flaw size that were tested hydrostatically. This finding is significant because it indicates that the hydrostatic test is adequate to evaluate the fracture resistance of the cylinders and that it is not necessary to conduct the more complex pneumatic tests on a routine basis. In particular, it is important to note that a leak occurred in the pneumatic test under the same conditions as a leak in the hydrostatic test. This indicates that the hydrostatic test does not mis-predict a fracture result in this test.

7 Discussion

7.1 Background

The objective of this report was to compile the results of the flawed-cylinder burst tests that were conducted during the development of the flawed-cylinder burst test method. The test results obtained in this programme can be used to evaluate the effectiveness of the flawed-cylinder burst test, as a test method to measure the fracture performance of seamless steel cylinders, and to derive suitable criteria for using the test to evaluate new designs of cylinders and cylinders during production. No extensive discussion or analysis of the test data will be presented in this report.

The objective of the flawed-cylinder burst test is to evaluate new designs of cylinder by determining the leak-fracture boundary for a range of flaw lengths. The leak-fracture boundary is defined in terms of the ratio, $P_{\mathrm{f}}/P_{\mathrm{s}}$, of the failure pressure, P_{f}, to the marked service pressure, P_{s}, of the cylinder. As required by ISO 9809-2, a flaw of the specified size and shape in the wall of the cylinder and the cylinder shall fail by leaking at a pressure above the marked service pressure of the cylinder.

The tests results reported here were obtained by the members of WG 14. These test results were used to demonstrate that the flawed-cylinder burst test adequately evaluates the fracture resistance of seamless steel cylinders of all strength levels presently used for cylinder construction. The results of these tests were used to establish the procedure for conducting the flawed-cylinder burst test and for defining the acceptance criteria for passing the test. The flawed-cylinder burst test procedure and acceptance criteria developed by WG 14 are included in 8.2.3 of ISO 9809-2.

7.2 ISO 9809-2 flawed-cylinder burst test procedures and acceptance criteria

Based on the test results reported here, WG 14 developed specific test procedures and acceptance criteria for using the flawed-cylinder burst test to evaluate new cylinder designs and new cylinder materials and to evaluate samples of production cylinders. The specific test procedures finally adopted by WG 14 and published in 8.2.3 of ISO 9809-2:2000, differ slightly from the procedures used to carry out most of the tests described in this report.

In ISO 9809-2, the flaw shape used in the flawed-cylinder burst is the same as the flaw shape used in the test conducted in this study and described in 5.3 and Figure 1. The final procedure adopted by WG 14 and published in ISO 9809-2 specifies that cylinders with only a single defined flaw length are required to be tested to evaluate the fracture performance of the cylinders. This is in contrast to the test results reported here in which cylinders with a range of flaw lengths were tested for many of the material groups to evaluate the total fracture performance of the cylinders. In tests conducted during the development of the flawed-cylinder burst 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, l_{o}, was $10 \times t_{\mathrm{d}}$. However, the single flaw length used in the tests conducted in accordance with ISO 9809-2 is defined differently than the way the flaw length 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 $l_{\mathrm{o}} = 1{,}6(D \times t_{\mathrm{d}})^{0{,}5}$. 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 fracture strength of a flawed-cylinder is a known function of the cylinder diameter, the cylinder wall thickness and the flaw length. Because many of the tests results reported here used cylinders of about 230 mm in diameter and about 6 mm thick, the flaw length calculated in accordance with ISO 9809-2 is about the same (i.e. $10 \times t_{\mathrm{d}}$) as that used in any of the tests.

In the tests conducted in accordance with ISO 9809-2, the cylinder is pressurized to failure, the failure pressure, P_{f}, is measured and recorded, and the failure mode (leak or fracture) is recorded in the same way as for all of the tests reported here. However, in ISO 9809-2, the failure pressure is then adjusted to account for local variations in the cylinder wall thickness. This is done because the actual thickness in the vicinity of the flaw, t_{a}, is generally significantly different than the design minimum wall thickness of the cylinder, t_{d}. The adjusted failure pressure, $P_{\mathrm{f\ adjusted}}$, is calculated as $P_{\mathrm{f,\ adjusted}} = (P_{\mathrm{f}} \times t_{\mathrm{d}}/t_{\mathrm{a}})$. This adjustment to the failure pressure is based on the assumption that the failure pressure of a cylinder without a flaw is directly proportional to the actual thickness of the cylinder wall, t_{a}. Because the actual cylinder wall thickness is nearly always greater than the design minimum wall thickness, the effect of this adjustment is to lower the ratio of the adjusted failure pressure to the service pressure ($P_{\mathrm{f,\ adjusted}}/P_{\mathrm{s}}$) below that of the ratio of the measured failure pressure to the service pressure ($P_{\mathrm{f}}/P_{\mathrm{s}}$).

ISO 9809-2 requires that an acceptable result of the flawed-cylinder burst test is that the failure is by leaking (any extension of the flaw is less than 10 %) and that the ratio of the adjusted failure pressure to the service pressure ($P_{\mathrm{f,\ adjusted}}/P_{\mathrm{s}}) > 1{,}0$. In conducting the test, if the cylinder fails by leaking and the ratio ($P_{\mathrm{f,adjusted}}/P_{\mathrm{s}}) < 1{,}0$, then the cylinder may be welded to close the flaw and retested, as required, with a shallower flaw until the test fails by leaking and the ratio ($P_{\text{f, adjusted}}/P_{\text{s}} \geqslant 1{,}0$ is obtained. On the other hand, if the cylinder fails by fracturing and the ratio ($P_{\text{f, adjusted}}/P_{\text{s}}) > 1{,}0$ then the cylinder may be welded to close the flaw and retested, as required, with a deeper flaw until the test fails by leaking and the ratio ($P_{\text{f, adjusted}}/P_{\text{s}}) \geqslant 1{,}0$ is obtained. Either of these results is acceptable and the cylinder is considered to have adequate fracture resistance. It should be noted that the procedure specified by ISO 9809-2 only requires that the flawed-cylinder burst test results in leaking at a specified value of the $P_{\text{f}}/P_{\text{s}}$ ratio and does not require that the leak-fracture boundary be determined by getting both leak and fracture results in the test.

The flawed-cylinder burst test is conducted in accordance with ISO 9809-2 in two different ways for either “prototype” cylinders or for sample cylinders from a production “batch”. “Prototype” cylinders shall be produced and tested whenever there are changes in:

- the manufacturing process;
- the factory in which the cylinders are manufactured;
- the alloy steel's composition;
- the heat treatment;
- the guaranteed minimum yield strength (R_{e}) or the guaranteed minimum tensile strength (R_{g});
- the nominal diameter or design minimum wall thickness of the cylinder;
- the length of the cylinder is increased by more than 50 %.

A production “batch” of cylinders is defined as a group of cylinders (less than 1 000) produced from the same heat of steel and produced under identical conditions. Sample cylinders are taken from each production batch and tested to destruction.

When used to evaluate the fracture performance of “prototype” cylinders, at least two cylinders from an initial production run of 50 cylinders shall be tested and shall successfully meet the performance criteria described above. Although it is not required by ISO 9809-2, when a substantial change is made, such as when a new or higher strength alloy steel is used, it is recommended that the fracture performance of the “prototype” cylinders be evaluated by conducting flawed-cylinder burst tests with a wide range of flaw lengths and to establish the entire leak-fracture boundary over this range. It should be noted that the procedure specified by ISO 9809-2 only requires that the flawed-cylinder burst test results in leaking at a specified value of the $P_{\text{f}}/P_{\text{s}}$ ratio and does not require that the leak-fracture boundary be determined.

When used to evaluate the fracture performance of cylinders from a production “batch”, the flawed-cylinder burst test is required to be conducted for cylinders in which the wall thickness is less than 3 mm thick. For cylinders in which the wall thickness is greater than 3 mm, the flawed-cylinder burst test may be conducted to evaluate the fracture resistance of the cylinder. However, because the Charpy-V-notch (CVN) impact test has been widely used as a quality control test for cylinder production for some time, ISO/TC 58/SC 3 decided to permit the use of the CVN impact test as an alternate test method for evaluating the fracture performance of cylinders. As described below, the results of the flawed-cylinder burst tests reported here were used in part to establish the CVN impact test energy requirements when the Charpy-V-notch test is used to evaluate the fracture performance of production cylinders. If the CVN impact test requirements are not met, then the flawed-cylinder burst test shall be conducted and all flawed-cylinder burst tests that are conducted shall successfully meet the performance criteria described above. In evaluating the fracture performance of the production cylinders, the flawed-cylinder burst test is considered to be the definitive reference test.

7.3 Analysis by WG 14 to relate the flawed-cylinder burst test to Charpy-V-notch energy values

Empirical equations have been developed to predict the fracture performance of flawed pressure vessels (such as cylinders or pipes) in terms of the diameter, thickness, tensile strength, pressure, flaw size, and Charpy-V-notch impact test energy [8]. These equations use the specified diameter, thickness, tensile strength, flaw size and the CVN impact test energy of the pressure vessel to predict the failure pressure and to predict whether failure will be by leaking or by fracturing. These equations were originally developed to predict the initiation of fracture in large diameter steel pipelines made from non-heat-treated steels. A large number of flawed pipe tests were tested to failure and the failure pressure and failure modes were related to the pressure vessel properties. These equations were developed from empirical correlations between the measured failure pressure and the pressure vessel properties. There is no specific analytic basis to these equations.

WG 14 conducted a limited evaluation to determine if the same empirical correlations developed for predicting fracture in pipes could be used to predict the fracture performance of the high strength steel cylinders tested here. The properties of the cylinders tested in this investigation, particularly the Charpy-V-notch impact test energy, were used to predict the failure pressure and failure mode of the cylinders in the flawed-cylinder burst test. The results of these predictions were compared with the results of the flawed-cylinder burst test. The results of this evaluation have been described in previously published reports [9, 10].

WG 14 concluded that the performance of the flawed-cylinder burst test could be adequately predicted from the cylinder dimensions and the mechanical properties of the cylinders, particularly the Charpy-V-notch impact test energy. No analysis of the uncertainty in these predictions was carried out. On this basis, the WG 14 established an alternate to the flawed-cylinder burst test in terms of the Charpy-V-notch impact test energy to predict acceptable fracture resistance of high strength steel cylinders. The alternate requirements that use the Charpy-V-notch impact test energy to predict acceptable fracture performance is permitted only for production batch testing of cylinders. For the evaluation of the fracture performance of “prototype” cylinders, flawed-cylinder burst tests shall be conducted. These results are included in ISO 9809-2 as a minimum requirement for production batch testing of cylinders. The requirements for cylinders of all strength levels are:

— Charpy-V-notch tests to be conducted;

— 3 specimens from each cylinder;

— transverse specimen orientation;

— test temperature to be at – 50 °C;

— minimum acceptable test results (average of 3 specimens):

Cylinder minimum wall thickness, t_d, mm	Minimum CVN energy, J/cm^2
3 to 5	40
5 to 7,5	50
7,5 to 12	60

7.4 Adjustment to the measured P_f/P_s ratio to account for the local cylinder wall thickness

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 values of the P_f/P_s ratio for all of the flawed-cylinder burst tests conducted in this study. The adjusted ratio of the failure pressure to the service pressure, $P_{f,\ adjusted}/P_s$ is given in the last column in Tables 12 to 16. The test results with adjusted $P_{f,\ adjusted}/P_s$) ratios are also shown in Figures 21 to 34 for cylinders in material subgroups in which flawed-cylinder burst tests were conducted over a range of flaw lengths. For cylinders in material subgroups that were tested at only one flaw length and in which both leak and fracture test results were obtained, the results with adjusted $P_{f,\ adjusted}/P_s$ ratios are shown in Table 19. For cylinders in material subgroups that were tested at only one flaw length and in which only leak or fracture test results were obtained, the results with adjusted $P_{f,\ adjusted}/P_s$) ratios are shown in Table 20.

Because the actual cylinder wall thickness, t_a, should always be thicker than cylinder design minimum wall thickness, t_d, the adjusted failure pressure to service pressure ratio is generally smaller than the measured failure pressure to service pressure ratio, P_f/P_s). The only exceptions are for a few of the cylinders in material group A. These are older cylinders that can be expected to have unusually large variations in the thickness of the cylinder wall due to the production practices used. In a few of these cylinders, the actual cylinder wall thickness at the location of the machined flaw was slightly less than the design minimum wall thickness.

8 Summary and conclusions

Extensive test results of flawed-cylinder burst 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 burst to accurately evaluate the fracture performance of steel cylinders.

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 burst test.

The flawed-cylinder burst test is required to be conducted on steel cylinders in accordance with ISO 9809-2 for high strength steel cylinders.

Table 1 — Cylinder description for group A materials

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$	$R_{\text{g max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
Material group A-1											
1	A-1-1	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
2	A-1-1	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
3	A-1-1	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
4	A-1-1	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
5	A-1-2	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
6	A-1-2	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
7	A-1-2	Billet		—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
8	A-1-2	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
9	A-1-2	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
10	A-1-3	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
11	A-1-3	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
12	A-1-4	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
13	A-1-4	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
14	A-1-4	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
15	A-1-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
16	A-1-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6
17	A-1-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	43	230	232	155	6,6

Table 1 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength $R_{\text{g min}}$ MPa	$R_{\text{g max}}$ MPa	Cylinder specification	Material (steel alloy & special notes)	Vol. l	Dia. D mm	Design test pressure P_h bar	Design service pressure P_s bar	Design thickness t_d mm
Material group A-2											
18	A-1-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
19	A-1-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
20	A-2-2	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
21	A-2-3	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
22	A-2-3	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
23	A-2-4	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
24	A-2-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
25	A-2-5	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
26	A-2-6	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6
27	A-2-6	Billet	640	—	U.S.DOT 3A	Carbon Steel	50	232	232	155	6,6

Table 2 — Cylinder description for group B materials

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$	$R_{\text{g max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
Material Group B-2											
28	B-2-1	Billet	1 069	1 207	Experimental tempered to vary strength	Cr-Mo-V	45	236	465	310	6,6
29	B-2-1	Billet	1 069	1 207		Cr-Mo-V	45	236	465	310	6,6
30	B-2-1	Billet	1 069	1 207		Cr-Mo-V	45	236	465	310	6,6
31	B-2-1	Billet	1 069	1 207		Cr-Mo-V	45	236	465	310	6,6
32	B-2-1	Billet	1 069	1 207		Cr-Mo-V	45	236	465	310	6,6
Material Group B-3											
33	B-3-1	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
34	B-3-2	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
35	B-3-3	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
36	B-3-4	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
37	B-3-5	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
38	B-3-6	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
39	B-3-7	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
40	B-3-8	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
41	B-3-9	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
42	B-3-10	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
43	B-3-11	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8
44	B-3-12	Billet	724	—	U. S. DOT 3AA	Cr-Mo	50	236	276	184	5,8

Table 2 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\mathrm{g\ min}}$	$R_{\mathrm{g\ max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
Material Group B-4											
45	B-4-1	Tube	—	—	French 49.901	Ni-Cr-Mo	50	230	221	147	6,5
46	B-4-2	Tube	—	—	French 49.901	Ni-Cr-Mo	50	230	221	147	6,5
47	B-4-3	Tube	—	—	French 49.901	Ni-Cr-Mo	50	230	221	147	6,5
48	B-4-4	Tube	—	—	French 49.901	Ni-Cr-Mo	50	230	221	147	6,5
Material Group B-5											
49	B-5-1	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
50	B-5-2	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
51	B-5-3	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
52	B-5-4	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
53	B-5-5	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
54	B-5-6	Tube	—	—	French 49.901	Cr-Mo	50	230	300	200	6,0
Material Group B-6											
55	B-6-1	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
56	B-6-2	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
57	B-6-3	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
58	B-6-4	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
59	B-6-5	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
60	B-6-6	Billet	724	—	U. S. DOT 3AA	Cr-Mo	45	230	276	184	6,4
Material Group B-7											
61	B-7-1	Billet	724	897	U. S. DOT 3AA	Cr-Mo	43	236	414	276	8,7
62	B-7-2	Billet	724	897	U. S. DOT 3AA	Cr-Mo	43	236	414	276	8,7
63	B-7-3	Billet	724	897	U. S. DOT 3AA	Cr-Mo	43	236	414	276	8,7

Table 2 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
Material Group B-8											
64	B-8-1	Billet	724	897	U. S. DOT 3AA	Cr-Mo	38	238	690	460	14,4
65	B-8-2	Billet	724	897	U. S. DOT 3AA	Cr-Mo	38	238	690	460	14,4
66	B-8-3	Billet	724	897	U. S. DOT 3AA	Cr-Mo	38	238	690	460	14,4
Material Group B-9											
67	B-9-1	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
68	B-9-2	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
69	B-9-3	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
70	B-9-4	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
71	B-9-5	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
72	B-9-6	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
73	B-9-7	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
74	B-9-8	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
75	B-9-9	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
76	B-9-10	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
77	B-9-11	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
78	B-9-12	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
79	B-9-13	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
80	B-9-14	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
81	B-9-15	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
82	B-9-16	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
83	B-9-17	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
84	B-9-18	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8

Table 2 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$ MPa	$R_{\text{g max}}$ MPa			l	D mm	P_h bar	P_s bar	t_d mm
85	B-9-19	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
86	B-9-20	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
87	B-9-21	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
88	B-9-22	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
89	B-9-23	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
90	B-9-24	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
91	B-9-25	Billet	687	862	U. S. DOT 3AA	Cr-Mo	22	178	232	155	3,8
Material Group B-10											
92	B-10-1	Billet	800	950	ISO 9809-1	Cr-Mo	50	232	300	200	6,0
Material Group B-11											
93	B-11-1	Tube	750	880	ISO 9809-1	Cr-Mo	47	232	255	170	5,4
Material Group B-12											
94	B-12-1	Tube	815	930	ISO 9809-1	Cr-Mo	49	232	300	200	5,9
Material Group B-13											
95	B-13-1	Tube	890	1 090	ISO 9809-1	C-Mn	10	189	318	212	4,6
96	B-13-2	Tube	890	1 090	ISO 9809-1	C-Mn	10	189	318	212	4,6
97	B-13-3	Tube	890	1 090	ISO 9809-1	C-Mn	10	189	318	212	4,6
Material Group B-14											
98	B-14-1	Billet	800	950	ISO 9809-1	C-Mn	47	232	263	175	5,2
99	B-14-2	Billet	800	950	ISO 9809-1	C-Mn	47	232	263	175	5,2
100	B-14-3	Billet	800	950	ISO 9809-1	C-Mn	47	232	263	175	5,2

Table 2 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$ MPa	$R_{\text{g max}}$ MPa			l	D mm	P_{h} bar	P_{s} bar	t_{d} mm
Material Group B-15											
101	B-15-1	Billet	800	950	ISO 9809-1	Cr-Mo	50	232	295	197	5,5
102	B-15-2	Billet	800	950	ISO 9809-1	Cr-Mo	50	232	295	197	5,5
103	B-15-3	Billet	800	950	ISO 9809-1	Cr-Mo	50	232	295	197	5,5

Table 3 — Cylinder description for group C materials

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\,min}$	$R_{g\,max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
Material group C-3					Experimental tempered to vary strength						
104	C-3-1	Billet	724	—		Cr-Mo	49	235	276	184	6,1
105	C-3-1	Billet	724	—		Cr-Mo	49	235	276	184	6,1
106	C-3-1	Billet	724	—		Cr-Mo	49	235	276	184	6,1
107	C-3-2	Billet	724	—		Cr-Mo	49	235	276	184	6,1
108	C-3-3	Billet	724	—		Cr-Mo	49	235	276	184	6,1
109	C-3-3	Billet	724	—		Cr-Mo	49	235	276	184	6,1
110	C-3-4	Billet	724	—		Cr-Mo	49	235	276	184	6,1
111	C-3-5	Billet	724	—		Cr-Mo	49	235	276	184	6,1
112	C-3-5	Billet	724	—		Cr-Mo	49	235	276	184	6,1
113	C-3-6	Billet	724	—		Cr-Mo	49	235	276	184	6,1
Material group C-4					Experimental tempered to vary strength						
114	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
115	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
116	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
117	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
118	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
119	C-4-1	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
120	C-4-2	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
121	C-4-2	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
122	C-4-2	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
123	C-4-2	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6
124	C-4-2	Billet	1 069	1 207		Special alloy	45	236	465	310	6,6

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength $R_{g\,min}$ MPa	$R_{g\,max}$ MPa	Cylinder specification	Material (steel alloy & special notes)	Vol. l	Dia. D mm	Design test pressure P_h bar	Design service pressure P_s bar	Design thickness t_d mm
Material group C-5											
125	C-5-1	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
126	C-5-2	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
127	C-5-3	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
128	C-5-4	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
129	C-5-5	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
130	C-5-6	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
131	C-5-7	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
131	C-5-8	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
132	C-5-9	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
133	C-5-10	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
134	C-5-11	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
135	C-5-12	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
136	C-5-13	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
137	C-5-14	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
138	C-5-15	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
139	C-5-16	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
140	C-5-17	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
141	C-5-18	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
142	C-5-19	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
143	C-5-20	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0
144	C-5-21	Tube	880	1 030	1982 French spec.	Cr-Mo	50	229	300	200	6,0

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$	$R_{\text{g max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
Material group C-6											
145	C-6-1	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
146	C-6-2	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
147	C-6-3	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
148	C-6-4	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
149	C-6-5	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
150	C-6-6	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
151	C-6-7	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
152	C-6-8	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
153	C-6-9	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
154	C-6-10	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
155	C-6-11	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
156	C-6-12	Tube	880	1 030	1982 French spec.	Cr-Mo	20	203	300	200	5,6
Material group C-7											
157	C-7-1	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
158	C-7-2	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
159	C-7-3	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
160	C-7-4	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
161	C-7-5	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
162	C-7-6	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
163	C-7-7	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0
164	C-7-8	Tube	880	1 030	1982 French spec.	Cr-Mo	50	230	300	200	6,0

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\mathrm{g\,min}}$	$R_{\mathrm{g\,max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
Material group C-8						All Cr-Mo Special notes:					
165	C-8-1	Tube	880	1 030	1982 French spec.	Tested at + 20 °C	20	203	300	200	5,6
166	C-8-2	Tube	880	1 030	1982 French spec.	Tested at + 20 °C	20	203	300	200	5,6
167	C-8-3	Tube	880	1 030	1982 French spec.	Tested at - 50 °C	20	203	300	200	5,6
168	C-8-4	Tube	880	1 030	1982 French spec.	Tested at - 50 °C	20	203	300	200	5,6
169	C-8-5	Tube	880	1 030	1982 French spec.	Tested at - 50 °C	20	203	300	200	5,6
170	C-8-6	Tube	880	1 030	1982 French spec.	Tested at + 20 °C	20	203	300	200	5,6
Material group C-9						All Cr-Mo Special notes:					
171	C-9-1	Tube	880	1 030	1982 French spec.	Tested at + 20 °C	50	230	300	200	6,0
172	C-9-2	Tube	880	1 030	1982 French spec.	Tested at - 50 °C	50	230	300	200	6,0
173	C-9-3	Tube	880	1 030	1982 French spec.	Tested at + 20 °C	50	230	300	200	6,0
174	C-9-4	Tube	880	1 030	1982 French spec.	Tested at - 50 °C	50	230	300	200	6,0
Material group C-10											
175	C-10-1	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
176	C-10-1	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
177	C-10-3	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
178	C-10-4	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
179	C-10-5	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
180	C-10-6	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
181	C-10-7	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
182	C-10-8	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$	$R_{\text{g max}}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
183	C-10-9	Billet	930	1 068	Expt.	Special alloy	50	235	345	230	5,6
Material group C-11											
184	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
185	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
186	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
187	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
188	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
189	C-11-1	Billet	1 068	1 206	Expt.	Special alloy	45	238	466	311	6,6
Material group C-12											
190	C-12-1	Tube	950	1 100	ISO 9809	Cr-Mo	14	191	476	317	6,6
191	C-12-2	Tube	950	1 100	ISO 9809	Cr-Mo	14	191	490	317	6,6
Material group C-13											
192	C-13-1	Billet	1 000	1 150	ISO 9809	Cr-Mo	47	232	285	190	4,6
Material group C-14											
193	C-14-1	Billet	900	1 100	ISO 9809	Cr-Mo	47	232	245	163	4,3
194	C-14-2	Billet	900	1 100	ISO 9809	Cr-Mo	47	232	245	163	4,3
195	C-14-3	Billet	900	1 100	ISO 9809	Cr-Mo	47	232	245	163	4,3
Material group C-15											
196	C-15-1	Tube	950	1 050	ISO 9809	Cr-Mo	10	191	420	280	5,8
197	C-15-2	Tube	950	1 050	ISO 9809	Cr-Mo	10	191	420	280	5,8
198	C-15-3	Tube	950	1 050	ISO 9809	Cr-Mo	10	191	420	280	5,8

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$ MPa	$R_{g\ max}$ MPa			l	D mm	P_h bar	P_s bar	t_d mm
Material group C-16											
199	C-16-1	Billet	950	1 100	ISO 9809	Cr-Mo	50	232	330	220	5,5
200	C-16-2	Billet	950	1 100	ISO 9809	Cr-Mo	50	232	330	220	5,5
201	C-16-3	Billet	950	1 100	ISO 9809	Cr-Mo	50	232	330	220	5,5
Material group C-17											
202	C-17-1	Tube	950	1 050	ISO 9809	C-Mn	47	232	324	216	5,4
203	C-17-2	Tube	950	1 050	ISO 9809	C-Mn	47	232	324	216	5,4
204	C-17-3	Tube	950	1 050	ISO 9809	C-Mn	47	232	324	216	5,4
Material group C-18											
205	C-18-1	Tube	950	1 050	ISO 9809	Cr-Mo	49	232	309	206	5,2
206	C-18-2	Tube	950	1 050	ISO 9809	Cr-Mo	49	232	309	206	5,2
207	C-18-3	Tube	950	1 050	ISO 9809	Cr-Mo	49	232	309	206	5,2
Material group C-19											
208	C-19-1	Tube	950	1 050	ISO 9809	C-Mn	10	140	343	163	3,1
209	C-19-2	Tube	950	1 050	ISO 9809	C-Mn	10	140	343	163	3,1
210	C-19-3	Tube	950	1 050	ISO 9809	C-Mn	10	140	343	163	3,1
Material group C-20											
211	C-20-1	Billet	900	1 010	ISO 9809	C-Mn	47	230	316	210	5,5
212	C-20-2	Billet	900	1 010	ISO 9809	C-Mn	47	230	316	210	5,5
213	C-20-3	Billet	900	1 010	ISO 9809	C-Mn	47	230	316	210	5,5

Table 3 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
Material group C-21											
214	C-21-1	Billet	930	1 060	ISO 9809	Cr-Mo	50	232	363	242	6,2
215	C-21-2	Billet	930	1 060	ISO 9809	Cr-Mo	50	232	363	242	6,2
216	C-21-3	Billet	930	1 060	ISO 9809	Cr-Mo	50	232	363	242	6,2
Material group C-22											
219	C-22-1	Billet	1 000	1 170	ISO 9809	Cr-Mo	50	232	390	260	6,2
220	C-22-2	Billet	1 000	1 170	ISO 9809	Cr-Mo	50	232	390	260	6,2
221	C-22-3	Billet	1 000	1 170	ISO 9809	Cr-Mo	50	232	390	260	6,2
Material group C-23											
222	C-23-1	Tube	830	1 000	ISO 9809	C-Mn	47	232	288	192	5,5
223	C-23-2	Tube	900	1 100	ISO 9809	C-Mn	47	232	288	192	5,5
224	C-23-3	Tube	900	1 100	ISO 9809	C-Mn	47	232	288	192	5,5

Table 4 — Cylinder description for group D materials

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$ MPa	$R_{g\ max}$ MPa			l	D mm	P_h bar	P_s bar	t_d mm
Material group D-2											
225	D-2-1	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
225	D-2-2	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
226	D-2-3	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
227	D-2-4	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
228	D-2-5	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
229	D-2-6	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
230	D-2-7	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
231	D-2-8	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
232	D-2-9	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
233	D-2-10	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
234	D-2-11	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
235	D-2-12	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
236	D-2-13	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
237	D-2-14	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
238	D-2-15	Billet	1 100	1 160	ISO 9809-2	Cr-Mo	50	230	300	200	4,5
Material group D-3											
239	D-3-1	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
240	D-3-2	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
241	D-3-3	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
242	D-3-4	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
243	D-3-5	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
244	D-3-6	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
245	D-3-7	Billet	934	—	Expt.	Cr-Mo	50	230	300	200	5,2
Material group D-4											
246	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
247	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
248	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
249	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
250	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
251	D-4-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
Material group D-5											
252	D-5-1	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
253	D-5-2	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
254	D-5-3	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
255	D-5-4	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
256	D-5-5	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
257	D-5-6	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
258	D-5-7	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
259	D-5-8	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
260	D-5-9	Billet	1 069	1 207	ISO 9809-2	Pneumatic test	50	237	465	310	6,6
261	D-5-10	Billet	1 069	1 207	ISO 9809-2	Pneumatic test	50	237	465	310	6,6
262	D-5-11	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
263	D-5-12	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
264	D-5-13	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
265	D-5-14	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\mathrm{g\ min}}$	$R_{\mathrm{g\ max}}$				D	P_{h}	P_{s}	t_{d}
			MPa	MPa			l	mm	bar	bar	mm
266	D-5-15	Billet	1 069	1 207	ISO 9809-2	Special alloy	50	237	465	310	6,6
Material group D-6											
267	D-6-1	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
268	D-6-2	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
269	D-6-3	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
270	D-6-4	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
271	D-6-5	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
272	D-6-6	Billet	1 069	1 207	ISO 9809-2	Cr-Mo	50	236	465	310	6,6
Material group D-9											
273	D-9-1	Billet	930	1 068	ISO 9809-2	Cr-Mo	50	235	345	230	5,6
274	D-9-2	Billet	930	1 068	ISO 9809-2	Cr-Mo	50	235	345	230	5,6
275	D-9-3	Billet	930	1 068	ISO 9809-2	Cr-Mo	50	235	345	230	5,6
276	D-9-4	Billet	930	1 068	ISO 9809-2	Cr-Mo	50	235	345	230	5,6
Material group D-10											
277	D-10-1	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
278	D-10-2	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
279	D-10-3	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
280	D-10-4	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
281	D-10-5	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
282	D-10-6	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
283	D-10-7	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
284	D-10-8	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
285	D-10-9	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$ MPa	$R_{g\ max}$ MPa			l	D mm	P_h bar	P_s bar	t_d mm
286	D-10-10	Billet	1 068	1 206	Expt.	Cr-Mo	45	236	465	310	6,6
Material group D-11											
287	D-11-1	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
288	D-11-2	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
289	D-11-3	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
290	D-11-4	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
291	D-11-5	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
292	D-11-6	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
293	D-11-7	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
294	D-11-8	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
295	D-11-8	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
296	D-11-10	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
297	D-11-11	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
298	D-11-12	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
299	D-11-13	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
300	D-11-14	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
301	D-11-15	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
302	D-11-16	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
303	D-11-17	Billet	1 069	1 207	Expt.	Cr-Mo	50	230	450	300	6,4
Material group D-13											
304	D-13-1	Billet	1 050	1 200	ISO 9809	Special alloy	47	232	300	200	4,6
Material group D-14											
305	D-14-1	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
306	D-14-2	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
307	D-14-3	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
308	D-14-4	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
309	D-14-5	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
310	D-14-6	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
311	D-14-7	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
312	D-14-8	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
313	D-14-9	Billet	1 069	1 207	Expt.	Special alloy	30	229	465	310	5,0
314	D-14-10	Billet	1 069	1 207	Expt.	Special alloy	30	229	465	310	5,0
315	D-14-11	Billet	1 069	1 207	Expt.	Special alloy	30	229	465	310	5,0
316	D-14-12	Billet	1 069	1 207	Expt.	Special alloy	30	229	465	310	5,0
317	D-14-13	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
318	D-14-14	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
319	D-14-15	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
320	D-14-16	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
321	D-14-17	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
322	D-14-18	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
323	D-14-19	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
324	D-14-20	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
325	D-14-21	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
326	D-14-22	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
327	D-14-23	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
328	D-14-24	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
329	D-14-25	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
330	D-14-26	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
331	D-14-27	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
332	D-14-28	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
333	D-14-29	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
334	D-14-30	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
335	D-14-31	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
336	D-14-32	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
337	D-14-33	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
338	D-14-34	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
339	D-14-35	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
340	D-14-36	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
341	D-14-37	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
342	D-14-38	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
343	D-14-39	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
344	D-14-40	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
345	D-14-41	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
346	D-14-42	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
347	D-14-43	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
348	D-14-44	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
349	D-14-45	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
350	D-14-46	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
351	D-14-47	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6

Table 4 (*continued*)

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{g\ min}$	$R_{g\ max}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
352	D-14-48	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
353	D-14-49	Billet	1 069	1 207	Expt.	Special alloy	45	236	465	310	6,6
Material group D-15											
354	D-15-1	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	191	426	284	5,3
355	D-15-2	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	191	426	284	5,3
356	D-15-2	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	191	426	284	5,3
Material group D-16											
357	D-16-1	Billet	1 000	1 150	ISO 9809	Cr-Mo	50	232	347	231	5,5
358	D-16-2	Billet	1 000	1 150	ISO 9809	Cr-Mo	50	232	347	231	5,5
359	D-16-2	Billet	1 000	1 150	ISO 9809	Cr-Mo	50	232	347	231	5,5
Material group D-17											
360	D-17-1	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	232	338	225	5,1
361	D-17-2	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	232	338	225	5,1
362	D-17-2	Tube	1 050	1 150	ISO 9809	Cr-Mo	10	232	338	225	5,1
Material group D-18											
363	D-18-1	Tube	1 150	1 250	ISO 9809	Cr-Mo	49	232	375	250	5,2
364	D-18-2	Tube	1 150	1 250	ISO 9809	Cr-Mo	49	232	375	250	5,2
365	D-18-2	Tube	1 150	1 250	ISO 9809	Cr-Mo	49	232	375	250	5,2
Material group D-19											
366	D-19-1	Billet	1 100	1 270	ISO 9809	Cr-Mo	50	232	420	280	6,2
367	D-19-2	Billet	1 100	1 270	ISO 9809	Cr-Mo	50	232	420	280	6,2
368	D-19-2	Billet	1 100	1 270	ISO 9809	Cr-Mo	50	232	420	280	6,2

Table 5 — Cylinder description for group E materials

Test No.	Cylinder No.	Type of cylinder Mfg.	Specified tensile strength		Cylinder specification	Material (steel alloy & special notes)	Vol.	Dia.	Design test pressure	Design service pressure	Design thickness
			$R_{\text{g min}}$	$R_{\text{g max}}$				D	P_h	P_s	t_d
			MPa	MPa			l	mm	bar	bar	mm
Material group E-1											
369	E-1-1	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
370	E-1-2	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
371	E-1-3	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
372	E-1-4	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
373	E-1-5	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
374	E-1-6	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
375	E-1-7	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
376	E-1-8	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
377	E-1-9	Billet	—	—	Expt.	Cr-Mo-V	50	236	345	230	5,56
Material group E-2											
378	E-2-1	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60
379	E-2-2	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60
380	E-2-3	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60
381	E-2-4	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60
382	E-2-5	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60
383	E-2-6	Billet	—	—	Expt.	Cr-Mo-V	45	238	466	311	6,60

Table 6 — Mechanical properties of group A materials

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group A-1										
1	A-1-1	513	748	28,0	10 × 5	18,6	3,4	10 × 4	34,5	3,4
2	A-1-1	513	748	28,0	10 × 5	18,6	3,4	10 × 4	34,5	3,4
3	A-1-1	513	748	28,0	10 × 5	18,6	3,4	10 × 4	34,5	3,4
4	A-1-1	513	748	28,0	10 × 5	18,6	3,4	10 × 4	34,5	3,4
5	A-1-2	496	648	26,5	10 × 5	32,0	5,0	10 × 4	63,0	15,0
6	A-1-2	496	648	26,5	10 × 5	32,0	5,0	10 × 4	63,0	15,0
7	A-1-2	496	648	26,5	10 × 5	32,0	5,0	10 × 4	63,0	15,0
8	A-1-2	496	648	26,5	10 × 5	32,0	5,0	10 × 4	63,0	15,0
9	A-1-2	496	648	26,5	10 × 5	32,0	5,0	10 × 4	63,0	15,0
10	A-1-3	497	731	27,0	10 × 5	20,0	11,0	10 × 4	45,0	9,0
11	A-1-3	497	731	27,0	10 × 5	20,0	11,0	10 × 4	45,0	9,0
12	A-1-4	535	790	23,0	10 × 5	17,0	6,0	10 × 4	39,0	12,0
13		535	790	23,0	10 × 5	17,0	6,0	10 × 4	39,0	12,0
14		535	790	23,0	10 × 5	17,0	6,0	10 × 4	39,0	12,0
15	A-1-5	481	678	23,3	10 × 5	24,0	2,8	10 × 4	28,0	10,0
16	A-1-5	481	678	23,3	10 × 5	24,0	2,8	10 × 4	28,0	10,0
17	A-1-5	481	678	23,3	10 × 5	24,0	2,8	10 × 4	28,0	10,0
Material group A-2										
18	A-2-1	413	641	35,0	10 × 5	23,0	5,6	10 × 5	41,8	5,7
19	A-2-1	413	641	35,0	10 × 5	23,0	5,6	10 × 5	41,8	5,7
20	A-2-2	—	—	—	—	—	—	—	—	—
21	A-2-3	510	751	24,0	10 × 5	12,7	4,2	10 × 4	28,2	6,7
22		510	751	24,0	10 × 5	12,7	4,2	10 × 4	28,2	6,7
23	A-2-4	—	—	—	10 × 5	—	—	—	—	—
24	A-2-5	483	696	21,0	10 × 5	12,7	4,2	10 × 4	27,1	3,4
25	A-2-5	483	696	21,0	10 × 5	12,7	4,2	10 × 4	27,1	3,4
26	A-2-6	—	—	—	—	—	—	—	—	—
27	A-2-6	—	—	—	—	—	—	—	—	—

Table 7 — Mechanical properties of group B materials

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group B-2										
28	B-2-1	832	910	23,0	10 × 5	103	105	—	—	—
29	B-2-1	832	910	23,0	10 × 5	103	105	—	—	—
30	B-2-1	832	910	23,0	10 × 5	103	105	—	—	—
31	B-2-1	832	910	23,0	10 × 5	103	105	—	—	—
32	B-2-1	832	910	23,0	10 × 5	103	105	—	—	—
Material group B-3										
33	B-3-1	580	745	—	—	—	—	—	—	—
34	B-3-2	642	794	—	—	—	—	—	—	—
35	B-3-3	607	752	—	—	—	—	—	—	—
36	B-3-4	538	704	—	—	—	—	—	—	—
37	B-3-5	690	814	—	—	—	—	—	—	—
38	B-3-6	598	745	—	—	—	—	—	—	—
39	B-3-7	738	869	—	—	—	—	—	—	—
40	B-3-8	697	780	—	—	—	—	—	—	—
41	B-3-9	696	821	—	—	—	—	—	—	—
42	B-3-10	669	800	—	—	—	—	—	—	—
43	B-3-11	662	787	—	—	—	—	—	—	—
44	B-3-12	649	787	—	—	—	—	—	—	—
Material group B-4										
45	B-4-1	—	—	—	—	—	—	—	—	—
46	B-4-2	—	—	—	—	—	—	—	—	—
47	B-4-3	—	—	—	—	—	—	—	—	—
48	B-4-4	683	847	20,0	10 × 5	64	54	10 × 4	92	78
Material group B-5										
49	B-5-1	890	949	16,7	10 × 5	132	94	10 × 4	107	99
50	B-5-2	—	—	—	—	—	—	—	—	—
51	B-5-3	—	—	—	—	—	—	—	—	—
52	B-5-4	—	—	—	—	—	—	—	—	—
53	B-5-5	—	—	—	—	—	—	—	—	—
54	B-5-6	—	—	—	—	—	—	—	—	—

Table 7 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group B-6										
55	B-6-1	655	778	22,0	10 × 5	62	55	10 × 4	139	122
56	B-6-2	657	788	20,0	10 × 5	51	51	10 × 4	113	104
57	B-6-3	755	870	23,0	10 × 5	54	53	10 × 4	122	117
58	B-6-4	577	743	27,0	—	—	—	—	—	—
59	B-6-5	635	748	28,0	—	—	—	—	—	—
60	B-6-6	658	731	27,0	—	—	—	—	—	—
Material group B-7										
61	B-7-1	648	786	28,0	10 × 5	64	52	10 × 4	164	138
62	B-7-2	—	—	—	—	—	—	—	—	—
63	B-7-3	—	—	—	—	—	—	—	—	—
Material group B-8										
64	B-8-1	669	807	31,5	10 × 5	81	55	10 × 4	165	149
65	B-8-2	—	—	—	—	—	—	—	—	—
66	B-8-3	—	—	—	—	—	—	—	—	—
Material group B-9										
67	B-9-1	570	776	26,7	10 × 5	28	24	10 × 4	113	96
68	B-9-2	577	774	23,6	10 × 5	32	27	10 × 4	96	89
69	B-9-3	584	817	22,9	—	—	—	—	—	—
70	B-9-4	625	783	22,8	—	—	—	—	—	—
71	B-9-5	623	797	21,3	—	—	—	—	—	—
72	B-9-6	587	762	23,9	10 × 5	29	26	10 × 4	99	82
73	B-9-7	563	808	22,3	—	—	—	—	—	—
74	B-9-8	577	800	22,4	—	—	—	—	—	—
75	B-9-9	635	811	23,4	—	—	—	—	—	—
76	B-9-10	604	825	20,1	—	—	—	—	—	—
77	B-9-11	541	826	21,2	10 × 5	31	25	10 × 4	98	92
78	B-9-12	536	736	23,1	—	—	—	—	—	—
79	B-9-13	582	802	21,3	—	—	—	—	—	—
80	B-9-14	560	811	22,9	—	—	—	—	—	—
81	B-9-15	630	832	24,2	—	—	—	—	—	—
82	B-9-16	670	815	23,6	10 × 5	31	25	10 × 4	98	92
83	B-9-17	599	808	23,6	10 × 5	25	21	10 × 4	89	91

Table 7 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
84	B-9-18	595	796	24,4	—	—	—	—	—	—
85	B-9-19	643	829	23,8	—	—	—	—	—	—
86	B-9-20	557	838	21,1	—	—	—	—	—	—
87	B-9-21	615	823	21,9	—	—	—	—	—	—
88	B-9-22	619	831	20,2	—	—	—	—	—	—
89	B-9-23	603	787	24,1	10 × 5	24	22	10 × 4	91	78
90	B-9-24	665	843	24,6	—	—	—	—	—	—
91	B-9-25	623	811	25,0	—	—	—	—	—	—
Material group B-10										
92	B-10-1	748	875	14,1	10 × 4	40	34	10 × 4	99	85
Material group B-11										
93	B-11-1	713	824	17,0	10 × 4	39	37	10 × 4	101	82
Material group B-12										
94	B-12-1	763 (T)	872 (T)	17,5 (T)	10 × 4	64	58	10 × 4	145	135
Material group B-13										
95	B-13-1	790	930	14,3	10 × 4	54	49	10 × 4	86	77
96	B-13-2	821	950	14,1	—	—	—	—	—	—
97	B-13-3	—	—	—	—	—	—	—	—	—
Material group B-14										
98	B-14-1	715 (T)	851 (T)	18,8 (T)	10 × 4	40	92	10 × 4	92	85
99	B-14-2	—	—	—	—	—	—	—	—	—
100	B-14-3	—	—	—	—	—	—	—	—	—
Material group B-15										
101	B-15-1	765 (T)	909 (T)	18,8 (T)	10 × 4	100	40	10 × 4	118	48
102	B-15-2	—	—	—	—	—	—	—	—	—
103	B-15-3	—	—	—	—	—	—	—	—	—

Table 8 — Mechanical properties of group C materials

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group C-3										
104	C-3-1	1 067	1 121	17,2	10 × 5	18	15	10 × 5	64	55
105	C-3-1	1 067	1 121	17,2	10 × 5	18	15	10 × 5	64	55
106	C-3-1	1 067	1 121	17,2	10 × 5	18	15	10 × 5	64	55
107	C-3-2	1 047	1 108	20,0	—	—	—	—	—	—
108	C-3-3	1 053	1 093	17,8	—	—	—	—	—	—
109	C-3-3	1 053	1 093	17,8	—	—	—	—	—	—
110	C-3-4	935	999	13,5	—	—	—	—	—	—
111	C-3-5	955	1 023	12,0	—	—	—	—	—	—
112	C-3-5	955	1 023	12,0	—	—	—	—	—	—
113	C-3-6	1 016	1 088	16,5	—	—	—	—	—	—
Material group C-4										
114	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
115	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
116	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
117	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
118	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
119	C-4-1	928	992	24,0	10 × 5	121	101	—	—	—
120	C-4-2	973	1 049	19,0	10 × 5	64	49	—	—	—
121	C-4-2	973	1 049	19,0	10 × 5	64	49	—	—	—
122	C-4-2	973	1 049	19,0	10 × 5	64	49	—	—	—
123	C-4-2	973	1 049	19,0	10 × 5	64	49	—	—	—
124	C-4-2	973	1 049	19,0	10 × 5	64	49	—	—	—
Material group C-5										
125	C-5-1	—	—	—	—	—	—	—	—	—
126	C-5-2	—	—	—	—	—	—	—	—	—
127	C-5-3	—	—	—	—	—	—	—	—	—
128	C-5-4	—	—	—	—	—	—	—	—	—
129	C-5-5	—	—	—	—	—	—	—	—	—
130	C-5-6	—	—	—	—	—	—	—	—	—
131	C-5-7	878	996	—	10 × 5	118	88	10 × 5	125	57
131	C-5-8	887	989	—				—		
132	C-5-9	867	992	—	10 × 5	118	88	—	125	57

Table 8 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
133	C-5-10	855	961	—	—	—	—	—	—	—
134	C-5-11	—	—	—	—	—	—	—	—	—
135	C-5-12	—	—	—	—	—	—	—	—	—
136	C-5-13	840	949	—	10 × 5	107	99		132	99
137	C-5-14	—	---	—	—	—	—	—	—	—
138	C-5-15	—	—	—	—	—	—	—	—	—
139	C-5-16	—	—	—	—	—	—	—	—	—
140	C-5-17	—	—	—	—	—	—	—	—	—
141	C-5-18	—	—	—	—	—	—	—	—	—
142	C-5-19	835	949	—	10 × 5	125	110		82	81
143	C-5-20	—	—	—	—	—	—	—	—	—
144	C-5-21	—	—	—	—	—	—	—	—	—
Material group C-6										
145	C-6-1	—	—	—	—	—	—	—	—	—
146	C-6-2	—	—	—	—	—	—	—	—	—
147	C-6-3	852	964	—	10 × 5	130	124	10 × 5	128	57
148	C-6-4	—	—	—	—	—	—	—	—	—
149	C-6-5	—	—	—	—	—	—	—	—	—
150	C-6-6	—	—	—	—	—	—	—	—	—
151	C-6-7	—	—	—	—	—	—	—	—	—
152	C-6-8	—	—	—	—	—	—	—	—	—
153	C-6-9	—	—	—	—	—	—	—	—	—
154	C-6-10	—	—	—	—	—	—	—	—	—
155	C-6-11	—	—	—	—	—	—	—	—	—
156	C-6-12	—	—	—	—	—	—	—	—	—
Material group C-7										
157	C-7-1	—	—	—	—	—	—	—	—	—
158	C-7-2	898 (T)	1 000 (T)			150	130		37	27
159	C-7-3	850 (T)	950 (T)			—	—		57	47
160	C-7-4	—	—	—	—	—	—	—	—	—
161	C-7-5	922 (T)	1 000 (T)			126	108		39	33
162	C-7-6	—	—	—	—	—	—	—	—	—
163	C-7-7	898 (T)	1 000 (T)			109	102		66	63
164	C-7-8	—	—	—	—	—	—	—	—	—

Table 8 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group C-8										
165	C-8-1	850 (T)	960 (T)	—	—	96	76	—	—	—
166	C-8-2	—	—	—	—	—	—	—	—	—
167	C-8-3	—	—	—	—	—	—	—	—	—
168	C-8-4	—	—	—	—	—	—	—	—	—
169	C-8-5	—	—	—	—	74	74	—	—	—
170	C-8-6	—	—	—	—	—	—	—	—	—
Material group C-9										
171	C-9-1	898 (T)	1 000 (T)	—	—	—	—	—	—	—
172	C-9-2	—	—	—	—	—	—	—	—	—
173	C-9-3	—	—	—		74	72			
174	C-9-4	—	—	—	—	—	—	—	—	—
Material group C-10										
175	C-10-1	896	1 000	21,0	10 × 5	38	34	10 × 4	119	119
176	C-10-1	862	972	23,0	—	—	—	—	—	—
177	C-10-3	828	938	21,0	—	—	—	—	—	—
178	C-10-4	896	986	21,0	—	—	—	—	—	—
179	C-10-5	938	1 027	21,0	—	—	—	—	—	—
180	C-10-6	793	862	25,0	10 × 5	63	57	10 × 4	147	133
181	C-10-7	979	1 048	20,0	—	—	—	—	—	—
182	C-10-8	952	1 041	20,0	—	—	—	—	—	—
183	C-10-9	952	1 027	21,0	—	—	—	—	—	—
Material group C-11										
184	C-11-1	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
185	"	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
186	"	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
187	"	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
188	"	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
189	"	1 003	1 069	21,5	10 × 5	—	40	10 × 4	—	118
Material group C-12										
190	C-12-1	842	962	13,7	10 × 4	77	75	10 × 4	132	123
191	C-12-2	969	1 067	12,7	10 × 4	56	53	10 × 4	100	92

Table 8 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group C-13										
192	C-13-1	999	1 072	14,4	10 × 4	98	89	10 × 4	141	128
Material group C-14										
193	C-14-1	921	985	16,2	10 × 4	52	43	10 × 4	134	130
194	C-14-2	—	—	—	—	—	—	—	—	—
195	C-14-3	—	—	—	—	—	—	—	—	—
Material group C-15										
196	C-15-1	865	969	16	10 × 4	70	63	10 × 4	114	117
197	C-15-2	861	964	15	—	—	—	—	—	—
198	C-15-3	—	—	—	—	—	—	—	—	—
Material group C-16										
199	C-16-1	886 (T)	1 013 (T)	14,7 (T)	10 × 4	42	37	10 × 4	97	81
200	C-16-2	—	—	—	—	—	—	—	—	—
201	C-16-3	—	—	—	—	—	—	—	—	—
Material group C-17										
202	C-17-1	841 (T)	960 (T)	15 (T)	10 × 4	45	41	10 × 4	85	47
203	C-17-2	—	—	—	—	—	—	—	—	—
204	C-17-3	—	—	—	—	—	—	—	—	—
Material group C-18										
205	C-18-1	919 (T)	991 (T)	14 (T)	10 × 4	58	54	10 × 4	129	117
206	C-18-2	—	—	—	—	—	—	—	—	—
207	C-18-3	—	—	—	—	—	—	—	—	—
Material group C-19										
208	C-19-1	920 (T)	980 (T)	14 (T)	10 × 4	48	42	10 × 4	94	48
209	C-19-2	—	—	—	—	—	—	—	—	—
210	C-19-3	—	—	—	—	—	—	—	—	—
Material group C-20										
211	C-20-1	827	956	14	10 × 4	36	34	10 × 4	101	94
212	C-20-2	—	—	—	—	—	—	—	—	—
213	C-20-3	—	—	—	—	—	—	—	—	—
Material group C-21										
214	C-21-1	857	955	15	10 × 4	40	34	10 × 4	107	105
215	C-21-2	—	—	—	—	—	—	—	—	—
216	C-21-3	—	—	—	—	—	—	—	—	—

Table 8 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group C-22										
219	C-22-1	965	1 041	13	10 × 4	33	28	10 × 4	88	89
220	C-22-2	—	—	—	—	—	—	—	—	—
221	C-22-3	—	—	—	—	—	—	—	—	—
Material group C-23										
222	C-23-1	876	983	15	10 × 4	92	52	10 × 4	104	85
223	C-23-2	—	—	—	—	—	—	—	—	—
224	C-23-3	—	—	—	—	—	—	—	—	—

Table 9 — Mechanical properties of group D materials

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group D-2										
225	D-2-1	1 087	1 154	14,3	10 × 5	46	26	10 × 5	91	—
225	D-2-2	1 054	1 122	15,3	10 × 5	68	42	10 × 5	103	—
226	D-2-3	1 072	1 135	15,2	10 × 5	53	39	10 × 5	96	—
227	D-2-4	1 060	1 128	14,4	10 × 5	55	38	10 × 5	97	—
228	D-2-5	1 070	1 135	14,0	10 × 5	53	38	10 × 5	95	—
229	D-2-6	1 042	1 112	15,6	10 × 5	56	46	10 × 5	105	—
230	D-2-7	1 063	1 136	14,0	10 × 5	56	36	10 × 5	93	—
231	D-2-8	1 052	1 117	15,3	10 × 5	57	38	10 × 5	99	—
232	D-2-9	1 060	1 124	14,4	10 × 5	61	43	10 × 5	102	—
233	D-2-10	1 059	1 127	14,0	10 × 5	59	44	10 × 5	103	---
234	D-2-11	1 069	1 143	15,0	10 × 5	58	43	10 × 5	100	—
235	D-2-12	1 056	1 126	14,1	10 × 5	36	28	10 × 5	109	104
236	D-2-13	1 067	1 135	14,0	10 × 5	85	52	10 × 5	108	64
237	D-2-14	1 041	1 117	15,1	10 × 5	94	58	10 × 5	117	68
238	D-2-15	1 017	1 104	15,2	10 × 5	60	41	10 × 5	111	69
Material group D-3										
239	D-3-1	1 023	1 092	14,7	10 × 5	28	26	10 × 5	95	86
240	D-3-2	1 005	1 076	14,2	10 × 5	25	22	10 × 5	98	85
241	D-3-3	995	1 061	14,2	10 × 5	24	24	10 × 5	103	87
242	D-3-4	1 004	1 069	14,2	10 × 5	40	36	10 × 5	124	101
243	D-3-5	1 039	1 104	14,2	10 × 5	25	22	10 × 5	101	84
244	D-3-6	987	1 060	15,0	10 × 5	69	58	10 × 5	124	107
245	D-3-7	1 017	1 104	15,2	10 × 5	60	41	10 × 5	111	69
Material group D-4										
246	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—
247	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—
248	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—
249	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—
250	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—
251	D-4-1	1 024	1 111	18,5	10 × 5	68	56	—	—	—

Table 9 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group D-5										
252	D-5-1	1 098	1 180	18,0	10 × 5	67	37	10 × 5	85	—
253	D-5-2	—	—	—	—	—	—	—	—	—
254	D-5-3	—	—	—	—	—	—	—	—	—
255	D-5-4	—	—	—	—	—	—	—	—	—
256	D-5-5	—	—	—	—	—	—	—	—	—
257	D-5-6	—	—	—	—	—	—	—	—	—
258	D-5-7	—	—	—	—	—	—	—	—	—
259	D-5-8	—	—	—	—	—	—	—	—	—
260	D-5-9	—	—	—	—	—	—	—	—	—
261	D-5-10	—	—	—	—	—	—	—	—	—
262	D-5-11	—	—	—	—	—	—	—	—	—
263	D-5-12	—	—	—	—	—	—	—	—	—
264	D-5-13	—	—	—	—	—	—	—	—	—
265	D-5-14	—	—	—	—	—	—	—	—	—
266	D-5-15	—	—	—	—	—	—	—	—	—
Material group D-6										
267	D-6-1	1 139	1 166	—	10 × 5	24	17	10 × 5	68	—
268	D-6-2	1 118	1 139	—	—	—	—	—	—	—
269	D-6-3	1 139	1 173	—	—	—	—	—	—	—
270	D-6-4	1 076	1 111	—	—	—	—	—	—	—
271	D-6-5	1 083	1 118	—	—	—	—	—	—	—
272	D-6-6	1 063	1 097	—	—	—	—	—	—	—
Material group D-9										
273	D-9-1	1 027	1 103	18,0	—	—	—	—	—	—
274	D-9-2	1 039	1 089	20,0	10 × 5	44	41	10 × 4	107	98
275	D-9-3	1 061	1 110	20,0	—	—	—	—	—	—
276	D-9-4	1 124	1 179	17,0	10 × 5	37	34	10 × 4	94	81
Material group D-10										
277	D-10-1	1 045	1 139	21,0	10 × 5	70	63	10 × 5	126	—
278	D-10-2	1 046	1 140	22,0	10 × 5	74	66	10 × 5	138	—
279	D-10-3	1 073	1 168	22,0	10 × 5	99	88	10 × 5	138	—
280	D-10-4	1 034	1 134	21,0	10 × 5	106	96	10 × 5	130	—

Table 9 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea} MPa	R_m MPa	A %	Size mm	at + 20 °C J/cm^2	at − 50 °C J/cm^2	Size mm	at + 20 °C J/cm^2	at − 50 °C J/cm^2
281	D-10-5	943	1 036	19,0	10 × 5	104	89	10 × 5	137	—
282	D-10-6	1 115	1 206	20,0	10 × 5	63	54	10 × 5	125	—
283	D-10-7	993	1 077	23,0	10 × 5	102	95	10 × 5	140	—
284	D-10-8	1 060	1 146	21,0	10 × 5	95	85	10 × 5	132	—
285	D-10-9	1 096	1 182	20,0	10 × 5	76	67	10 × 5	117	—
286	D-10-10	1 001	1 083	20,0	10 × 5	70	70	10 × 5	129	—
Material group D-11										
287	D-11-1	1 027	1 102	15,7	10 × 5	—	83	—	—	128
288	D-11-2	—	—	—	—	—	—	—	—	—
289	D-11-3	—	—	—	—	—	—	—	—	—
290	D-11-4	—	—	—	—	—	—	—	—	—
291	D-11-5	—	—	—	—	—	—	—	—	—
292	D-11-6	—	—	—	—	—	—	—	—	—
293	D-11-7	—	—	—	—	—	—	—	—	—
294	D-11-8	—	—	—	—	—	—	—	—	—
295	D-11-8	—	—	—	—	—	—	——	—	—
296	D-11-10	—	—	—	—	—	—	—	—	—
297	D-11-11	—	—	—	—	—	—	—	—	—
298	D-11-12	—	—	—	—	—	—	—	—	—
299	D-11-13	—	—	—	—	—	—	—	—	—
300	D-11-14	—	—	—	—	—	—	—	—	—
301	D-11-15	—	—	—	—	—	—	—	—	—
302	D-11-16	—	—	—	—	—	—	—	—	—
303	D-11-17	—	—	—	—	—	—	—	—	—
Material group D-13										
304	D-13-1	1 072	1 124	15,0	10 × 4	88	79	—	131	—
Material group D-14										
305	D-14-1	1 010	1 137	21,0	10 × 5	—	36	—	—	—
306	D-14-2	—	—	—	—	—	—	—	—	—
307	D-14-3	1 065	1 139	20,0	10 × 5	—	56	—	—	—
308	D-14-4	—	—	—	—	—	—	—	—	—
309	D-14-5	1 085	1 156	19,5	10 × 5	—	37	—	—	—
310	D-14-6	—	—	—	—	—	—	—	—	—
311	D-14-7	1 086	1 157	18,5	10 × 5	—	31	—	—	—

Table 9 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
312	D-14-8	1 069	1 135	20,0	10 × 5	—	33	—	—	—
313	D-14-9	1 012	1 076	21	10 × 5	—	80	—	—	—
314	D-14-10	—	—	—	—	—	—	—	—	—
315	D-14-11	—	—	—	—	—	—	—	—	—
316	D-14-12	—	—	—	—	—	—	—	—	—
317	D-14-13	1 086	1 157	18,5	10 × 5	—	31	—	—	—
318	D-14-14	—	—	—	—	—	—	—	—	—
319	D-14-15	—	—	—	—	—	—	—	—	—
320	D-14-16	—	—	—	—	—	—	—	—	—
321	D-14-17	—	—	—	—	—	—	—	—	—
322	D-14-18	—	—	—	—	—	—	—	—	—
323	D-14-19	—	—	—	—	—	—	—	—	—
324	D-14-20	—	—	—	—	—	—	—	—	—
325	D-14-21	—	—	—	—	—	—	—	—	—
326	D-14-22	—	—	—	—	—	—	—	—	—
327	D-14-23	—	—	—	—	—	—	—	—	—
328	D-14-24	—	—	—	—	—	—	—	—	—
329	D-14-25	—	—	—	—	—	—	—	—	—
330	D-14-26	—	—	—	—	—	—	—	—	—
331	D-14-27	—	—	—	—	—	—	—	—	—
332	D-14-28	—	—	—	—	—	—	—	—	—
333	D-14-29	—	—	—	—	—	—	—	—	—
334	D-14-30	—	—	—	—	—	—	—	—	—
335	D-14-31	1 020	1 081	20,0	10 × 5	—	80	—	—	—
336	D-14-32	—	—	—	—	—	—	—	—	—
337	D-14-33	—	—	—	—	—	—	—	—	—
338	D-14-34	—	—	—	—	—	—	—	—	—
339	D-14-35	1 069	1 081	20,0	10 × 5	—	80	—	—	—
340	D-14-36	—	—	—	—	—	—	—	—	—
341	D-14-37	—	—	—	—	—	—	—	—	—
342	D-14-38	—	—	—	—	—	—	—	—	—
343	D-14-39	1 000	1 073	21,0	10 × 5	—	80	—	—	—
344	D-14-40	—	—	—	—	—	—	—	—	—

Table 9 (*continued*)

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea} MPa	R_{m} MPa	A %	Size mm	at + 20 °C J/cm^2	at − 50 °C J/cm^2	Size mm	at + 20 °C J/cm^2	at − 50 °C J/cm^2
345	D-14-41	—	—	—	—	—	—	—	—	—
346	D-14-42	—	—	—	—	—	—	—	—	—
347	D-14-43	—	—	—	—	—	—	—	—	—
348	D-14-44	1 022	1 077	20,0	10 × 5	—	65	—	—	—
349	D-14-45	—	—	—	—	—	—	—	—	—
350	D-14-46	—	—	—	—	—	—	—	—	—
351	D-14-47	1 020	1 081	20,0	10 × 5	—	80	—	—	—
352	D-14-48	—	—	—	—	—	—	—	—	—
353	D-14-49	—	—	—	—	—	—	—	—	—
Material group D-15										
354	D-15-1	989	1 084	13,1	10 × 4	59	57	10 × 4	107	100
355	D-15-2	986	1 078	13,8	—	—	—	—	—	—
356	D-15-2	—	—	—	—	—	—	—	—	—
Material group D-16										
357	D-16-1	963 (T)	1 079 (T)	13,8 (T)	10 × 4	35	26	10 × 4	78	53
358	D-16-2	—	—	—	—	—	—	—	—	—
359	D-16-2	—	—	—	—	—	—	—	—	—
Material group D-17										
360	D-17-1	1 024 (T)	1 098 (T)	12 (T)	10 × 4	49	42	10 × 4	100	62
361	D-17-2	—	—	—	—	—	—	—	—	—
362	D-17-2	—	—	—	—	—	—	—	—	—
Material group D-18										
363	D-18-1	1 107 (T)	1 180 (T)	12 (T)	10 × 4	42	37	10 × 4	89	46
364	D-18-2	—	—	—	—	—	—	—	—	—
365	D-18-2	—	—	—	—	—	—	—	—	—
Material group D-19										
366	D-19-1	1 084	1 155	11,1	10 × 4	24	22	10 × 4	78	76
367	D-19-2	—	—	—	—	—	—	—	—	—
368	D-19-2	—	—	—	—	—	—	—	—	—

Table 10 — Mechanical properties of group E materials

Test No.	Cylinder No.	Tensile test results			Charpy- V- notch test results					
		Yield strength	Tensile strength	Elong.	Transverse orientation			Longitudinal orientation		
		R_{ea}	R_m	A	Size	at + 20 °C	at − 50 °C	Size	at + 20 °C	at − 50 °C
		MPa	MPa	%	mm	J/cm^2	J/cm^2	mm	J/cm^2	J/cm^2
Material group E-1										
311	E-1-1	—	—	—	—	—	—	—	—	—
312	E-1-2	1 186	1 317	12,5	10 × 5	—	17,0	10 × 4	—	24,3
313	E-1-3	—	—	—	—	—	—		—	—
314	E-1-4	1 123	1 275	15,5	10 × 5	—	17,0	10 × 4	—	24,2
315	E-1-5	—	—	—	—	—	—	—	—	—
316	E-1-6	—	—	—	—	—	—	—	—	—
317	E-1-7	—	—	—	—	—	—	—	—	—
318	E-1-8	—	—	—	—	—	—	—	—	—
319	E-1-9	—	—	—	—	—	—	—	—	—
Material group E-2										
320	E-2-1	1 331	1 386	15,0	10 × 5	—	19,2	10 × 4	—	33,9
321	E-2-2	—	—	—	—	—	—	—	—	—
322	E-2-3	—	—	—	—	—	—	—	—	—
323	E-2-4	1 330	1 399	14,0	10 × 5	—	19,2	10 × 4	—	33,2
324	E-2-5	—	—	—	—	—	—	—	—	—
325	E-2-6	—	—	—	—	—	—	—	—	—

Table 11 — Fracture toughness test results

Burst test No.	Cylinder No.	Specimen type	Specimen orientation	Temperature °C	KIC value MPa/m
Material group B-3					
44	B-3-1	Compact tension	TL	20	52
45	B-3-2	Compact tension	TL	20	94
46	B-3-3	Compact tension	TL	20	75
47	B-3-4	Compact tension	TL	20	85
48	B-3-5	Compact tension	TL	20	90
49	B-3-6	Compact tension	TL	20	116
50	B-3-7	Compact tension	TL	20	90
51	B-3-8	Compact tension	TL	20	83
52	B-3-9	Compact tension	TL	20	59
53	B-3-10	Compact tension	TL	20	96
54	B-3-11	Compact tension	TL	20	80
55	B-3-12	Compact tension	TL	20	57
Material group B-5					
210	D-5-1	Compact tension	TL	20	140
Material group D-6					
225	D-6-1	Compact tension	TL	20	63
226	D-6-2	Compact tension	TL	20	68
227	D-6-3	Compact tension	TL	20	67
228	D-6-4	Compact tension	TL	20	47
229	D-6-5	Compact tension	TL	20	67
230	D-6-6	Compact tension	TL	20	68
Material group D-11					
245	D-11-1	Compact tension	TL	20	118

Table 12 — Flawed cylinder burst test results for group A materials

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group A-1										
1	A-1-1	232	155	5,0	95	6,70	166	Leak	1,07	1,06
2	A-1-1	232	155	5,0	90	7,40	152	Leak	0,98	0,88
3	A-1-1	232	155	5,0	85	7,20	172	Leak	1,12	1,02
4	A-1-1	232	155	5,0	80	7,10	290	Fracture	1,87	1,74
5	A-1-2	232	155	8,5	90	6,00	172	Leak	1,12	1,23
6	A-1-2	232	155	8,5	85	6,80	172	Leak	1,12	1,08
7	A-1-2	232	155	8,5	80	6,90	174	Leak	1,13	1,08
8	A-1-2	232	155	8,5	75	6,70	203	Leak	1,32	1,30
9	A-1-2	232	155	8,5	70	6,60	234	Fracture	1,52	1,52
10	A-1-3	232	155	10,0	85	6,30	172	Leak	1,12	1,17
11	A-1-3	232	155	10,0	80	6,70	190	Fracture	1,23	1,21
12	A-1-4	232	155	12,5	85	6,80	172	Leak	1,12	1,08
13	A-1-4	232	155	12,5	80	7,20	193	Leak	1,25	1,15
14	A-1-4	232	155	12,5	75	7,00	199	Fracture	1,29	1,21
15	A-1-5	232	155	15,0	90	6,30	100	Leak	0,65	0,68
16	A-1-5	232	155	15,0	85	7,10	169	Leak	1,09	1,02
17	A-1-5	232	155	15,0	80	6,60	172	Fracture	1,12	1,12

Table 12 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group A-2										
18	A-2-1	232	155	10,0	80	6,65	179	Leak	1,15	1,15
19	A-2-1	232	155	10,0	80	6,76	186	Fracture	1,20	1,17
20	A-2-2	232	155	12,5	80	7,54	189	Fracture	1,22	1,07
21	A-2-3	232	155	8,5	90	5,90	200	Leak	1,29	1,44
22	A-2-3	232	155	8,5	85	5,90	197	Fracture	1,27	1,42
23	A-2-4	232	155	5,5	90	6,90	260	Fracture	1,68	1,60
24	A-2-5	232	155	15,0	90	6,42	126	Leak	0,81	0,84
25	A-2-5	232	155	15,0	80	6,86	138	Fracture	0,89	0,86
26	A-2-6	232	155	12,5	85	6,48	155	Leak	1,00	1,02
27	A-2-6	232	155	12,5	80	7,51	172	Fracture	1,11	0,98

Table 13 — Flawed cylinder burst test results for group B materials

Burst test No.	Cylinder No.	Design test pressure	Design service pressure	Flaw length	Flaw depth	Thickness at flaw	Failure pressure	Failure mode	Measured	Adjusted
		bar	bar	$n = l_o/t_d$	% of t_d	t_a mm	P_f bar		P_f/P_s	$(P_f/P_s)(t_d/t_a)$
Material group B-2										
28	B-2-1	465	310	10,0	90	7,40	197	Leak	0,63	0,56
29	B-2-1	465	310	10,0	85	8,30	293	Leak	0,94	0,75
30	B-2-1	465	310	10,0	80	7,90	159	Leak	0,51	0,43
31	B-2-1	465	310	10,0	75	7,60	328	Leak	1,06	0,92
32	B-2-1	465	310	10,0	70	7,50	324	Fracture	1,04	0,92
Material group B-3										
33	B-3-1	276	184	3,4	67	7,50	379	Fracture	2,06	1,59
34	B-3-2	276	184	3,7	76	6,80	348	Fracture	1,89	1,61
35	B-3-3	276	184	3,4	86	7,30	360	Leak	1,96	1,55
36	B-3-4	276	184	7,0	67	7,20	307	Fracture	1,67	1,34
37	B-3-5	276	184	7,0	76	7,20	338	Fracture	1,84	1,48
38	B-3-6	276	184	6,8	86	7,40	276	Leak	1,50	1,18
39	B-3-7	276	184	9,9	67	6,90	270	Fracture	1,47	1,23
40	B-3-8	276	184	9,6	76	7,10	236	Fracture	1,28	1,05
41	B-3-9	276	184	9,5	86	7,20	245	Leak	1,33	1,07
42	B-3-10	276	184	10,0	67	7,60	336	Fracture	1,83	1,39
43	B-3-11	276	184	10,6	76	7,20	268	Fracture	1,46	1,17
44	B-3-12	276	184	10,3	86	7,40	203	Leak	1,10	0,86
Material group B-4										
45	B-4-1	221	147	13,0	80	7,30	212	Leak	1,44	1,28
46	B-4-2	221	147	13,0	70	6,80	277	Fracture	1,88	1,80

Table 13 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
47	B-4-3	221	147	13,0	60	7,20	310	Fracture	2,10	1,90
48	B-4-4	221	147	13,0	75	7,30	252	Leak	1,71	1,52
Material group B-5										
49	B-5-1	300	200	13,0	71	6,90	233	Fracture	1,17	1,01
50	B-5-2	300	200	13,0	72	7,60	260	Fracture	1,30	1,03
51	B-5-3	300	200	13,0	75	7,60	217	Leak	1,09	0,86
52	B-5-4	300	200	13,0	78	7,30	200	Leak	1,00	0,82
53	B-5-5	300	200	13,0	79	7,70	217	Leak	1,09	0,85
54	B-5-6	300	200	13,0	83	7,80	176	Leak	0,88	0,68
Material group B-6										
55	B-6-1	276	184	10,0	75	6,80	260	Fracture	1,41	1,32
56	B-6-2	276	184	10,0	80	6,60	241	Leak	1,31	1,26
57	B-6-3	276	184	15,0	85	6,90	143	Leak	0,78	0,72
58	B-6-4	276	184	10,0	80	6,30	220	Leak	1,20	1,21
59	B-6-5	276	184	8,0	85	6,90	269	Leak	1,46	1,35
60	B-6-6	276	184	15,0	70	6,70	194	Fracture	1,05	1,00
Material group B-7										
61	B-7-1	414	276	10,0	80	9,20	283	Fracture	1,03	0,97
62	B-7-2	414	276	10,0	75	9,70	269	Leak	0,97	0,87
63	B-7-3	414	276	10,0	80	9,90	236	Leak	0,86	0,75
Material group B-8										
64	B-8-1	690	460	10,0	80	15,90	462	Leak	1,00	0,91
65	B-8-2	690	460	10,0	75	15,90	441	Leak	0,96	0,87

Table 13 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
66	B-8-3	690	460	10,0	70	16,20	527	Leak	1,15	1,02
Material group B-9										
67	B-9-1	232	155	7,6	51	5,35	328	Fracture	2,12	1,51
68	B-9-2	232	155	7,4	59	5,48	331	Fracture	2,14	1,48
69	B-9-3	232	155	7,6	71	5,58	324	Fracture	2,09	1,43
70	B-9-4	232	155	7,4	79	5,08	293	Fracture	1,89	1,42
71	B-9-5	232	155	7,6	91	5,15	248	Leak	1,60	1,18
72	B-9-6	232	155	8,7	51	5,10	314	Fracture	2,03	1,51
73	B-9-7	232	155	8,4	60	5,35	310	Fracture	2,00	1,42
74	B-9-8	232	155	8,6	71	5,51	296	Fracture	1,91	1,32
75	B-9-9	232	155	8,5	80	5,33	283	Fracture	1,83	1,31
76	B-9-10	232	155	8,5	90	5,20	234	Leak	1,51	1,11
77	B-9-11	232	155	10,1	50	5,53	321	Fracture	2,07	1,43
78	B-9-12	232	155	9,7	58	5,43	290	Fracture	1,87	1,31
79	B-9-13	232	155	10,2	71	5,33	265	Fracture	1,71	1,22
80	B-9-14	232	155	9,8	78	5,33	245	Fracture	1,58	1,13
81	B-9-15	232	155	10,0	91	5,33	214	Leak	1,38	0,99
82	B-9-16	232	155	12,4	49	5,25	269	Fracture	1,74	1,26
83	B-9-17	232	155	13,1	63	5,02	245	Fracture	1,58	1,20
84	B-9-18	232	155	12,4	70	4,93	210	Fracture	1,35	1,05
85	B-9-19	232	155	12,2	78	5,41	200	Fracture	1,29	0,91
86	B-9-20	232	155	12,6	91	5,36	152	Leak	0,98	0,70
87	B-9-21	232	155	15,0	80	5,41	159	Fracture	1,03	0,72

Table 13 *(continued)*

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
88	B-9-22	232	155	15,4	62	4,95	224	Fracture	1,45	1,11
89	B-9-23	232	155	14,6	68	5,10	190	Fracture	1,23	0,92
90	B-9-24	232	155	14,7	79	5,20	172	Fracture	1,11	0,81
91	B-9-25	232	155	14,9	89	5,53	103	Leak	0,66	0,46
Material group B-10										
92	B-10-1	300	200	9,9	83	6,58	186	Leak	0,93	0,85
Material group B-11										
93	B-11-1	255	170	10,0	84	6,20	220	Leak	1,29	1,13
Material group B-12										
94	B-12-1	300	200	10,3	86	6,40	225	Leak	1,13	1,04
Material group B-13										
95	B-13-1	318	212	10,2	63	5,20	255	Leak	1,20	1,06
96	B-13-2	318	212	10,2	72	5,00	294	Fracture	1,39	1,28
97	B-13-3	318	212	9,8	76	4,90	265	Fracture	1,25	1,17
Material group B-14										
98	B-14-1	263	175	9,7	65	6,05	230	Leak	1,31	1,13
99	B-14-2	263	175	10,0	70	6,14	218	Leak	1,25	1,06
100	B-14-3	263	175	9,9	75	6,01	225	Leak	1,29	1,11
Material group B-15										
98	B-15-1	295	197	9,9	63	6,05	277	Fracture	1,41	1,28
99	B-15-2	295	197	9,8	70	6,14	275	Fracture	1,40	1,25
100	B-15-3	295	197	9,9	74	6,01	255	Leak	1,29	1,18

Table 14 — Flawed cylinder burst test results for group C materials

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-3										
104	C-3-1	276	184	9,0	90	6,80	159	Leak	0,86	0,77
105	C-3-1	276	184	8,0	80	7,20	234	Leak	1,27	1,08
106	C-3-1	276	184	10,0	70	7,10	231	Fracture	1,25	1,08
107	C-3-2	276	184	10,0	75	6,70	214	Fracture	1,16	1,06
108	C-3-3	276	184	10,0	80	6,60	207	Leak	1,12	1,04
109	C-3-3	276	184	8,0	70	7,80	290	Fracture	1,57	1,23
110	C-3-4	276	184	15,0	85	6,40	152	Fracture	0,82	0,79
111	C-3-5	276	184	15,0	90	6,60	124	Leak	0,67	0,62
112	C-3-5	276	184	8,0	75	7,40	241	Fracture	1,31	1,08
113	C-3-6	276	184	5,0	70	6,50	352	Fracture	1,91	1,79
Material group C-4										
114	C-4-1	465	310	10,0	90	7,00	210	Leak	0,68	0,64
115	C-4-1	465	310	10,0	85	8,70	303	Leak	0,98	0,74
116	C-4-1	465	310	10,0	80	7,80	310	Leak	1,00	0,85
117	C-4-1	465	310	10,0	75	8,30	283	Leak	0,91	0,72
118	C-4-1	465	310	10,0	70	7,30	328	Leak	1,06	0,95
119	C-4-1	465	310	10,0	65	6,70	355	Fracture	1,14	1,13
120	C-4-2	465	310	10,0	90	7,00	134	Leak	0,43	0,41
121	C-4-2	465	310	10,0	85	8,70	238	Leak	0,77	0,58
122	C-4-2	465	310	10,0	80	7,80	283	Leak	0,91	0,77
123	C-4-2	465	310	10,0	75	8,30	331	Leak	1,07	0,85
124	C-4-2	465	310	10,0	70	7,30	341	Fracture	1,10	0,99

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-5										
125	C-5-1	300	200	10,0	70	6,80	367	Fracture	1,84	1,61
126	C-5-2	300	200	10,0	70	6,70	368	Fracture	1,84	1,64
127	C-5-3	300	200	10,0	75	6,80	348	Leak	1,74	1,53
128	C-5-4	300	200	10,0	75	6,70	330	Leak	1,65	1,47
129	C-5-5	300	200	10,0	72	6,80	355	Fracture	1,78	1,56
130	C-5-6	300	200	10,0	65	6,80	380	Fracture	1,90	1,67
131	C-5-7	300	200	10,0	70	6,80	370	Fracture	1,85	1,62
131	C-5-8	300	200	10,0	75	6,80	340	Leak	1,70	1,49
132	C-5-9	300	200	10,0	75	6,70	340	Leak	1,70	1,51
133	C-5-10	300	200	10,0	80	6,90	320	Leak	1,60	1,38
134	C-5-11	300	200	10,0	80	6,60	300	Leak	1,50	1,36
135	C-5-12	300	200	10,0	78	6,50	320	Leak	1,60	1,47
136	C-5-13	300	200	13,0	71	6,90	233	Fracture	1,17	1,01
137	C-5-14	300	200	13,0	72	7,60	260	Fracture	1,30	1,02
138	C-5-15	300	200	13,0	75	7,60	217	Leak	1,09	0,85
139	C-5-16	300	200	13,0	78	7,30	200	Leak	1,00	0,82
140	C-5-17	300	200	13,0	79	7,70	217	Leak	1,09	0,84
141	C-5-18	300	200	13,0	83	7,80	176	Leak	0,88	0,67
142	C-5-19	300	200	10,0	76	6,60	272	Leak	1,36	1,23
143	C-5-20	300	200	10,0	80	7,00	305	Leak	1,53	1,30
144	C-5-21	300	200	10,0	75	6,80	332	Leak	1,66	1,46

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-6										
145	C-6-1	300	200	10,0	75	6,70	370	Leak	1,85	1,55
146	C-6-2	300	200	10,0	75	6,60	345	Leak	1,73	1,46
147	C-6-3	300	200	10,0	80	6,70	350	Leak	1,75	1,46
148	C-6-4	300	200	10,0	80	6,50	340	Leak	1,70	1,46
149	C-6-5	300	200	10,0	78	6,50	350	Leak	1,75	1,51
150	C-6-6	300	200	10,0	70	6,60	382	Fracture	1,91	1,62
151	C-6-7	300	200	10,0	65	6,70	400	Fracture	2,00	1,67
152	C-6-8	300	200	10,0	75	6,40	328	Leak	1,64	1,44
153	C-6-9	300	200	10,0	75	6,50	357	Leak	1,79	1,54
154	C-6-10	300	200	10,0	70	6,40	385	Fracture	1,93	1,68
155	C-6-11	300	200	10,0	70	6,20	397	Fracture	1,99	1,79
156	C-6-12	300	200	10,0	72	6,40	385	Fracture	1,93	1,68
Material group C-7										
157	C-7-1	300	200	13,0	73	7,50	200	Fracture	1,00	0,80
158	C-7-2	300	200	13,0	77	6,90	170	Leak	0,85	0,74
159	C-7-3	300	200	13,0	77	7,40	185	Leak	0,93	0,75
160	C-7-4	300	200	13,0	71	7,50	210	Fracture	1,05	0,84
161	C-7-5	300	200	10,0	78	7,30	265	Fracture	1,33	1,09
162	C-7-6	300	200	10,0	80	6,90	265	Fracture	1,33	1,15
163	C-7-7	300	200	10,0	80	7,10	250	Leak	1,25	1,06
164	C-7-8	300	200	10,0	79	6,50	270	Fracture	1,35	1,25

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-8										
165	C-8-1	300	200	10,0	74	6,80	325	Leak	1,63	1,34
166	C-8-2	300	200	10,0	69	6,90	365	Fracture	1,83	1,48
167	C-8-3	300	200	10,0	70	6,50	376	Leak	1,88	1,62
168	C-8-4	300	200	10,0	75	6,60	360	Leak	1,80	1,53
169	C-8-5	300	200	10,0	67	6,80	405	Fracture	2,03	1,67
170	C-8-6	300	200	10,0	67	6,80	382	Fracture	1,91	1,57
Material group C-9										
171	C-9-1	300	200	10,0	70	7,40	338	Fracture	1,69	1,37
172	C-9-2	300	200	10,0	70	7,40	356	Fracture	1,78	1,44
173	C-9-3	300	200	10,0	75	7,50	323	Leak	1,62	1,29
174	C-9-4	300	200	10,0	75	7,50	333	Leak	1,67	1,33
Material group C-10										
175	C-10-1	345	230	10,0	85	6,80	223	Leak	0,97	0,79
176	C-10-1	345	230	10,0	85	6,40	228	Leak	0,99	0,86
177	C-10-3	345	230	10,0	80	6,70	285	Leak	1,24	1,03
178	C-10-4	345	230	10,0	70	6,70	303	Fracture	1,32	1,09
179	C-10-5	345	230	10,0	85	6,00	228	Leak	0,99	0,92
180	C-10-6	345	230	10,0	85	6,60	245	Leak	1,07	0,90
181	C-10-7	345	230	10,0	75	6,30	269	Leak	1,17	1,03
182	C-10-8	345	230	10,0	70	6,70	279	Fracture	1,21	1,01
183	C-10-9	345	230	10,0	75	6,80	282	Fracture	1,23	1,00

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-11										
184	C-11-1	466	311	8,0	75	7,80	414	Fracture	1,33	1,13
185	C-11-1	466	311	8,0	85	7,32	345	Leak	1,11	1,00
186	C-11-1	466	311	8,0	80	7,72	355	Leak	1,14	0,98
187	C-11-1	466	311	6,0	80	6,60	434	Fracture	1,40	1,40
188	C-11-1	466	311	6,0	85	6,83	434	Fracture	1,40	1,35
189	C-11-1	466	311	6,0	90	6,83	414	Leak	1,33	1,29
Material group C-12										
190	C-12-1	476	317	10,0	85	6,50	333	Leak	1,05	1,07
191	C-12-2	490	317	10,0	86	6,30	353	Leak	1,11	1,17
Material group C-13										
192	C-13-1	285	190	9,9	86	4,71	255	Leak	1,34	1,31
Material group C-14										
193	C-14-1	245	163	10,0	83	4,75	227	Leak	1,39	1,26
194	C-14-2	245	163	10,0	86	4,90	196	Leak	1,20	1,05
195	C-14-3	245	163	10,0	85	4,70	191	Leak	1,17	1,07
Material group C-15										
196	C-15-1	420	280	9,8	65	6,20	436	Fracture	1,56	1,46
197	C-15-2	420	280	10,3	71	6,50	397	Fracture	1,42	1,27
198	C-15-3	420	280	9,9	75	6,70	368	Leak	1,31	1,14

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group C-16										
199	C-16-1	330	220	9,5	63	6,55	304	Fracture	1,38	1,16
200	C-16-2	330	220	9,7	68	6,38	279	Fracture	1,27	1,09
201	C-16-3	330	220	9,8	75	6,41	255	Fracture	1,16	0,99
Material group C-17										
202	C-17-1	324	216	9,8	65	6,23	306	Fracture	1,42	1,23
203	C-17-2	324	216	10,2	70	6,18	272	Fracture	1,26	1,10
204	C-17-3	324	216	9,8	74	6,42	280	Leak	1,30	1,09
Material group C-18										
205	C-18-1	309	206	9,9	65	5,86	317	Fracture	1,54	1,37
206	C-18-2	309	206	9,6	69	5,96	294	Fracture	1,43	1,25
207	C-18-3	309	206	10,5	75	5,88	243	Leak	1,18	1,04
Material group C-19										
208	C-19-1	343	163	9,9	65	3,23	214	Leak	1,31	1,26
209	C-19-2	343	163	10,0	70	3,32	214	Leak	1,31	1,22
210	C-19-3	343	163	10,0	75	3,23	193	Leak	1,18	1,13
Material group C-20										
211	C-20-1	316	210	10,2	65	7,80	250	Fracture	1,19	0,84
212	C-20-2	316	210	10,5	70	7,32	236	Fracture	1,12	0,84
213	C-20-3	316	210	10,2	74	7,72	222	Fracture	1,06	0,75
Material group C-21										
214	C-21-1	363	242	9,9	64	7,00	273	Fracture	1,13	1,00
215	C-21-2	363	242	10,3	70	7,10	268	Fracture	1,11	0,97

Table 14 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
216	C-21-3	363	242	10,5	75	7,00	245	Fracture	1,01	0,90
Material group C-22										
219	C-22-1	390	260	10,1	64	7,10	270	Fracture	1,04	0,91
220	C-22-2	390	260	10,3	70	6,90	218	Fracture	0,84	0,75
221	C-22-3	390	260	10,3	76	6,90	236	Fracture	0,91	0,82
Material group C-23										
222	C-23-1	288	192	10,0	83	6,43	309	Fracture	1,61	1,38
223	C-23-2	288	192	10,0	86	6,54	255	Leak	1,33	1,12
224	C-23-3	288	192	10,0	85	6,46	264	Leak	1,38	1,17

Table 15 — Flawed cylinder burst test results for group D materials

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group D-2										
225	D-2-1	300	200	8,3	83	4,80	300	Leak	1,50	1,41
225	D-2-2	300	200	7,0	94	4,80	300	Leak	1,50	1,41
226	D-2-3	300	200	10,0	90	5,00	300	Leak	1,50	1,35
227	D-2-4	300	200	10,0	85	5,00	300	Leak	1,50	1,35
228	D-2-5	300	200	10,0	80	5,00	300	Leak	1,50	1,35
229	D-2-6	300	200	10,0	75	5,00	300	Fracture	1,50	1,35
230	D-2-7	300	200	10,0	71	5,10	300	Fracture	1,50	1,32
231	D-2-8	300	200	10,0	77	5,20	300	Fracture	1,50	1,30
232	D-2-9	300	200	10,0	72	5,10	300	Fracture	1,50	1,32
233	D-2-10	300	200	10,0	68	5,10	300	Fracture	1,50	1,32
234	D-2-11	300	200	9,5	77	5,20	285	Leak	1,43	1,23
235	D-2-12	300	200	10,0	86	5,50	215	Leak	1,08	0,88
236	D-2-13	300	200	10,0	76	5,90	290	Leak	1,45	1,11
237	D-2-14	300	200	10,0	75	6,00	310	Leak	1,55	1,16
238	D-2-15	300	200	10,0	78	6,00	282	Leak	1,41	1,06
Material group D-3										
239	D-3-1	300	200	8,8	73	5,50	256	Leak	1,28	1,21
240	D-3-2	300	200	8,9	74	5,70	259	Leak	1,30	1,18
241	D-3-3	300	200	10,0	79	5,60	219	Leak	1,10	1,02
242	D-3-4	300	200	10,0	89	5,50	125	Leak	0,63	0,59
243	D-3-5	300	200	7,5	79	5,60	295	Leak	1,48	1,37
244	D-3-6	300	200	9,6	76	6,00	310	Fracture	1,55	1,34

Table 15 (*continued*)

Burst test No.	Cylinder No.	Design test pressure	Design service pressure	Flaw length	Flaw depth	Thickness at flaw	Failure pressure	Failure mode	Measured	Adjusted
		bar	bar	$n = l_o/t_d$	% of t_d	t_a mm	P_f bar		P_f/P_s	$(P_f/P_s)(t_d/t_a)$
245	D-3-7	300	200	10,0	78	6,00	282	Fracture	1,41	1,22
Material group D-4										
246	D-4-1	465	310	10,0	90	7,50	214	Leak	0,69	0,61
247	D-4-1	465	310	10,0	85	7,80	241	Leak	0,78	0,66
248	D-4-1	465	310	10,0	80	7,70	279	Leak	0,90	0,77
249	D-4-1	465	310	10,0	75	7,70	203	Leak	0,66	0,56
250	D-4-1	465	310	10,0	70	7,70	314	Leak	1,01	0,87
251	D-4-1	465	310	10,0	65	7,70	390	Fracture	1,26	1,08
Material group D-5										
252	D-5-1	465	310	3,6	62	7,00	632	Fracture	2,04	1,92
253	D-5-2	465	310	3,4	74	7,40	658	Fracture	2,12	1,89
254	D-5-3	465	310	3,3	84	7,80	634	Leak	2,04	1,73
255	D-5-4	465	310	6,9	70	7,40	554	Fracture	1,79	1,59
256	D-5-5	465	310	6,8	69	7,50	500	Fracture	1,61	1,42
257	D-5-6	465	310	6,7	75	7,60	516	Fracture	1,66	1,44
258	D-5-7	465	310	6,7	82	7,60	457	Leak	1,47	1,28
259	D-5-8	465	310	9,4	70	7,50	440	Fracture	1,42	1,25
260	D-5-9	465	310	9,5	85	7,40	338	Leak	1,09	0,97
261	D-5-10	465	310	9,4	96	7,40	297	Leak	0,96	0,85
262	D-5-11	465	310	9,8	86	7,10	324	Leak	1,04	0,97
263	D-5-12	465	310	9,5	91	7,40	316	Leak	1,02	0,91
264	D-5-13	465	310	10,2	68	7,40	442	Fracture	1,42	1,27
265	D-5-14	465	310	9,8	71	7,70	421	Fracture	1,36	1,16

Table 15 *(continued)*

Burst test No.	Cylinder No.	Design test pressure	Design service pressure	Flaw length	Flaw depth	Thickness at flaw	Failure pressure	Failure mode	Measured	Adjusted
		bar	bar	$n = l_o/t_d$	% of t_d	t_a mm	P_f bar		P_f/P_s	$(P_f/P_s)(t_d/t_a)$
266	D-5-15	465	310	10,7	86	7,10	281	Leak	0,91	0,84
Material group D-6										
267	D-6-1	465	310	3,4	76	7,50	417	Fracture	1,34	1,18
268	D-6-2	465	310	3,5	86	7,20	359	Fracture	1,16	1,06
269	D-6-3	465	310	7,1	76	7,20	252	Leak	0,81	0,74
270	D-6-4	465	310	6,5	86	7,80	266	Leak	0,86	0,73
271	D-6-5	465	310	9,7	76	7,80	228	Fracture	0,74	0,62
272	D-6-6	465	310	10,3	86	7,40	200	Fracture	0,64	0,58
Material group D-9										
273	D-9-1	345	230	10,0	75	6,50	296	Fracture	1,29	1,10
274	D-9-2	345	230	10,0	80	6,50	256	Leak	1,11	0,95
275	D-9-3	345	230	10,0	75	6,60	289	Fracture	1,26	1,06
276	D-9-4	345	230	10,0	75	6,80	263	Fracture	1,14	0,93
Material group D-10										
277	D-10-1	465	310	10,0	80	7,40	331	Fracture	1,07	0,95
278	D-10-2	465	310	10,0	85	7,50	345	Fracture	1,11	0,98
279	D-10-3	465	310	10,0	90	7,20	262	Leak	0,85	0,77
280	D-10-4	465	310	10,0	85	7,20	307	Leak	0,99	0,91
281	D-10-5	465	310	10,0	80	7,20	338	Leak	1,09	1,00
282	D-10-6	465	310	10,0	75	6,70	348	Fracture	1,12	1,11
283	D-10-7	465	310	10,0	80	7,30	328	Leak	1,06	0,96
284	D-10-8	465	310	10,0	60	7,40	310	Leak	1,00	0,89
285	D-10-9	465	310	10,0	50	7,40	310	Leak	1,00	0,89

Table 15 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
286	D-10-10	465	310	10,0	45	7,50	310	Leak	1,00	0,88
Material group D-11										
287	D-11-1	450	300	8,0	85	7,11	392	Leak	1,31	1,18
288	D-11-2	450	300	10,0	85	6,86	250	Leak	0,83	0,78
289	D-11-3	450	300	12,0	85	7,11	220	Leak	0,73	0,66
290	D-11-4	450	300	8,0	90	6,86	362	Leak	1,21	1,13
291	D-11-5	450	300	10,0	90	6,86	180	Leak	0,60	0,56
292	D-11-6	450	300	12,0	90	7,11	190	Leak	0,63	0,57
293	D-11-7	450	300	10,0	60	7,11	440	Fracture	1,47	1,32
294	D-11-8	450	300	10,0	60	7,11	493	Fracture	1,64	1,48
295	D-11-8	450	300	10,0	60	7,37	465	Fracture	1,55	1,35
296	D-11-10	450	300	20,0	65	6,90	270	Fracture	0,90	0,83
297	D-11-11	450	300	17,0	60	8,10	347	Fracture	1,16	0,91
298	D-11-12	450	300	18,0	68	7,80	255	Fracture	0,85	0,70
299	D-11-13	450	300	13,5	72	7,10	290	Fracture	0,97	0,87
300	D-11-14	450	300	13,2	72	6,80	292	Fracture	0,97	0,92
301	D-11-15	450	300	13,4	73	6,70	273	Leak	0,91	0,87
302	D-11-16	450	300	12,5	75	7,20	265	Leak	0,88	0,79
303	D-11-17	450	300	13,8	74	6,90	267	Leak	0,89	0,83
Material group D-13										
304	D-13-1	300	200	10,2	84	5,12	260	Leak	1,30	1,17
Material group D-14										
305	D-14-1	465	310	10,0	70	7,30	362	Fracture	1,17	1,06

Table 15 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
306	D-14-2	465	310	10,0	80	7,50	297	Leak	0,96	0,84
307	D-14-3	465	310	10,0	72	7,60	341	Fracture	1,10	0,96
308	D-14-4	465	310	10,0	78	7,60	324	Fracture	1,05	0,91
309	D-14-5	465	310	10,0	74	7,40	338	Fracture	1,09	0,97
310	D-14-6	465	310	10,0	78	7,10	324	Leak	1,05	0,97
311	D-14-7	465	310	10,0	73	7,20	366	Fracture	1,18	1,08
312	D-14-8	465	310	10,0	77	7,00	309	Leak	1,00	0,94
313	D-14-9	465	310	10,0	73	5,40	319	Fracture	1,03	0,95
314	D-14-10	465	310	10,0	74	5,70	285	Leak	0,92	0,81
315	D-14-11	465	310	10,0	75	5,80	328	Leak	1,06	0,91
316	D-14-12	465	310	10,0	77	5,70	300	Leak	0,97	0,85
317	D-14-13	465	310	10,0	70	7,00	310	Leak	1,00	0,94
318	D-14-14	465	310	10,0	71	7,10	369	Fracture	1,19	1,11
319	D-14-15	465	310	10,0	71	7,30	369	Fracture	1,19	1,08
320	D-14-16	465	310	10,0	72	7,10	362	Fracture	1,17	1,09
321	D-14-17	465	310	10,0	72	7,20	359	Fracture	1,16	1,06
322	D-14-18	465	310	10,0	73	7,30	345	Fracture	1,11	1,01
323	D-14-19	465	310	10,0	73	6,90	355	Fracture	1,15	1,10
324	D-14-20	465	310	10,0	74	7,20	345	Fracture	1,11	1,02
325	D-14-21	465	310	10,0	74	7,40	352	Fracture	1,14	1,01
326	D-14-22	465	310	10,0	74	7,50	313	Leak	1,01	0,89
327	D-14-23	465	310	10,0	75	7,40	310	Leak	1,00	0,89
328	D-14-24	465	310	10,0	76	7,40	328	Fracture	1,06	0,94

Table 15 (*continued*)

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
329	D-14-25	465	310	10,0	79	7,60	279	Leak	0,90	0,78
330	D-14-26	465	310	10,0	80	7,70	276	Leak	0,89	0,76
331	D-14-27	465	310	10,0	72	7,30	352	Fracture	1,14	1,03
332	D-14-28	465	310	10,0	73	7,30	341	Fracture	1,10	0,99
333	D-14-29	465	310	10,0	73	7,40	341	Fracture	1,10	0,98
334	D-14-30	465	310	10,0	74	7,50	335	Fracture	1,08	0,95
335	D-14-31	465	310	10,0	70	7,70	362	Fracture	1,17	1,00
336	D-14-32	465	310	10,0	71	7,90	459	Fracture	1,48	1,24
337	D-14-33	465	310	10,0	72	7,50	386	Fracture	1,25	1,10
338	D-14-34	465	310	10,0	73	7,00	395	Fracture	1,27	1,20
339	D-14-35	465	310	10,0	74	8,00	324	Leak	1,05	0,86
340	D-14-36	465	310	10,0	75	7,90	290	Leak	0,94	0,78
341	D-14-37	465	310	10,0	75	8,00	262	Leak	0,85	0,70
342	D-14-38	465	310	10,0	77	8,00	297	Leak	0,96	0,79
343	D-14-39	465	310	10,0	71	7,20	396	Fracture	1,28	1,17
344	D-14-40	465	310	10,0	74	7,40	389	Fracture	1,25	1,12
345	D-14-41	465	310	10,0	72	7,10	381	Fracture	1,23	1,14
346	D-14-42	465	310	10,0	73	7,10	383	Fracture	1,24	1,15
347	D-14-43	465	310	10,0	73	7,50	403	Fracture	1,30	1,14
348	D-14-44	465	310	10,0	71	7,20	393	Fracture	1,27	1,16
349	D-14-45	465	310	10,0	73	7,10	367	Fracture	1,18	1,10
350	D-14-46	465	310	10,0	74	7,30	352	Fracture	1,14	1,03
351	D-14-47	465	310	10,0	76	7,50	321	Leak	1,04	0,91

Table 15 *(continued)*

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
352	D-14-48	465	310	10,0	74	7,30	352	Fracture	1,14	1,03
353	D-14-49	465	310	10,0	76	7,50	321	Leak	1,04	0,91
Material group D-15										
354	D-15-1	426	284	9,7	66	6,20	382	Fracture	1,35	1,15
355	D-15-2	426	284	10,2	70	6,00	368	Fracture	1,30	1,14
356	D-15-2	426	284	9,8	73	6,00	353	Fracture	1,24	1,10
Material group D-16										
357	D-16-1	347	231	9,8	63	6,40	275	Fracture	1,19	1,02
358	D-16-2	347	231	10	67	6,20	270	Fracture	1,17	1,04
359	D-16-2	347	231	9,9	75	6,30	250	Fracture	1,08	0,94
Material group D-17										
360	D-17-1	338	225	9,5	61	5,90	338	Fracture	1,50	1,30
361	D-17-2	338	225	9,7	70	5,90	280	Fracture	1,24	1,08
362	D-17-2	338	225	9,8	74	6,00	278	Fracture	1,24	1,05
Material group D-18										
363	D-18-1	375	250	10,2	66	5,80	288	Fracture	1,15	1,03
364	D-18-2	375	250	9,9	64	5,90	289	Fracture	1,16	1,02
365	D-18-2	375	250	9,7	74	5,80	285	Fracture	1,14	1,02
Material group D-19										
366	D-19-1	420	280	10,4	65	7,10	235	Fracture	0,84	0,73
367	D-19-2	420	280	10,3	69	7,00	226	Fracture	0,81	0,71
368	D-19-2	420	280	10,5	75	7,10	203	Fracture	0,73	0,63

Table 16 — Flawed cylinder burst test results for group E materials

Burst test No.	Cylinder No.	Design test pressure bar	Design service pressure bar	Flaw length $n = l_o/t_d$	Flaw depth % of t_d	Thickness at flaw t_a mm	Failure pressure P_f bar	Failure mode	Measured P_f/P_s	Adjusted $(P_f/P_s)(t_d/t_a)$
Material group E-1										
369	E-1-1	345	230	6,0	75	6,42	401	Fracture	1,74	1,51
370	E-1-2	345	230	6,0	85	6,78	400	Fracture	1,74	1,43
371	E-1-3	345	230	6,0	90	6,65	322	Leak	1,40	1,17
372	E-1-4	345	230	8,0	75	6,32	334	Fracture	1,45	1,28
373	E-1-5	345	230	8,0	85	6,78	288	Leak	1,25	1,03
374	E-1-6	345	230	8,0	85	6,63	262	Leak	1,14	0,96
375	E-1-7	345	230	15,0	80	6,55	174	Leak	0,76	0,64
376	E-1-8	345	230	15,0	85	6,42	134	Leak	0,58	0,50
377	E-1-9	345	230	12,0	80	6,58	219	Leak	0,95	0,80
Material group E-2										
378	E-2-1	466	311	8,0	75	7,57	328	Fracture	1,05	0,92
379	E-2-2	466	311	8,0	85	7,24	276	Leak	0,89	0,81
380	E-2-3	466	311	8,0	80	7,64	310	Fracture	1,00	0,86
381	E-2-4	466	311	6,0	80	7,75	426	Fracture	1,37	1,17
382	E-2-5	466	311	6,0	85	7,87	360	Leak	1,16	0,97
383	E-2-6	466	311	6,0	90	7,49	426	Fracture	1,37	1,21

Table 17 — Flawed-cylinder burst test results for cylinder groups tested at only one flaw length

Material subgroup	Flaw length	Failure pressure		P_f/P_s		Estimated leak-fracture boundary
	$n = l_o/t_d$	Highest leak bar	Lowest fracture bar	Highest leak	Lowest fracture	P_f/P_s
B-2	10,0	328	324	1,06	1,04	1,05
B-4	13,0	252	277	1,71	1,88	1,79
B-5	13,0	217	233	1,09	1,17	1,13
B-7	10,0	269	283	0,97	1,03	1,00
B-13	10,0	255	265	1,20	1,25	1,28
B-15	9,9	255	275	1,29	1,40	1,35
C-6	10,0	270	382	1,85	1,91	1,88
C-7	10,0	250	265	1,25	1,33	1,28
C-7	13,0	185	200	0,93	1,00	0,97
C-8 + 20 C	10,0	325	365	1,63	1,83	1,73
− 50 C	10,0	376	405	1,88	4,05	1,97
C-9 + 20 C	10,0	323	338	1,62	1,69	1,66
− 50 C	10,0	333	356	1,67	1,78	1,73
C-10	10,0	285	279	1,24	1,21	1,23
C-15	10,0	397	368	1,31	1,41	1,37
C-17	10,0	306	280	1,42	1,30	1,86
C-18	10,0	243	294	1,8	1,43	1,31
C-23	10,0	264	309	1,38	1,61	1,50
D-2	10,0	300	300	1,50	1,50	1,50
D-4	10,0	314	390	1,01	1,26	1,14
D-10	10,0	328	331	1,06	1,07	1,07
D-14	10,0	321	319	1,04	1,03	1,04

Table 18 — Flawed-cylinder burst test results for cylinder groups tested at only one flaw length and only leak or fracture occurred

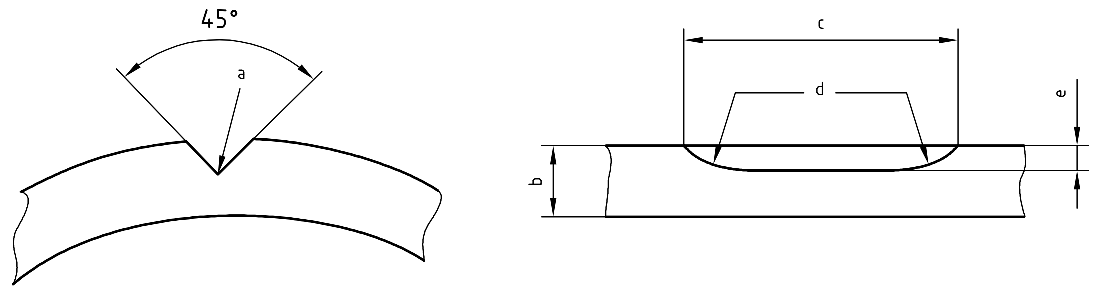
Material subgroup	Flaw length	Failure pressure		P_f/P_s		Estimated leak-fracture boundary
	$n = l_o/t_d$	Highest leak bar	Lowest fracture bar	Highest leak	Lowest fracture	P_f/P_s
B-8	10,0	527		1,15		$> 1{,}15$
B-10	9,9	186	—	0,93	—	$> 0{,}93$
B-11	10,0	220	—	1,29	—	$> 1{,}29$
B-12	10,3	225	—	1,13	—	$> 1{,}13$
B-14	10,0	230	—	1,31	—	$> 1{,}31$
C-12	9,9	353	—	1,11	—	$> 1{,}11$
C-13	9,9	255	—	1,34	—	$> 1{,}34$
C-14	10,0	227	—	1,39	—	$> 1{,}39$
C-16	9,7	—	255	—	1,16	$< 1{,}16$
C-19	10,0	214	—	1,31	—	$> 1{,}31$
C-20	10,2	—	222	—	1,06	$< 1{,}06$
C-21	10,3	—	245	—	1,01	$< 1{,}01$
C-22	10,3	—	218	—	0,84	$< 0{,}84$
D-13	10,2	260	—	1,30	—	$> 1{,}30$
D-15	10,0	—	353	—	1,24	$< 1{,}24$
D-16	10,0	—	250	—	1,08	$< 1{,}08$
D-17	9,7	—	278	—	1,24	$< 1{,}24$
D-18	9,9	—	285	—	1,14	$< 1{,}14$
D-19	10,3	—	203	—	0,73	$< 0{,}73$

Table 19 — Flawed-cylinder burst test results for cylinder groups tested at only one flaw length and adjusted for local thickness

Material subgroup	Flaw length	P_f/P_s adjusted for local thickness		Estimated leak-fracture boundary
	$n = l_o/t_d$	**Highest leak** bar	**Lowest fracture** bar	P_f/P_s
B-2	10,0	0,92	0,92	0,92
B-4	13,0	1,52	1,80	1,66
B-5	13,0	0,86	1,01	0,94
B-7	10,0	0,87	0,97	0,92
B-13	10,0	1,06	1,09	1,08
B-15	9,9	1,18	1,25	1,22
C-6	10,0	1,55	1,62	1,59
C-7	10,0	1,06	1,09	1,08
C-7	13,0	0,75	0,80	0,78
C-8 + 20 C	10,0	1,34	1,48	1,41
− 50 C	10,0	1,62	1,67	1,65
C-9 + 20 C	10,0	1,29	1,37	1,33
− 50 C	10,0	1,33	1,44	1,39
C-10	10,0	1,03	1,00	1,02
C-15	10,0	1,14	1,27	1,21
C-17	10,0	1,09	1,10	1,10
C-18	10,0	1,04	1,25	1,15
C-23	10,0	1,17	1,38	1,28
D-2	10,0	1,23	1,23	1,23
D-4	10,0	0,87	1,08	0,98
D-10	10,0	1,00	0,95	0,98
D-14	10,0	0,97	0,91	0,94

Table 20 — Flawed-cylinder burst test results for cylinder groups tested at only one flaw length and only leak or fracture occurred, adjusted for local thickness

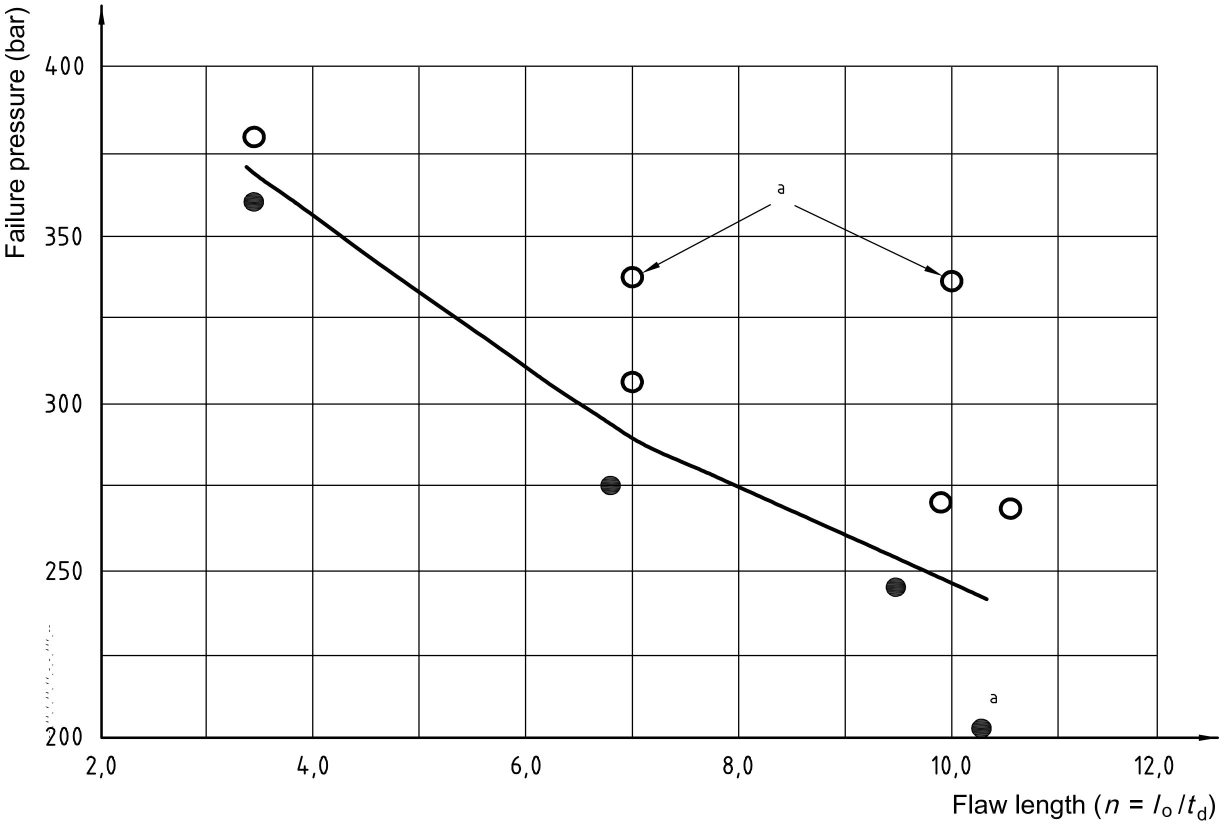
Material subgroup	Flaw length	P_f/P_s adjusted for local thickness		Estimated leak-fracture boundary
	$n = l_o/t_d$	Highest leak bar	Lowest fracture bar	P_f/P_s
B-8	10,0	1,02	—	$>$ 1,02
B-10	9,9	0,85	—	$>$ 0,85
B-11	10,0	1,13	—	$>$ 1,13
B-12	10,3	1,04	—	$>$ 1,04
B-14	10,0	1,13	—	$>$ 1,13
C-12	9,9	1,17	—	$>$ 1,17
C-13	9,9	1,31	—	$>$ 1,31
C-14	10,0	1,26	—	$>$ 1,26
C-16	9,7		0,99	$<$ 0,99
C-19	10,0	1,26		$>$ 1,26
C-20	10,2		0,75	$<$ 1,26
C-21	10,3	—	0,90	$<$ 0,90
C-22	10,3	—	0,75	$<$ 0,75
D-13	10,2	1,17	—	$>$ 1,17
D-15	10,0	—	1,10	$<$ 1,10
D-16	10,0	—	0,94	$<$ 0,94
D-17	9,7	—	1,08	$<$ 1,08
D-18	9,9	—	1,02	$<$ 1,02
D-19	10,3	—	0,63	$<$ 0,63



Key

- [a] Tip radius
- [b] Design wall thickness
- [c] Flaw length
- [d] Radius
- [e] Flaw depth

Figure 1 — Flaw geometry used in the flawed-cylinder test



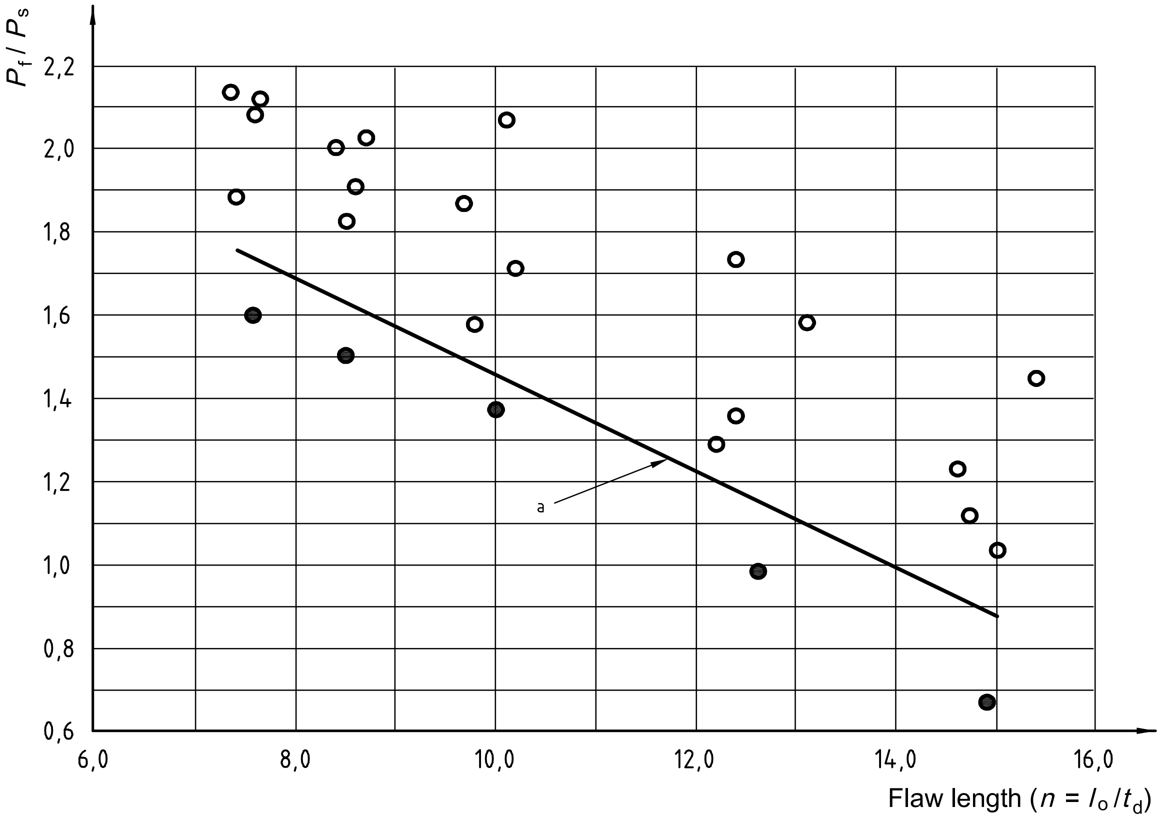
Key

● Leak

○ Fracture

a Unused points

Figure 2 — Unused data points

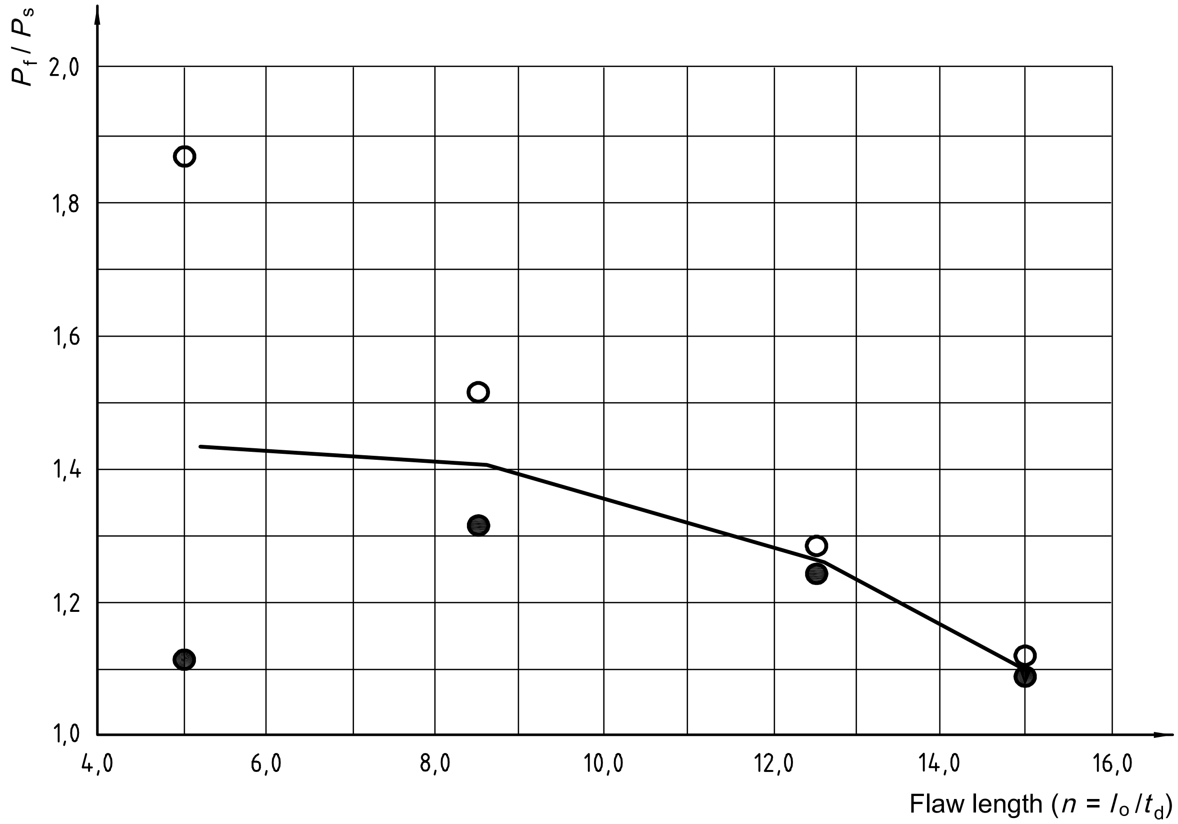


Key

- ● Leak
- ○ Fracture

[a] Boundary

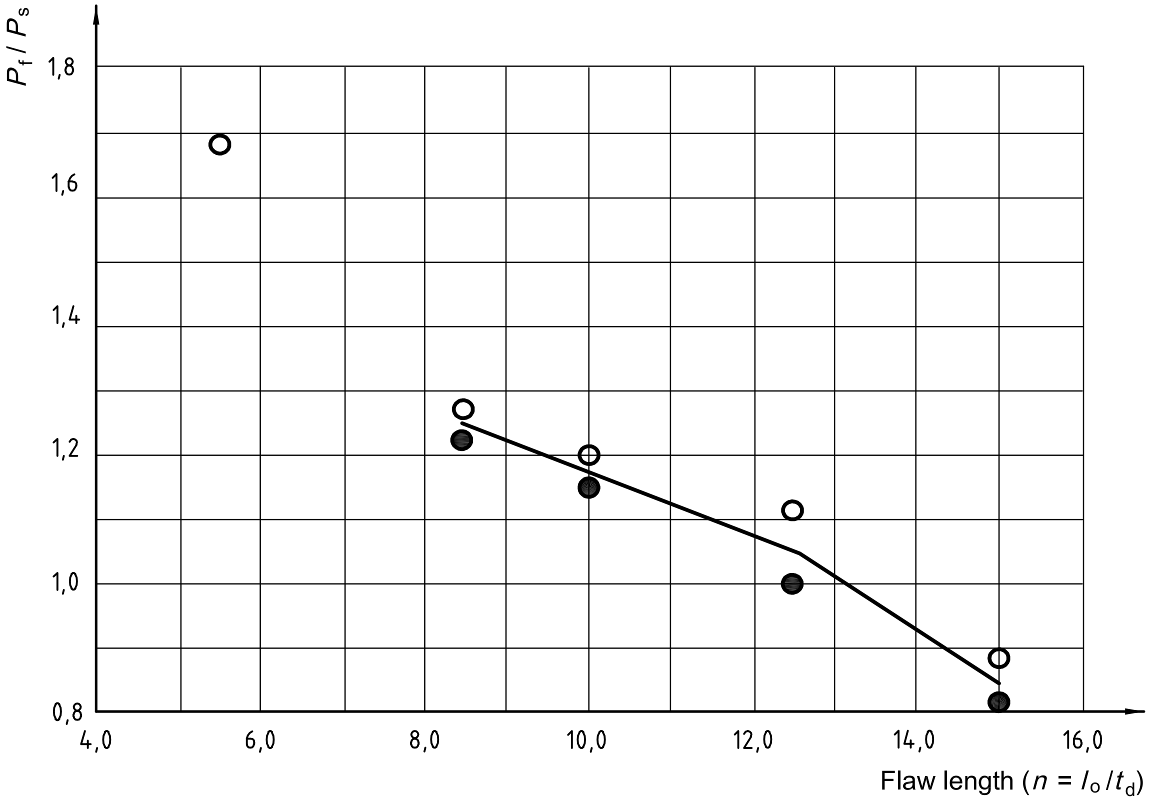
Figure 3 — Defining the leak-fracture boundary



Key

- ● Leak
- ○ Fracture

Figure 4 — Flawed-cylinder burst test results for A-1 material

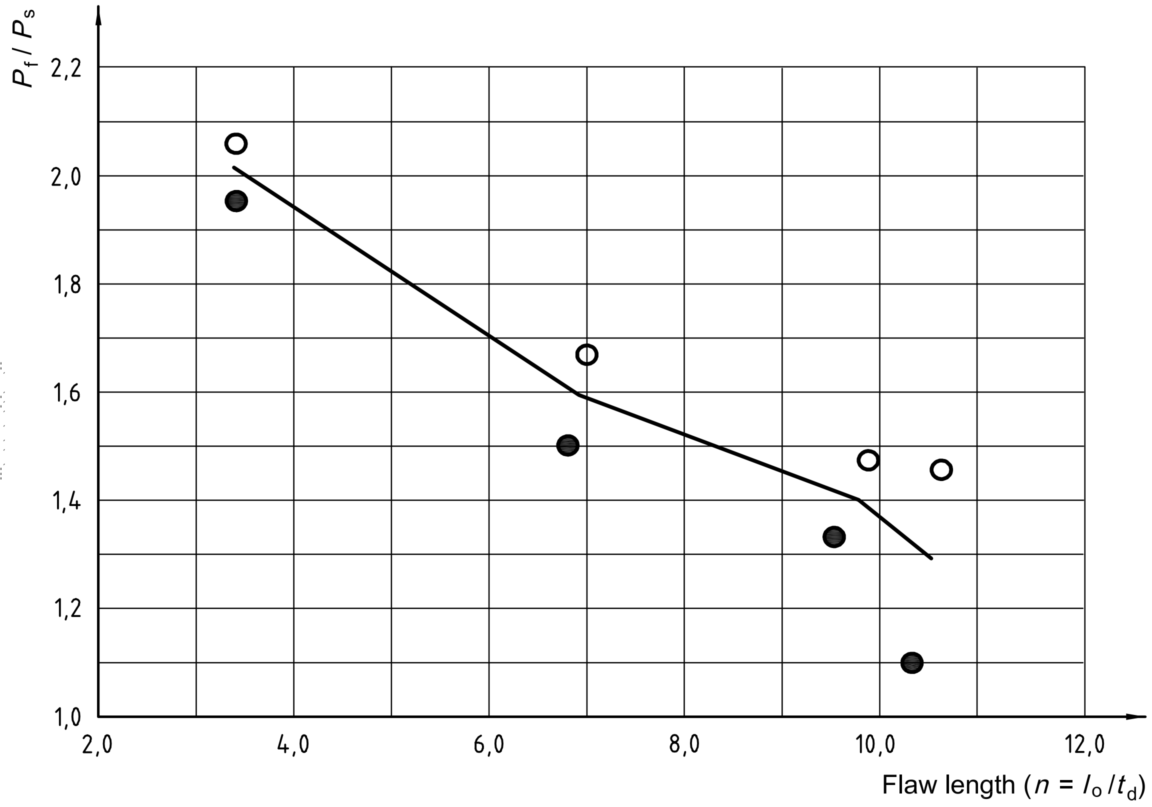


Key

● Leak

○ Fracture

Figure 5 — Flawed-cylinder burst test results for A-2 material

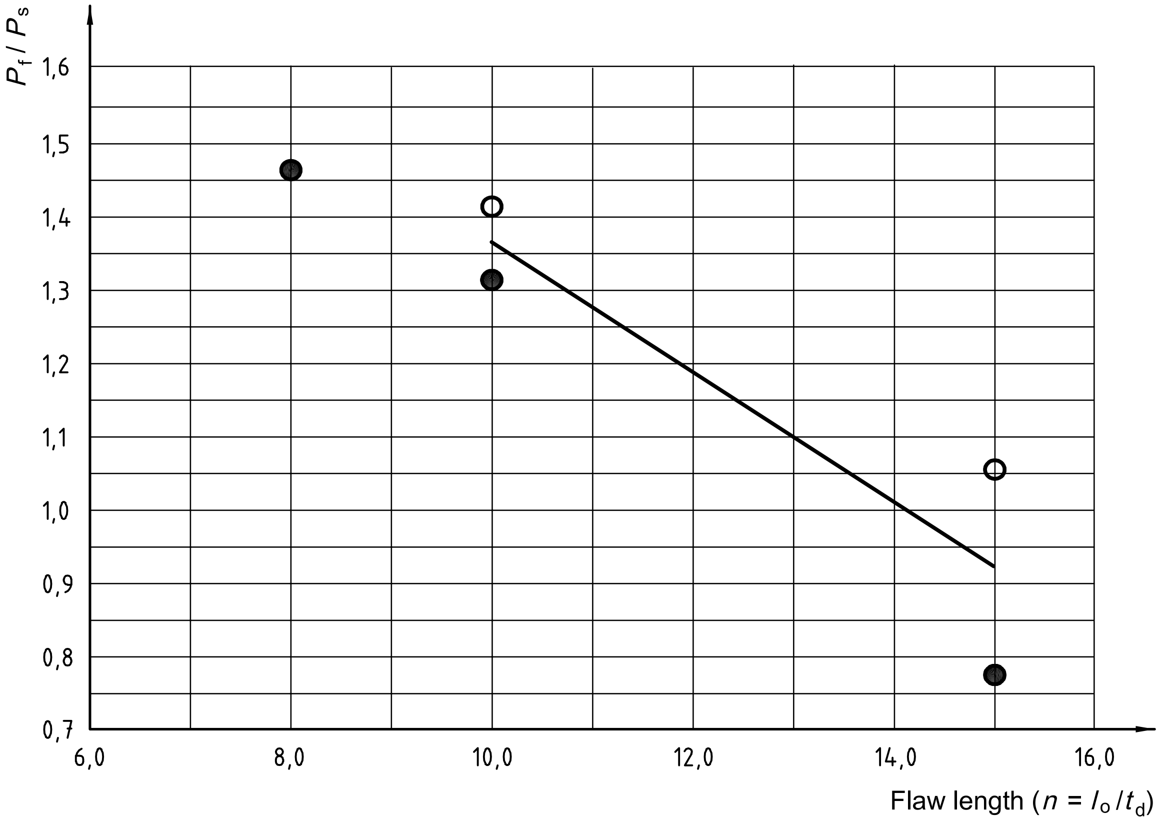


Key

● Leak

○ Fracture

Figure 6 — Flawed-cylinder burst test results for B-3 material

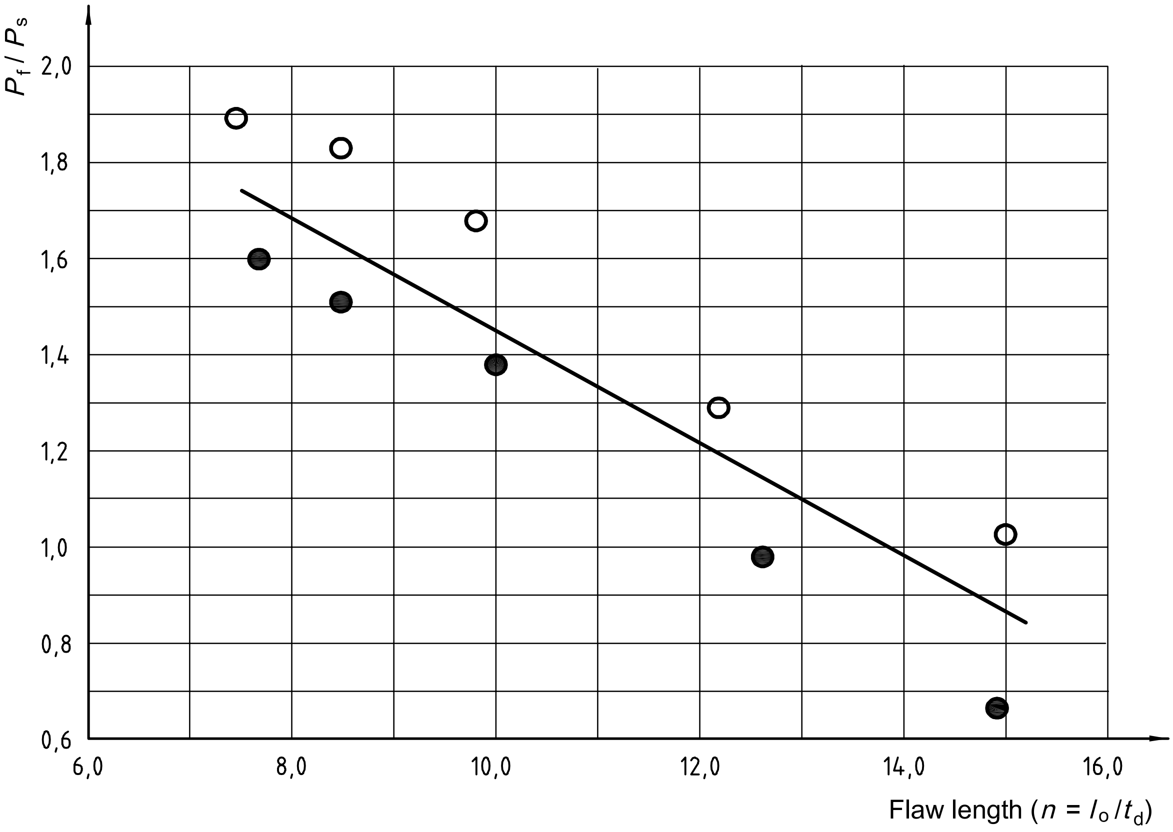


Key

● Leak

○ Fracture

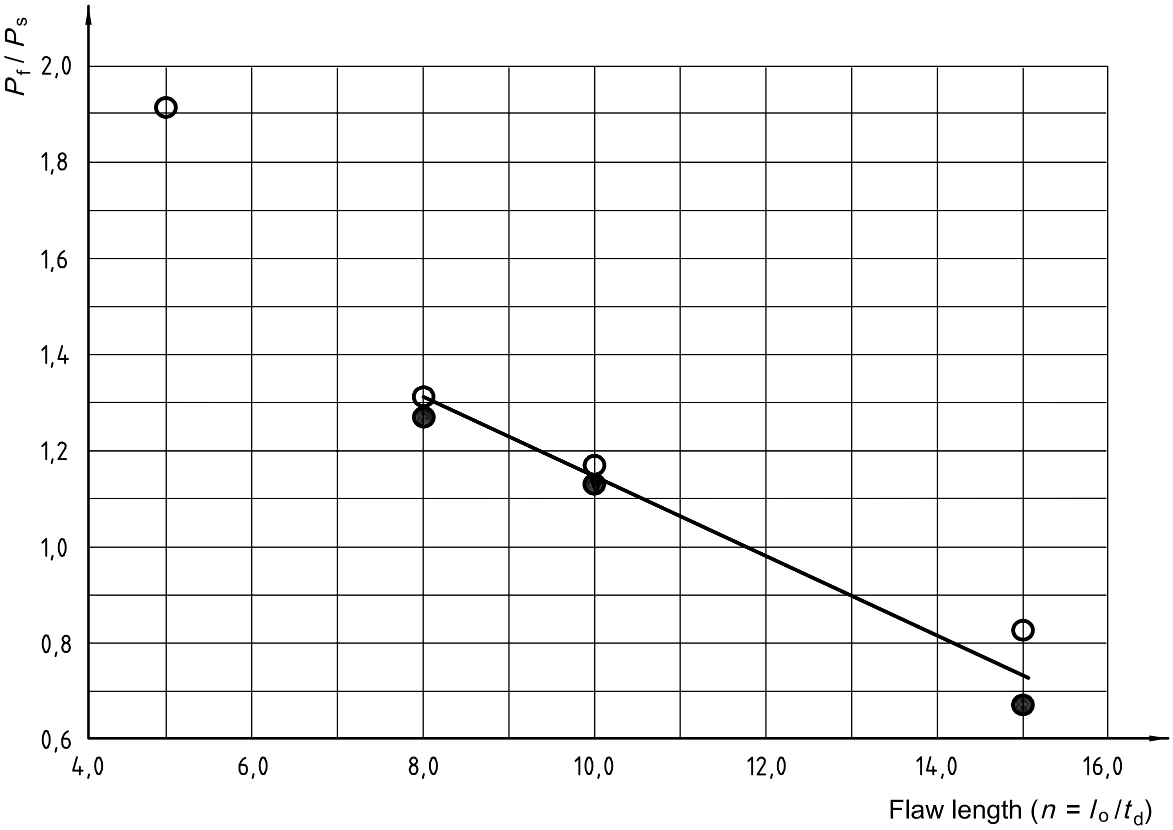
Figure 7 — Flawed-cylinder burst test results for B-6 material



Key

- ● Leak
- ○ Fracture

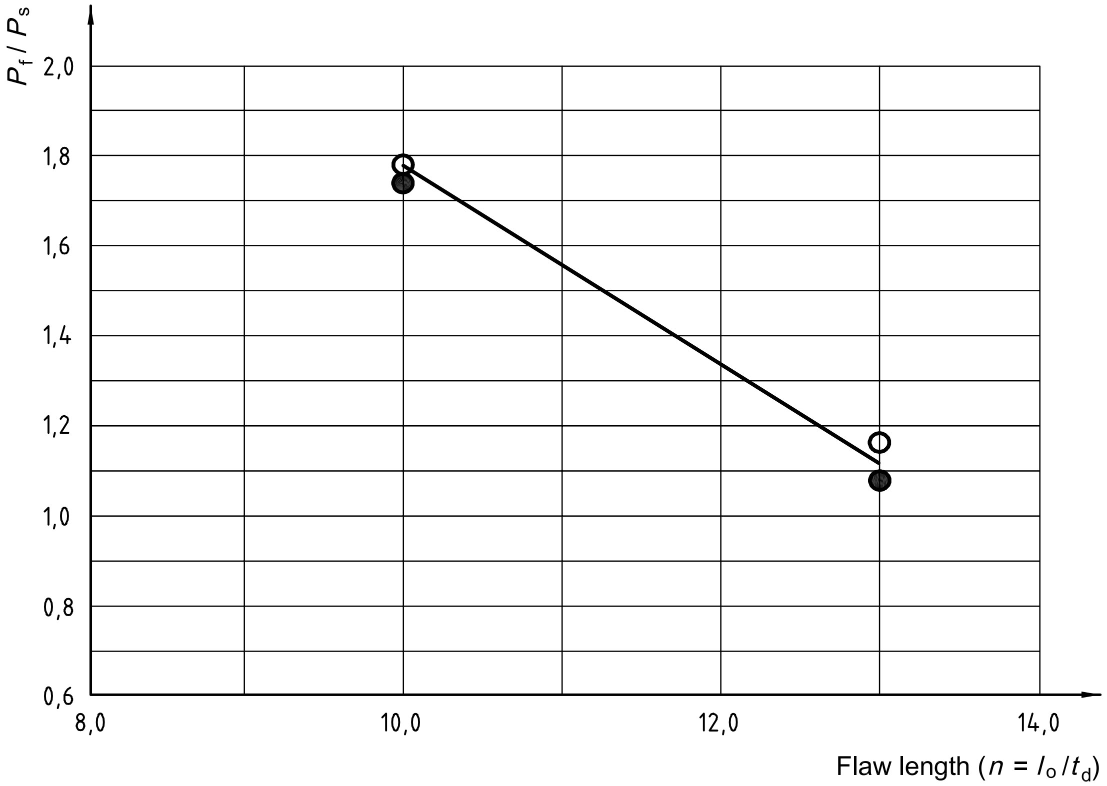
Figure 8 — Flawed-cylinder burst test results for B-9 material



Key

- ● Leak
- ○ Fracture

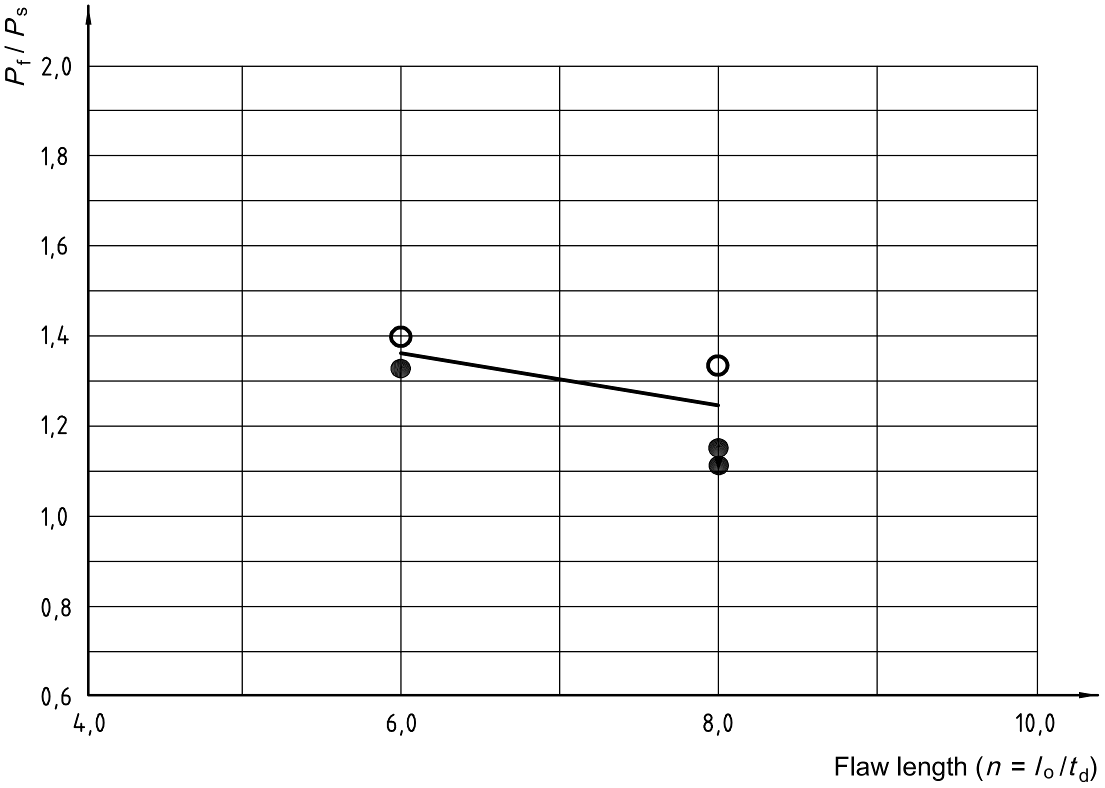
Figure 9 — Flawed-cylinder burst test results for C-3 material



Key

- ● Leak
- ○ Fracture

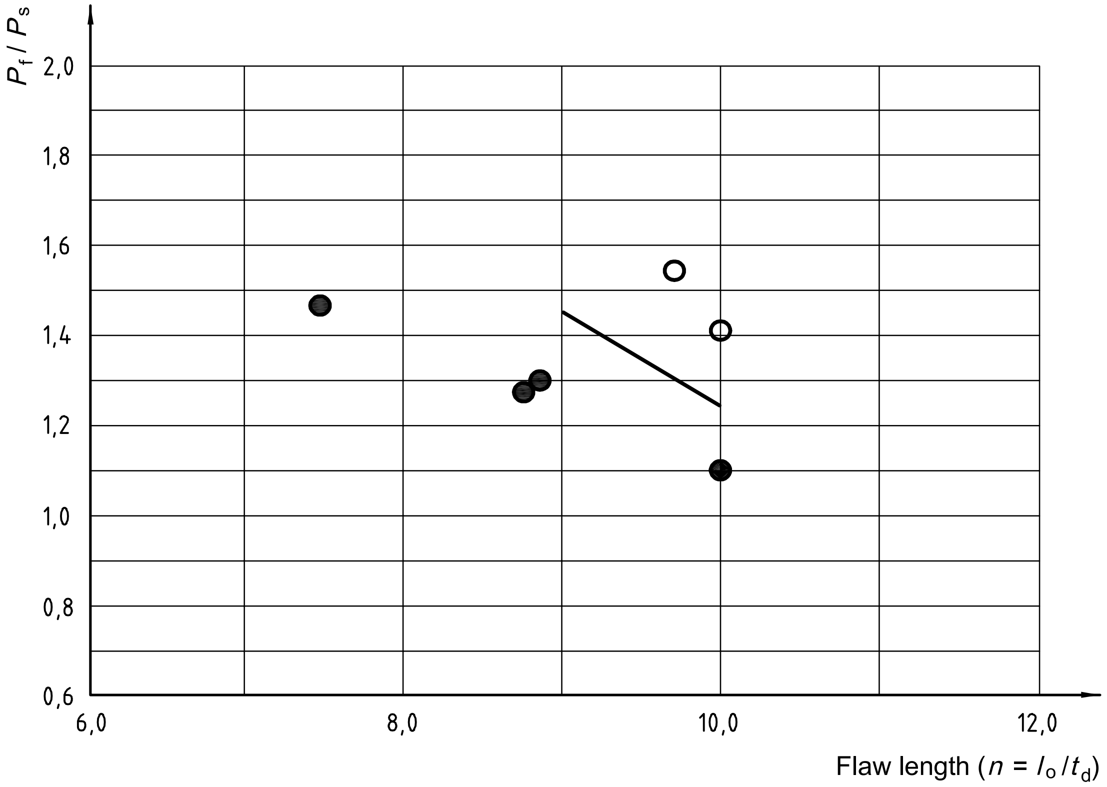
Figure 10 — Flawed-cylinder burst test results for C-7 material



Key

- ● Leak
- ○ Fracture

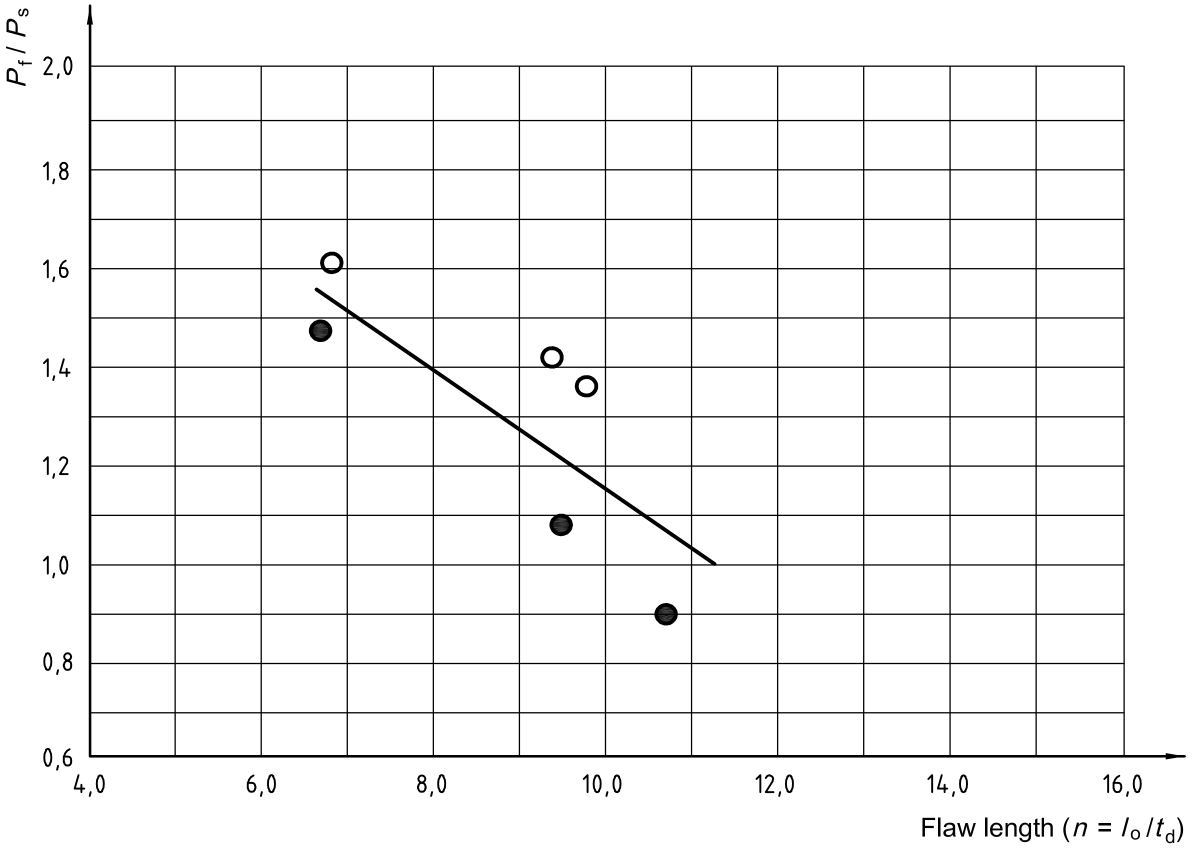
Figure 11 — Flawed-cylinder burst test results for C-11 material



Key

- ● Leak
- ○ Fracture

Figure 12 — Flawed-cylinder burst test results for D-3 material

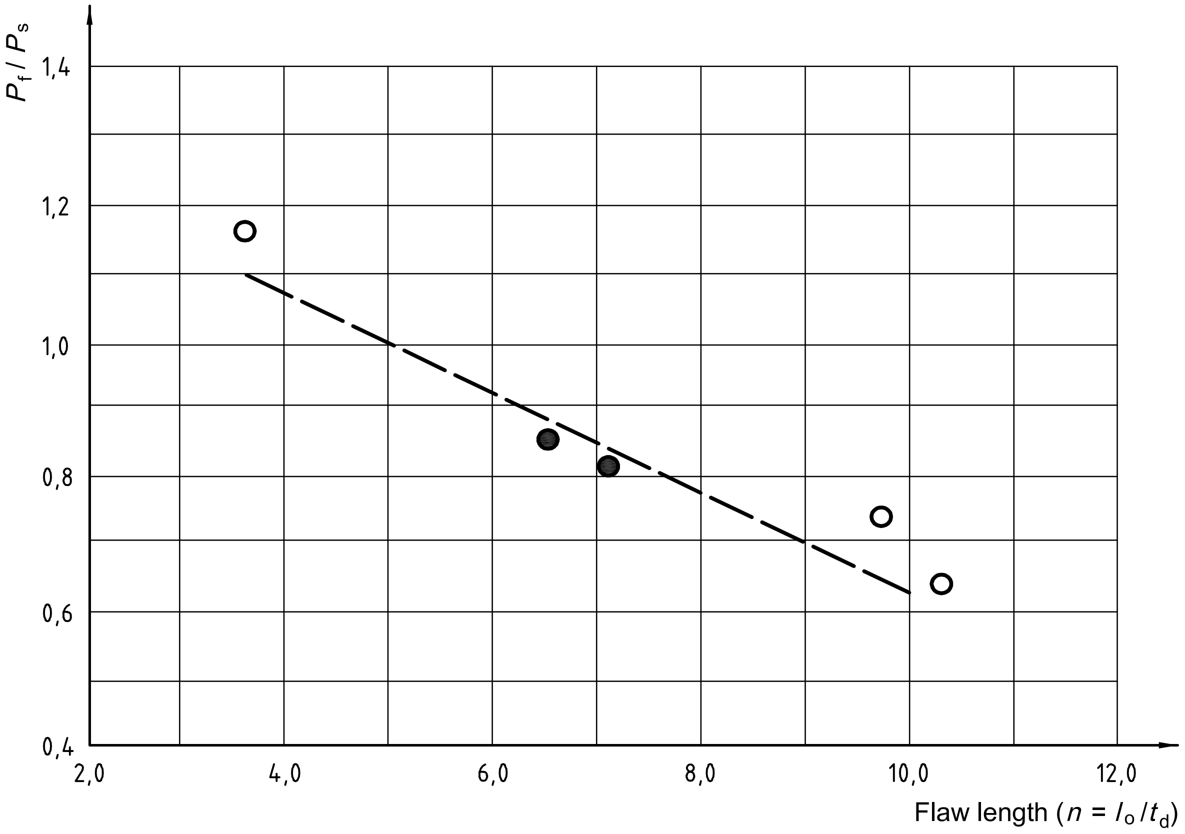


Key

● Leak

○ Fracture

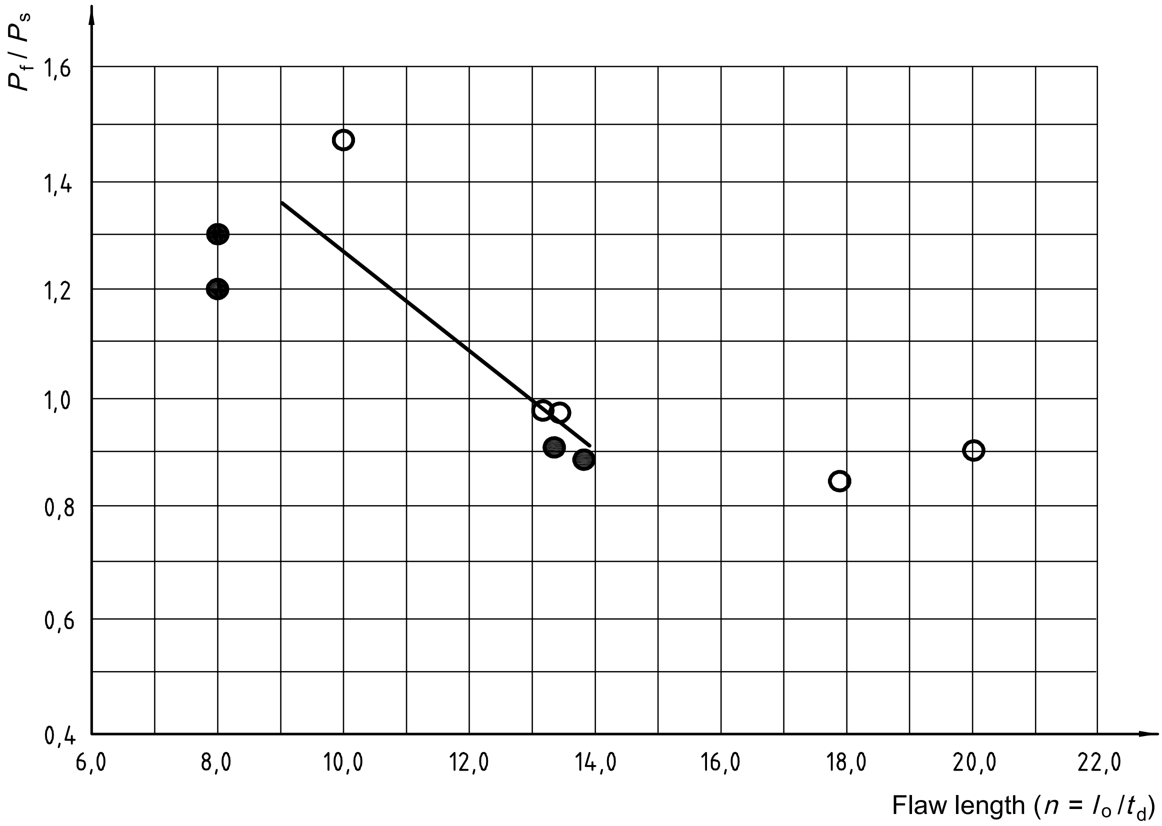
Figure 13 — Flawed-cylinder burst test results for D-5 material



Key

- ● Leak
- ○ Fracture

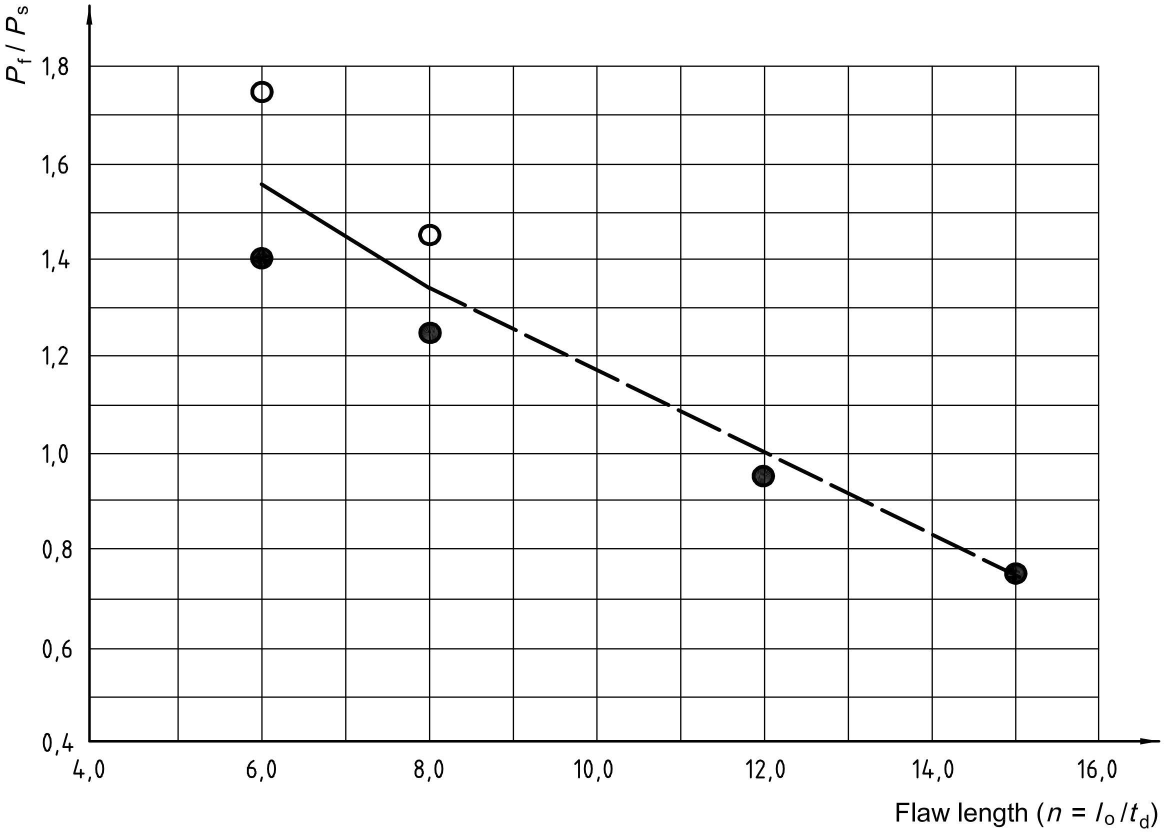
Figure 14 — Flawed-cylinder burst test results for D-6 material



Key

- ● Leak
- ○ Fracture

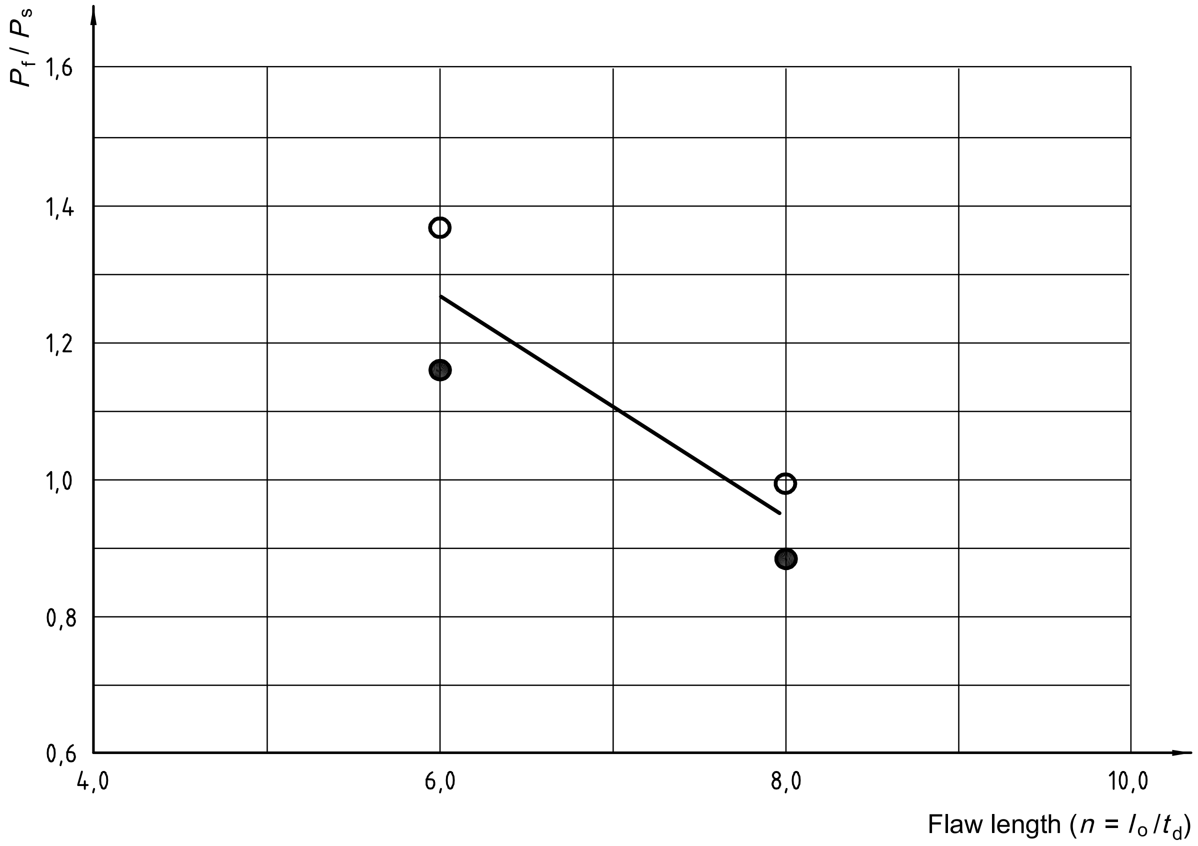
Figure 15 — Flawed-cylinder burst test results for D-11 material



Key

- ● Leak
- ○ Fracture

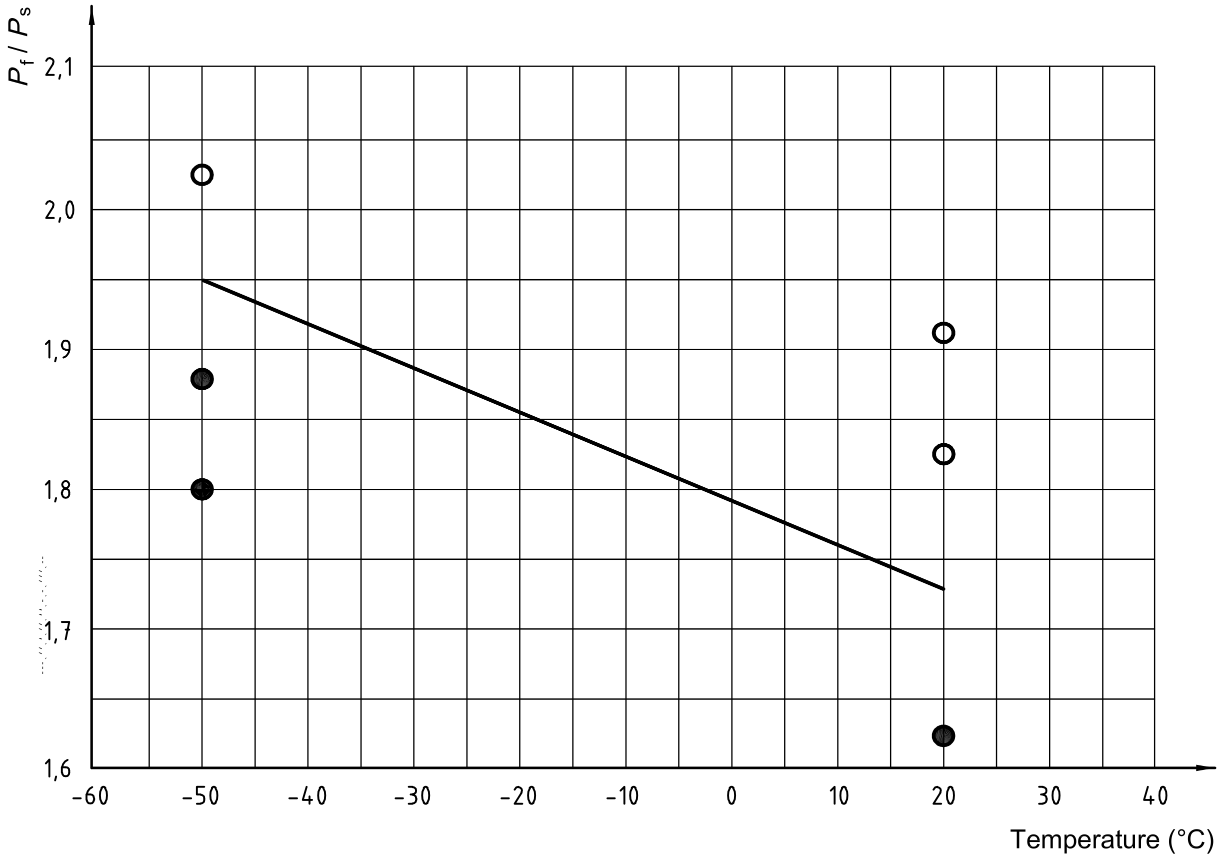
Figure 16 — Flawed-cylinder burst test results for E-1 material



Key

- ● Leak
- ○ Fracture

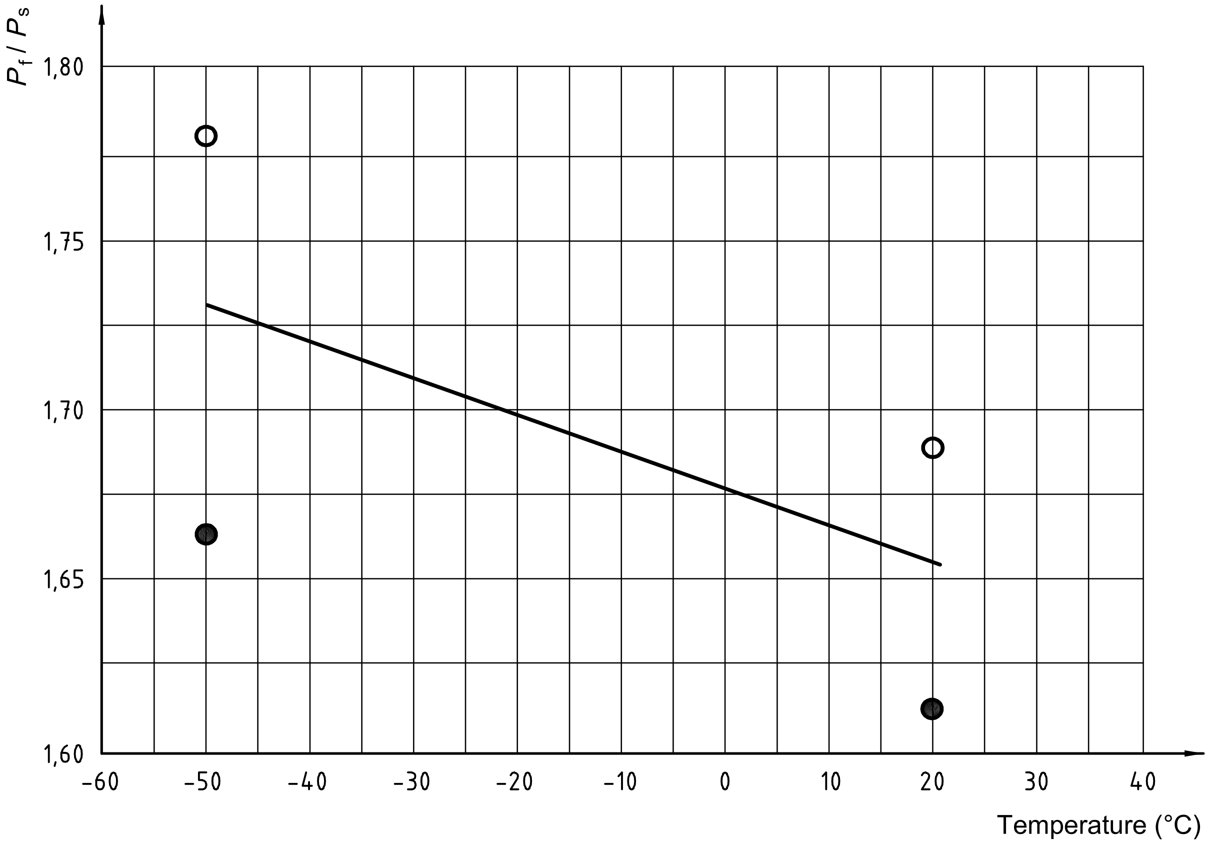
Figure 17 — Flawed-cylinder burst test results for E-2 material



Key

- ● Leak
- ○ Fracture

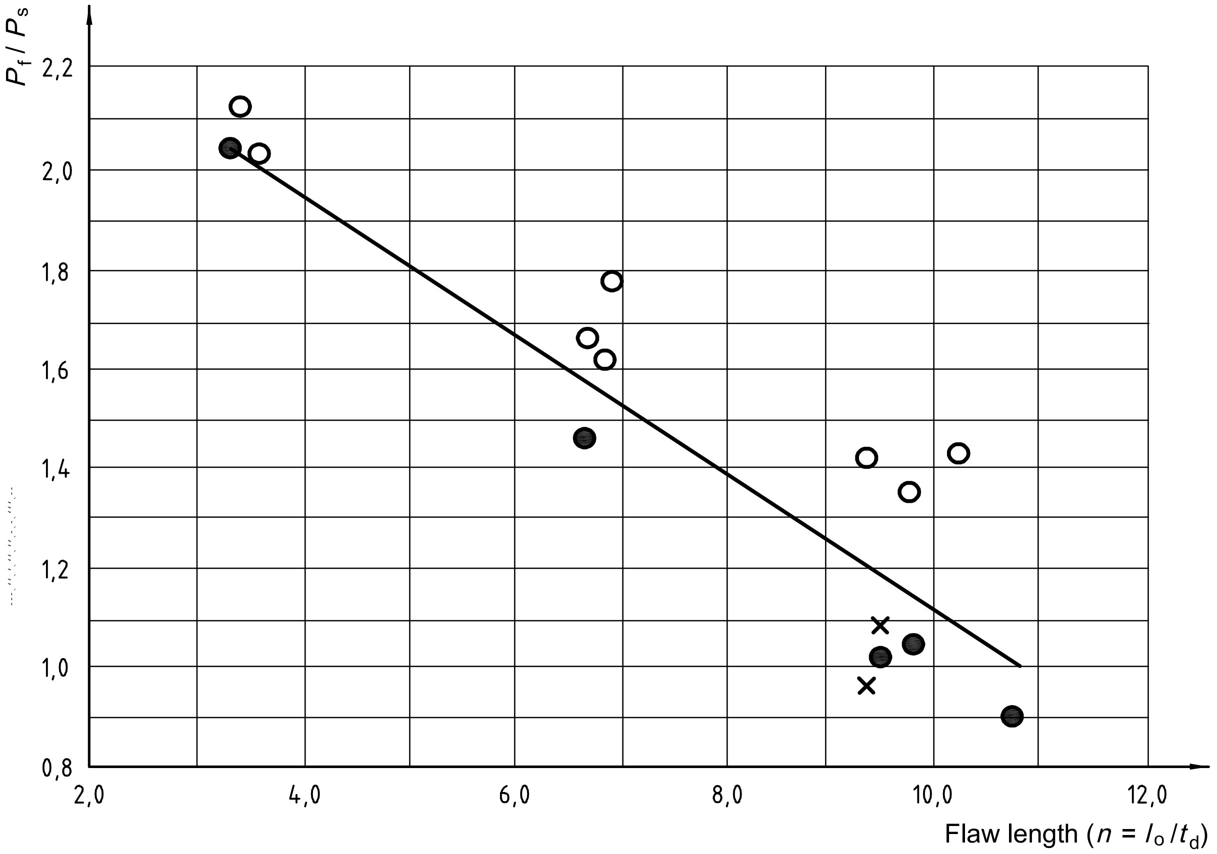
Figure 18 — Low temperature test (20 l cylinders)



Key

- ● Leak
- ○ Fracture

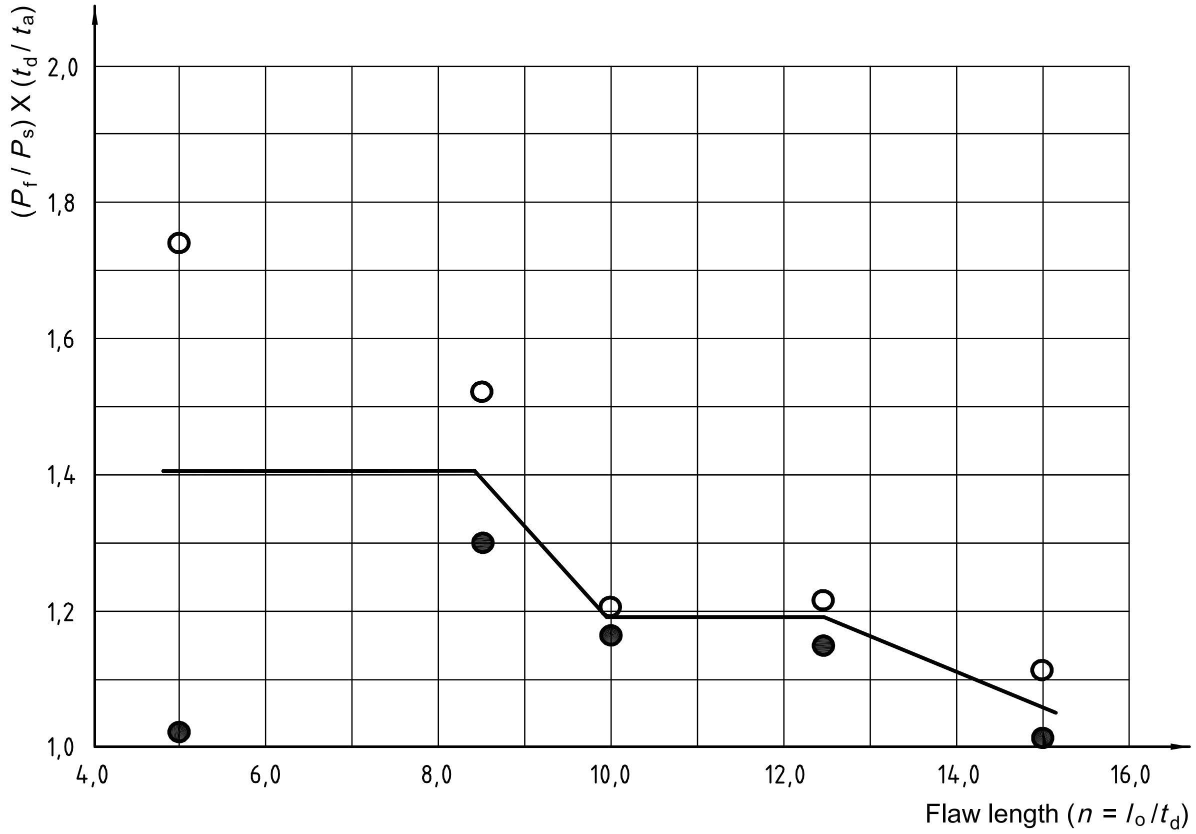
Figure 19 — Low temperature test (50 l cylinders)



Key

- ● Leak
- ○ Fracture
- X Pneumatic leak

Figure 20 — Comparison of pneumatic and hydrostatic tests

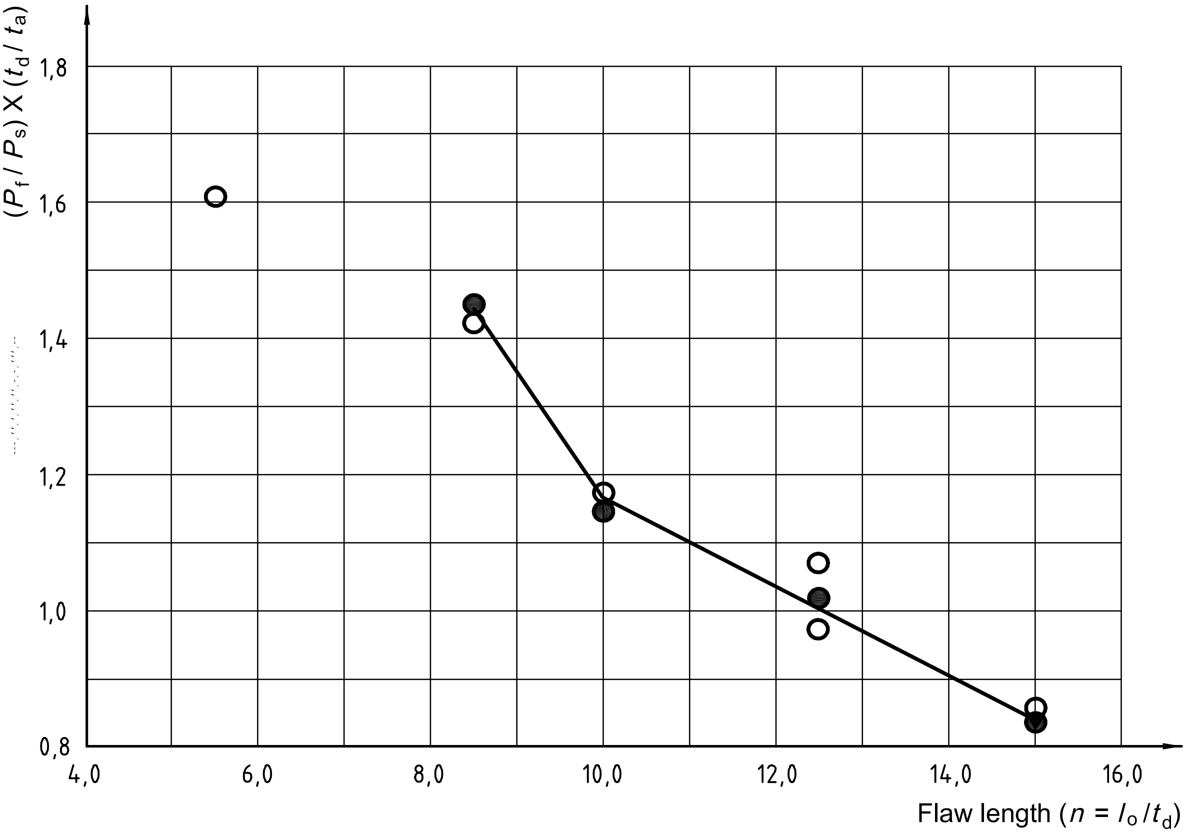


Key

● Leak

○ Fracture

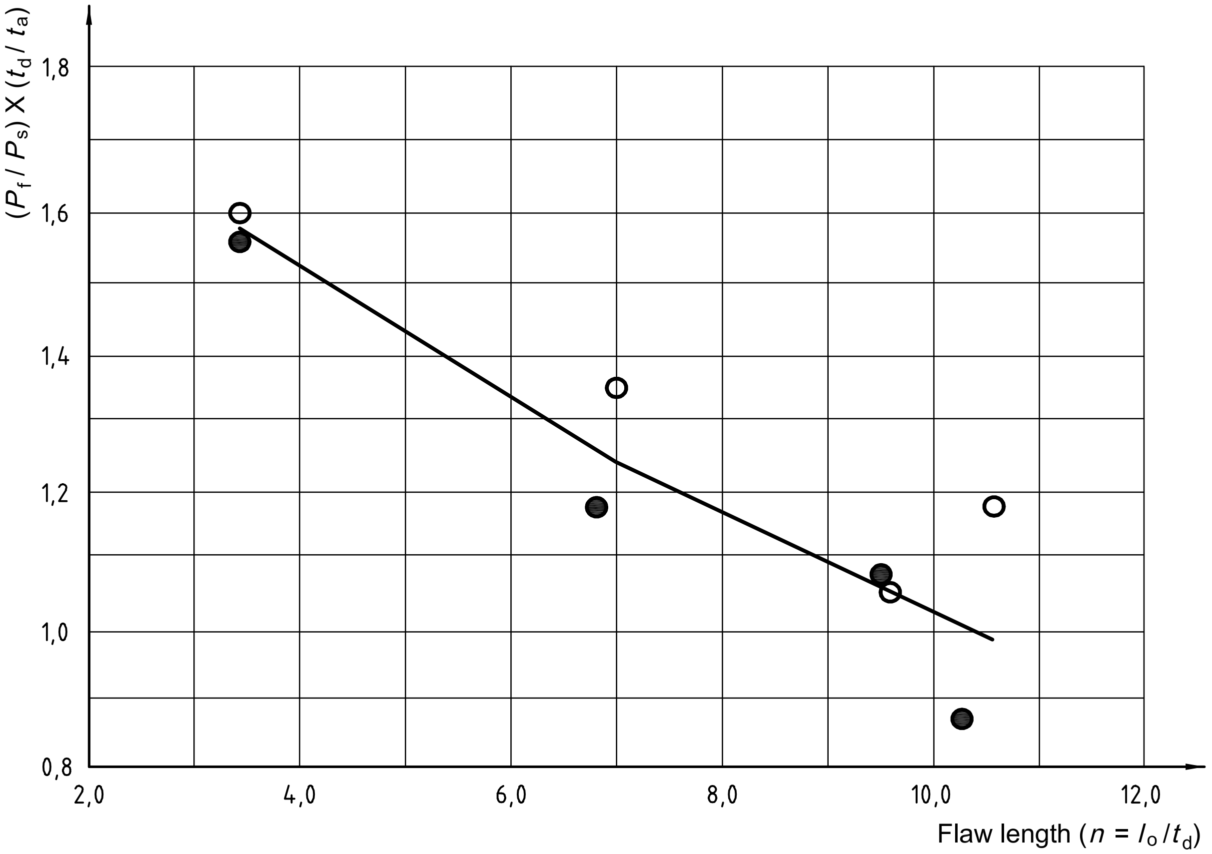
Figure 21 — Flawed-cylinder burst test results for A-1 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

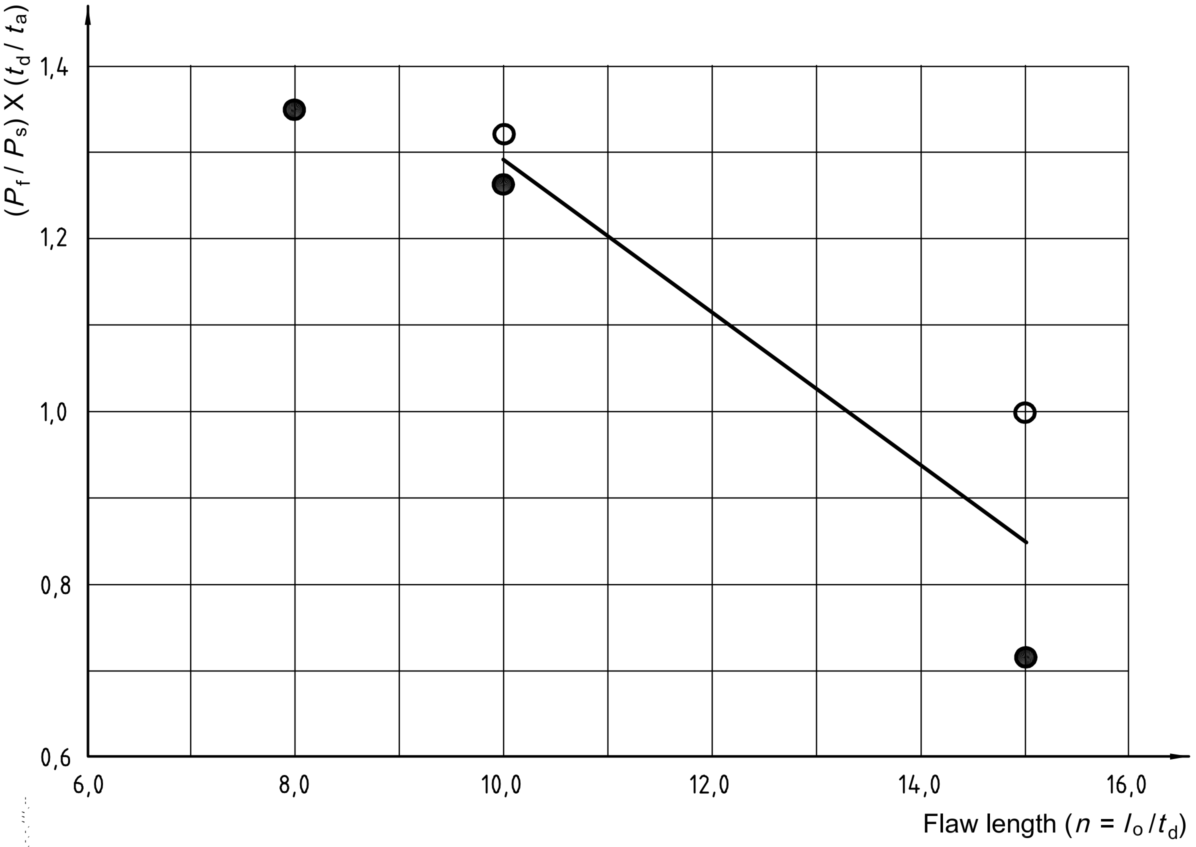
Figure 22 — Flawed-cylinder burst test results for A-2 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

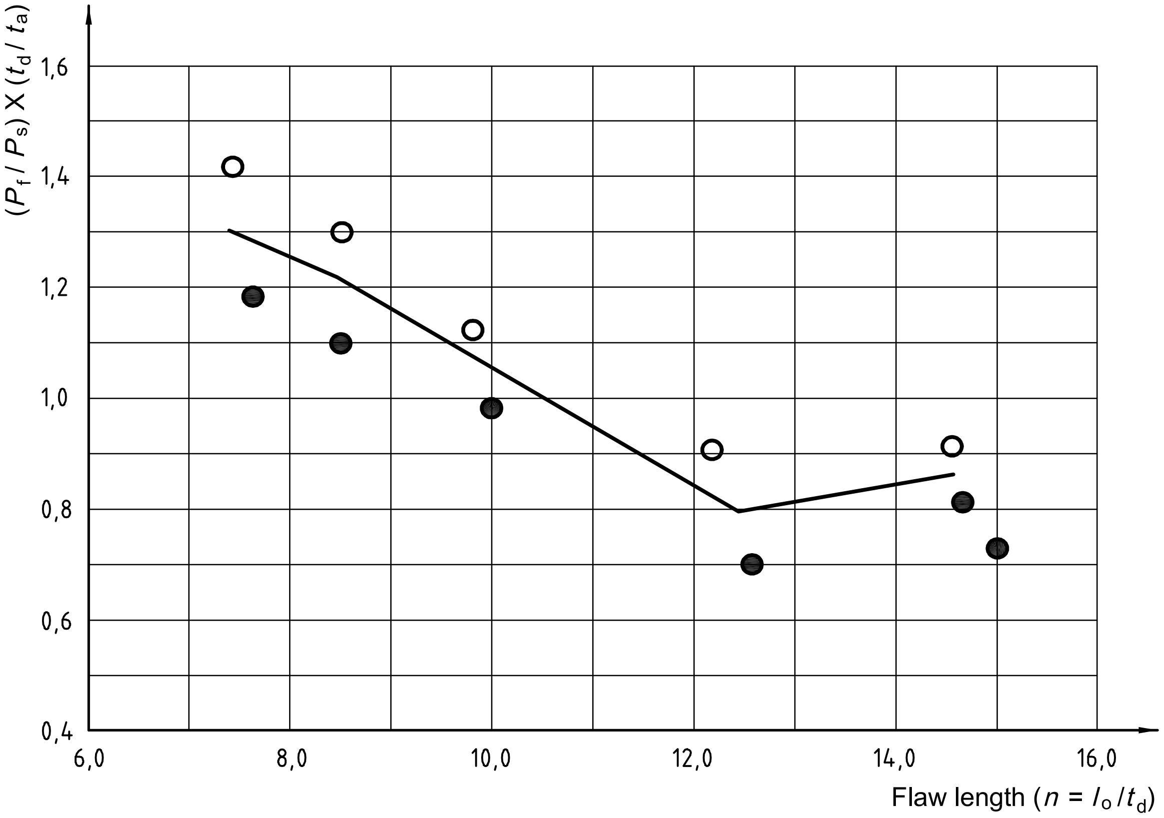
Figure 23 — Flawed-cylinder burst test results for B-3 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

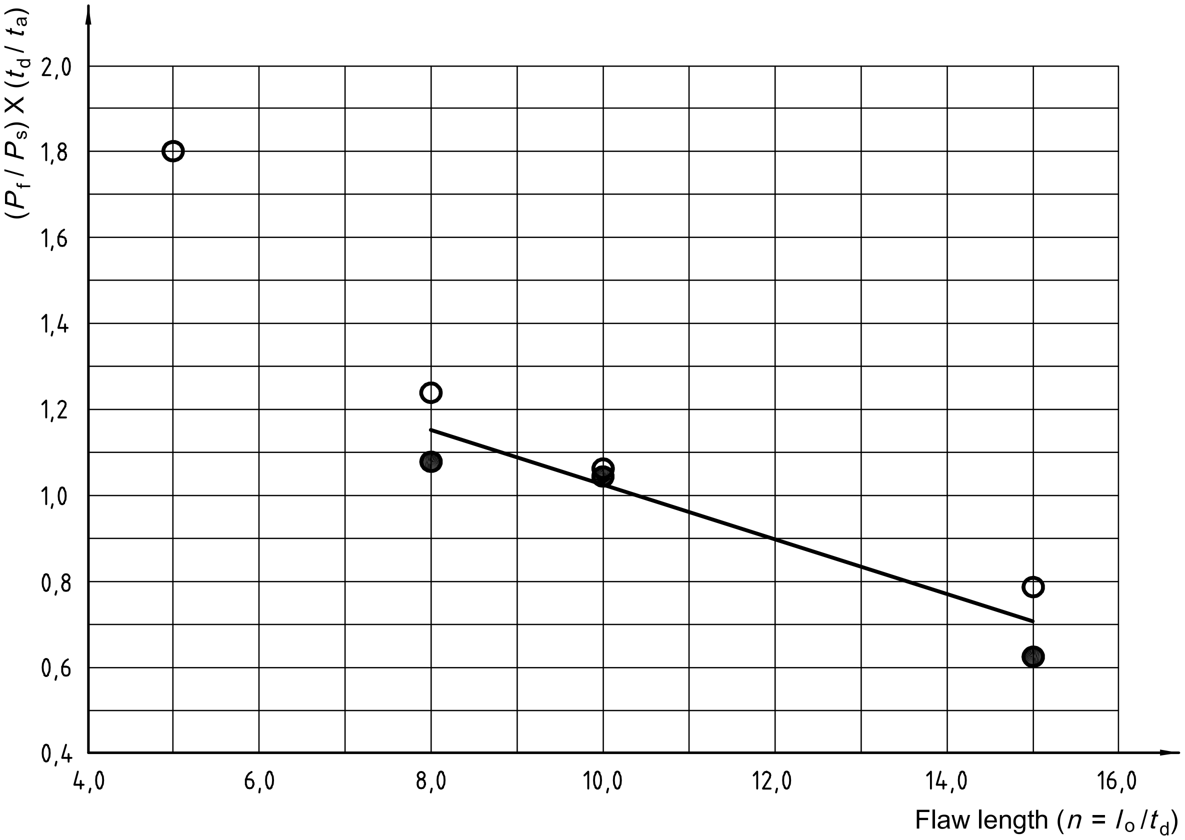
Figure 24 — Flawed-cylinder burst test results for B-6 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

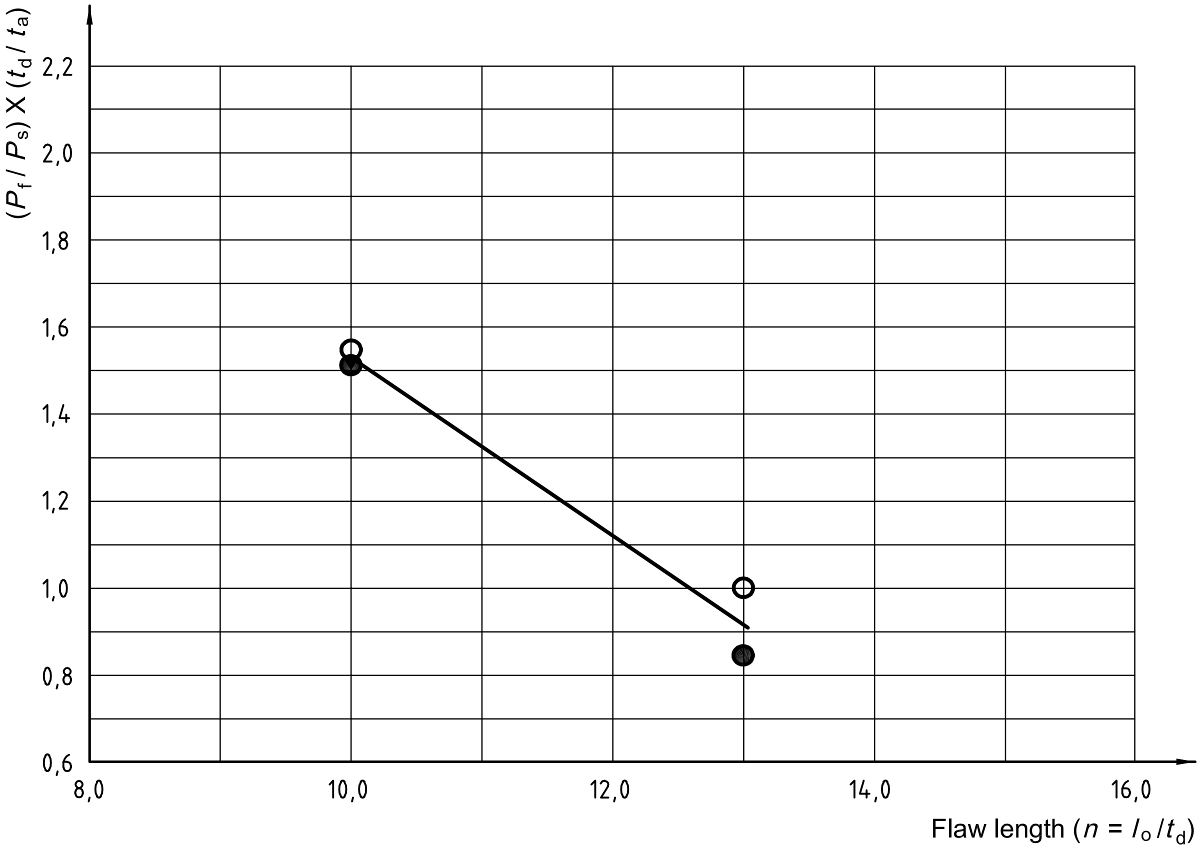
Figure 25 — Flawed-cylinder burst test results for B-9 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

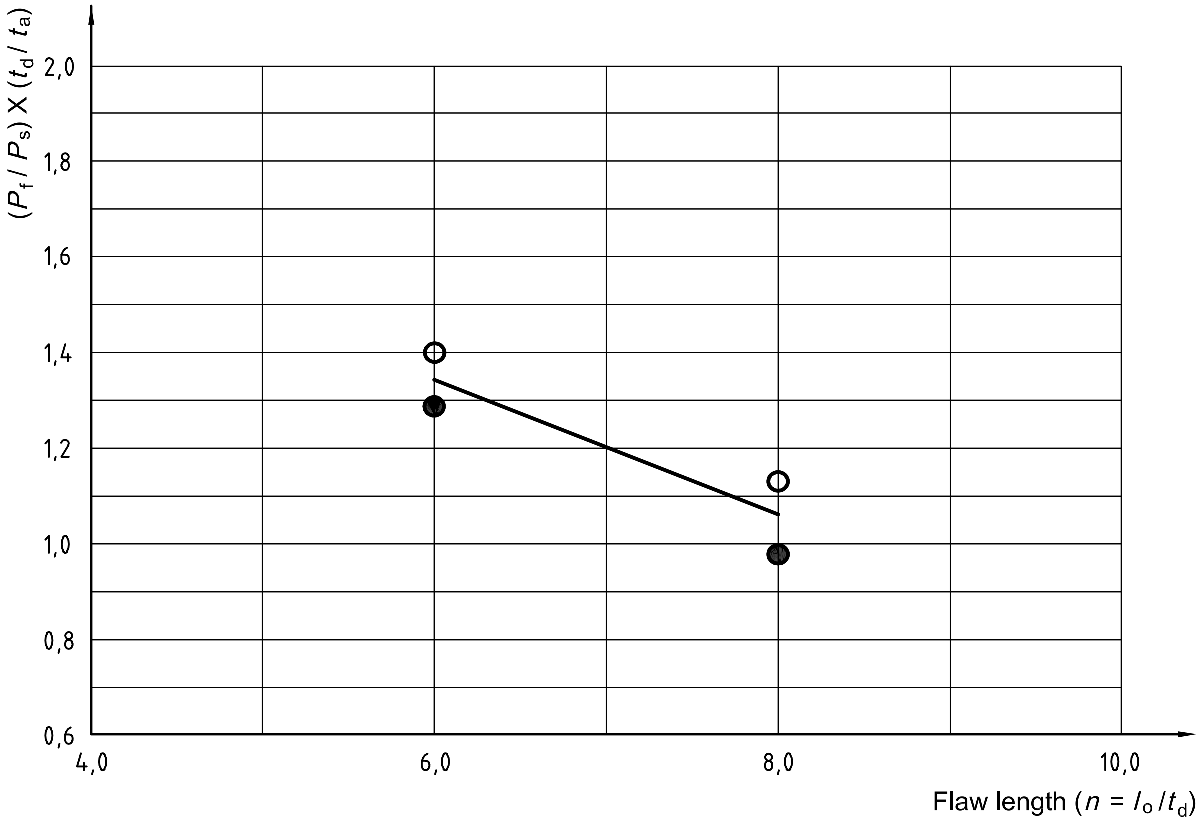
Figure 26 — Flawed-cylinder burst test results for C-3 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

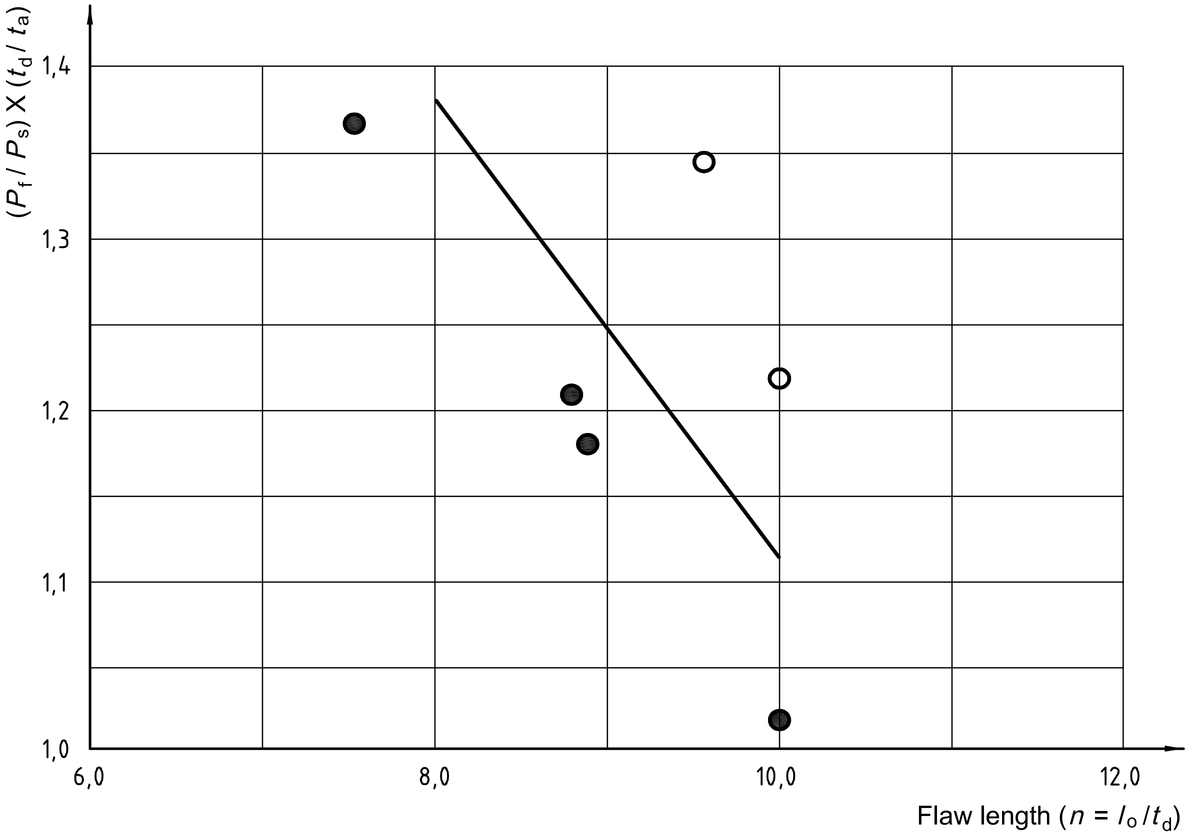
Figure 27 — Flawed-cylinder burst test results for C-7 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

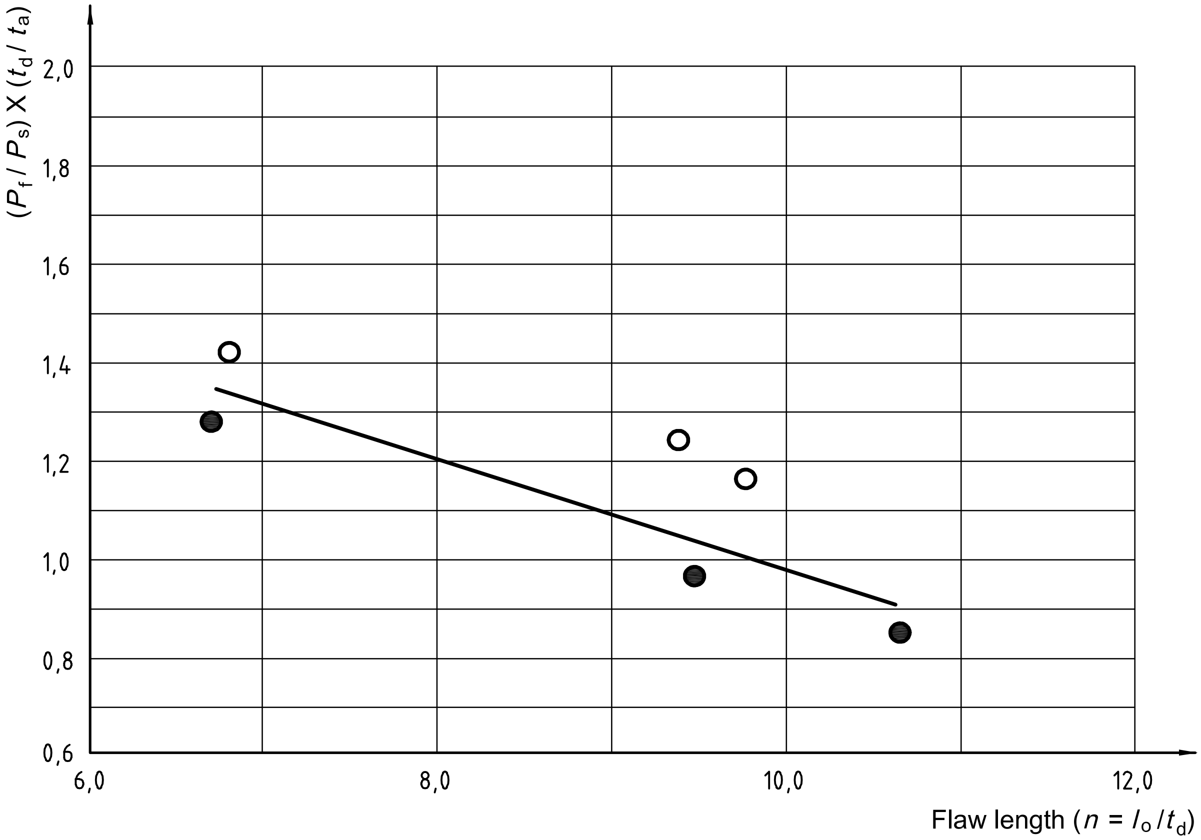
Figure 28 — Flawed-cylinder burst test results for C-11 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

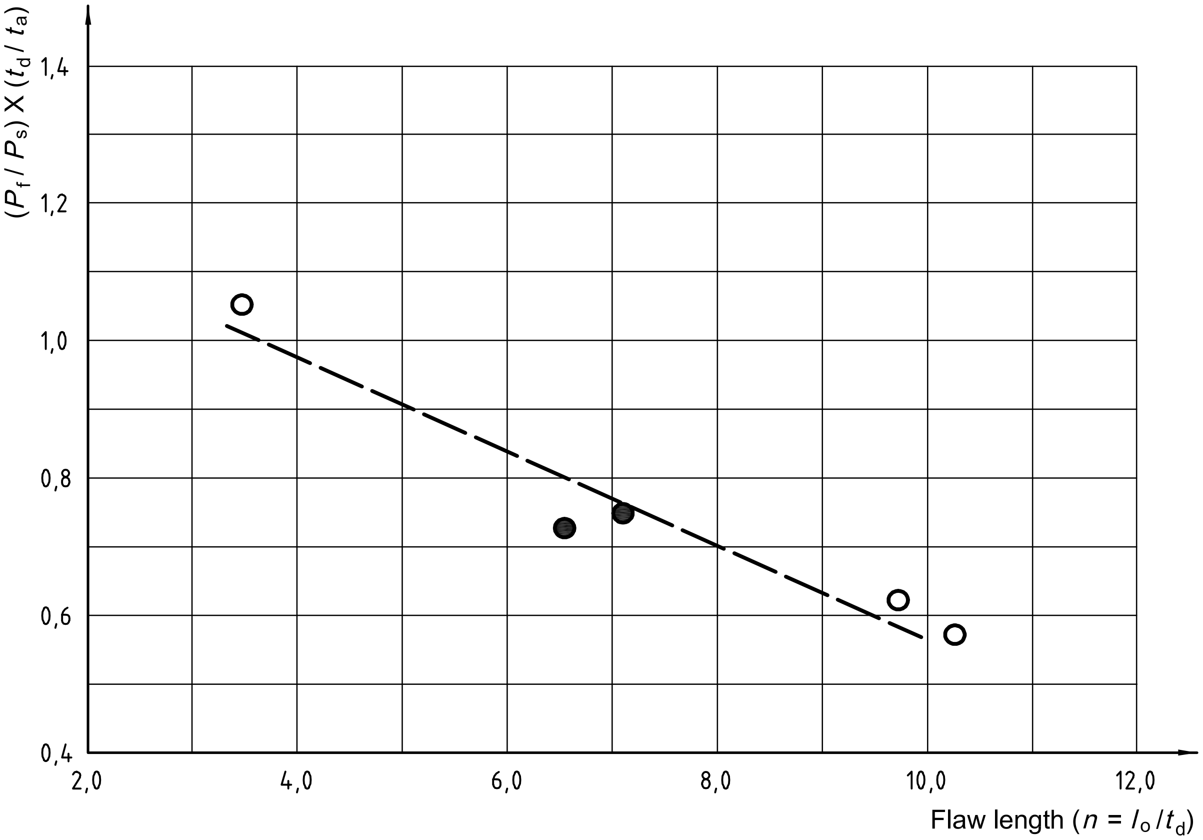
Figure 29 — Flawed-cylinder burst test results for D-3 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

Figure 30 — Flawed-cylinder burst test results for D-5 material adjusted for local thickness

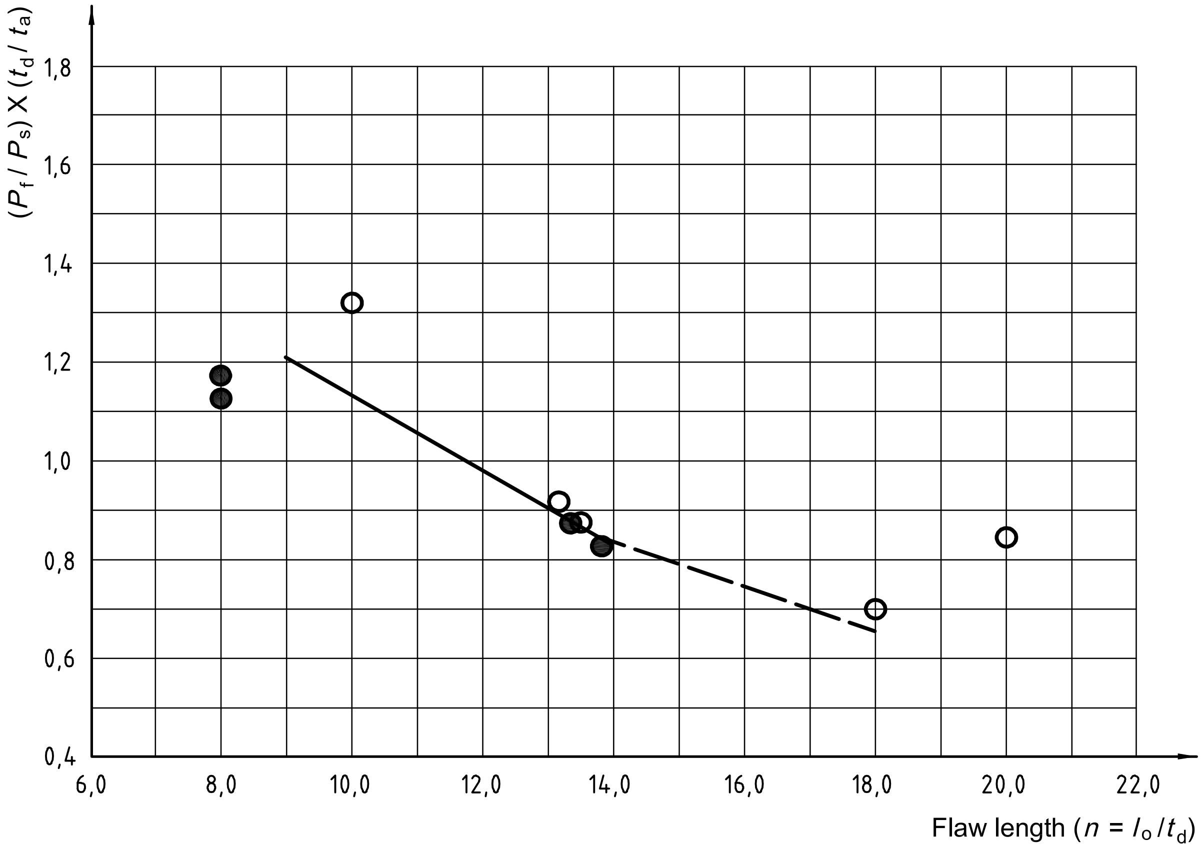


Key

● Leak

○ Fracture

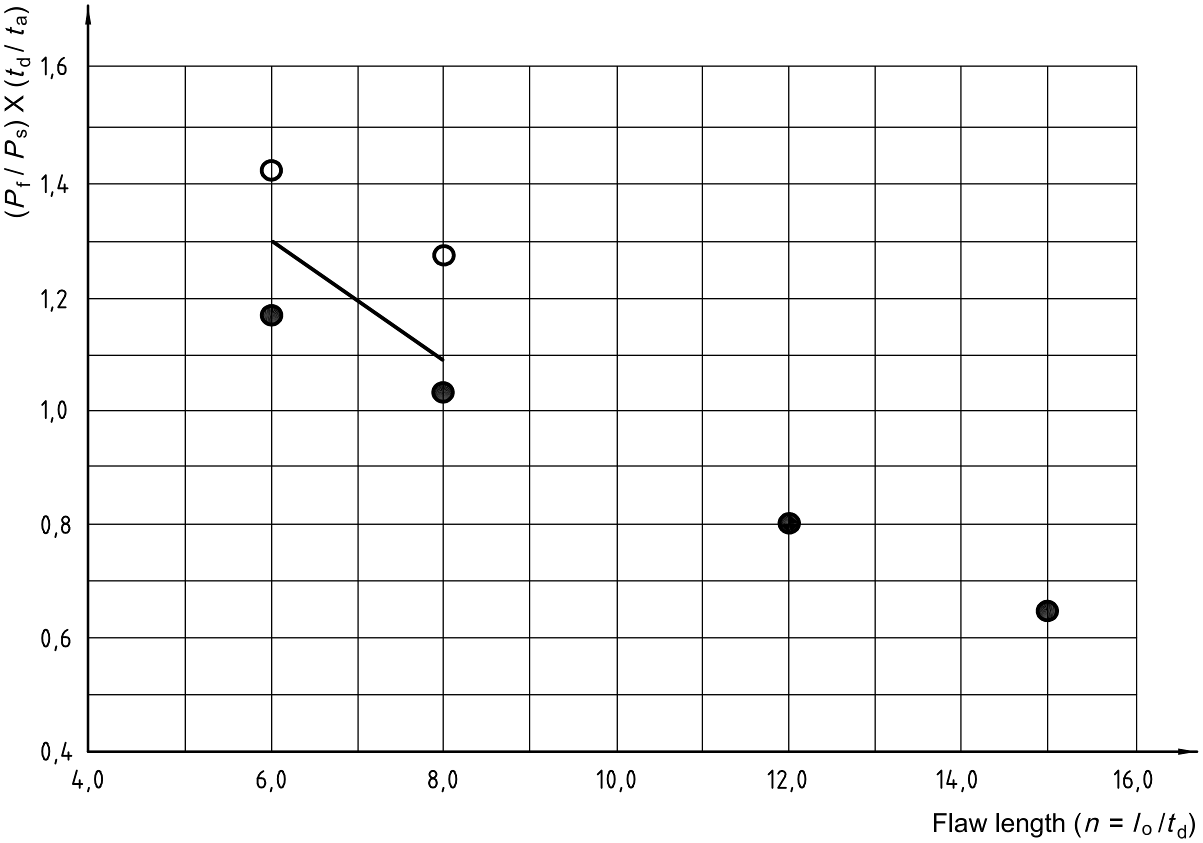
Figure 31 — Flawed-cylinder burst test results for D-6 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

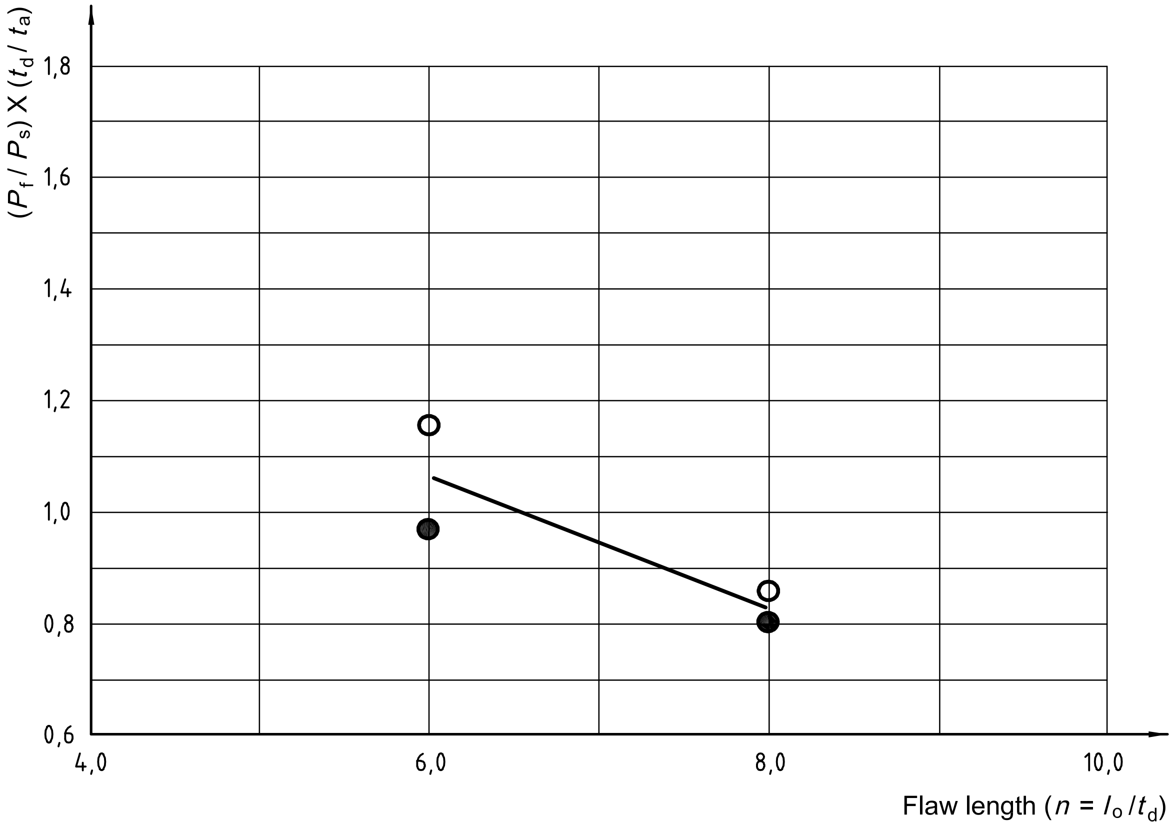
Figure 32 — Flawed-cylinder burst test results for D-11 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

Figure 33 — Flawed-cylinder burst test results for E-1 material adjusted for local thickness



Key

- ● Leak
- ○ Fracture

Figure 34 — Flawed-cylinder burst test results for E-2 material adjusted for local thickness

Annex A
(informative)

Evaluation of the measurement uncertainty in the flawed-cylinder burst test

A.1 Introduction to the evaluation of standard uncertainty

During the development of the flawed-cylinder burst test, no specific tests were conducted to evaluate the measurement uncertainty in the test method. However, it is possible to make some estimate of the measurement uncertainty in the flawed-cylinder burst test from an analysis of the test itself and from some of the test data that were obtained during the development of the test method. The evaluation of the measurement uncertainty in the flawed-cylinder burst test will follow procedures given in the *ISO Guide to the Expression of Uncertainty in Measurement* [11].

To evaluate the measurement uncertainty in the test method, it is first necessary to identify the parameters that may lead to uncertainty in the final measurement. The primary measurement that is made in the flawed-cylinder burst test is the failure pressure, P_f, for a cylinder with a certain defined size of partly through-machined flaw. The factors that affect the uncertainty of the measured failure pressure, P_f, are:

- the uncertainty in the pressure measurement, P_f;
- the flaw length l_o;
- the flaw depth, d;
- the cylinder wall thickness at the location of the flaw, t_a;
- the depth of the uncracked ligament beneath the flaw;
- the strength of the cylinder at the location of the flaw.

The *ISO Guide to the Expression of Uncertainty in Measurement* [11] requires that the evaluation include:

- “a type A evaluation of standard uncertainty” by statistical analysis and
- “a type B evaluation of standard uncertainty” by other means, usually based on scientific judgement of the specific measurement process.

A.2 Evaluation of the type A standard uncertainty

To evaluate the type A uncertainty in the measurements requires that a sufficient number of replicated tests be conducted so that a statistical analysis can be performed to determine the size of any random uncertainties in the measurement. For the flawed-cylinder burst test, this requires that several duplicate cylinders of the same material, size (diameter and wall thickness), tensile strength, length and flaw depth be tested and the tests result in the same failure mode. Unfortunately, of all of the flawed-cylinder burst tests that were conducted, the only test series in which at least three replicated tests of identical cylinders met these requirements was for the material subgroup D-14. The results of this series of tests were used to evaluate the type A uncertainties for the flawed-cylinder burst test.

For the test results for material subgroup D-14 the analysis in Table A.1 shows the type A uncertainties in the measurement:

Table A.1 — Type A uncertainties in the measurement

	For leak failure mode	For fracture failure mode
Mean value of P_f	280 bar	331 bar
Standard deviation of P_f	38 bar	21 bar
Mean value of P_f/P_s	0,904	1,068
Standard deviation of P_f/P_s	0,021	0,080

These values were estimated from the results of 17 tests in which the failure mode was by leaking and 32 tests in which the failure mode was by fracture. The flaw length was $l_o = 10 \times t_d$ for all cylinders tested. The cylinders ranged in actual wall thickness (measured at the flaw) from 5,4 mm to 8,0 mm. The tensile strength was measured on 12 of the 49 cylinders tested. The tensile strength ranged from 1 078 MPa to 1 157 MPa. The flaw depth ranged from 74 % to 80 % of the cylinder wall thickness for the cylinder that failed by leaking and from 70 % to 78 % of the cylinder wall thickness for the cylinder that failed by fracturing. Because the range of wall thickness and tensile strength was as wide as is likely to be found in conventional cylinders, this estimate of type A standard uncertainty should adequately include the uncertainty due to variations in cylinder wall thickness and tensile strength. No additional type B standard uncertainty should be required for variations in wall thickness and tensile strength.

This data for test from material subgroup D-14 was the only data that was adequate to evaluate the type A uncertainty in the flawed-cylinder burst test. These estimates should be used with caution as the estimate of type A uncertainty for the cylinders in the other material groups until the estimates of uncertainty are confirmed by sufficient test replicated tests on cylinders made from steels of the other alloys and strength levels.

A.3 Summary of type A standard uncertainty

Failure by leaking: (Measured failure pressure, P_f) ± 13,8 %

Failure by fracturing: (Measured failure pressure, P_f) ± 6,8 %

A.4 Evaluation of the type B standard uncertainty

To evaluate the type B standard uncertainty in the measurements, the uncertainty in each of the test parameters that affect the measurement was made by technical analysis and judgement of the test method. No experimental confirmation of these uncertainty estimates could be made from the test conducted here.

The measured failure pressure, P_f, may have an uncertainty due to

- the uncertainty in the measured pressure and
- due to overshooting of the measured pressure by not detecting the exact moment when the failure event occurs.

The personnel conducting the tests reported the pressure measurements to have been made to within ± 1 %. This accounts for any uncertainties in the pressure gauges and related pressurizing equipment. The measured failure pressure may be in error due to overshooting of the measured pressure, i.e., the pressure may continue to rise after the initial point of failure. This is expected to be more significant with cylinders that leak than for cylinders that fracture because the pressure may continue to rise after the initial leak before it is detected by a pressure drop or rise. This seems to be accounted for in the evaluation of the type A standard uncertainty discussed above where the standard uncertainty is larger for tests that fail by leaking than for those that fail by fracturing. The value of the type B standard uncertainty from this source should be ± 1 %.

The failure pressure and the failure mode are affected by the flaw length (l_o). The flaw length is defined in terms of the design minimum thickness of the cylinder (e.g. $10 \times t_d$ or $6 \times t_d$). The machined flaw length is specified and machined within the operating tolerances of the milling cutter. The length of the flaw is measured after the test. The length of the flaw is reported to within ± 0,25 mm. Because the total flaw length in the cylinders that were tested here ranged from 40 mm to 80 mm, the uncertainty in the actual flaw length (± 0,25 mm) should not have a measurable effect on the failure pressure or failure mode. The value of the type B standard uncertainty from this source may be considered to be negligible.

The actual flaw depth (t_a) is one factor that determines the failure pressure and the failure mode. The flaw depth is defined in terms of the design minimum wall thickness of the cylinder (e.g. 80 % t_d or 90 % t_d). The depth of the flaw is measured after the test. The depth of the flaw is reported to within ± 0,25 mm. Because the total flaw depth in the cylinders that were tested here ranged from 3 mm to 6 mm, the uncertainty in the actual flaw depth (± 0,25 mm) could have a measurable effect on the failure pressure. However, in the evaluation of type A standard uncertainties discussed above, the flaw depth for cylinders that failed by fracturing ranged from 4,62 mm to 5,15 mm (average depth ± 0,27 mm). No noticeable effect on the failure pressure that could be due to variations in the flaw depth was determined. Therefore, the value of the type B standard uncertainty from this source may be considered to be negligible.

The cylinder wall thickness at the location of the flaw (t_a) is expected to have an effect on the measured failure pressure. The cylinder wall thickness is measured after the test at the location of the flaw. The wall thickness is reported to within ± 0,25 mm. The wall thickness of the cylinder is variable throughout the cylinder diameter and length. Variations in thickness of up to 2 mm may be found on a given cylinder.

The actual strength (tensile strength and yield strength) of the cylinder varies with location within the cylinder. The estimated variation in the strength is ± 50 MPa. In the test used to evaluate the type A standard uncertainties discussed above, the tensile strength ranged from 1 078 MPa to 1 157 MPa. Therefore, the value of uncertainty due to variations in tensile strength is included in the estimate of type A standard uncertainty and the value of the type B standard uncertainty from this source may be considered to be negligible.

The specified service pressure of the cylinder, P_s, is defined by the manufacturer when the cylinder is designed. The defined service pressure for a given cylinder is specified by the cylinder type (strength and pressure range) and by the design code to which it is manufactured (e.g. DOT, ISO, other). Each of the design codes will define a different service pressure for a cylinder of the same diameter, thickness and material properties. Because the specific service pressure P_s is a calculated value using defined rather that measured values of cylinder diameter, cylinder thickness and specified minimum materials properties, there should be no uncertainty in this parameter. Therefore, the value of the type B standard uncertainty from this source may be taken as 0.

The leak-fracture boundary at a specified flaw length is used to estimate the fracture resistance of the cylinder. This parameter is estimated from the highest failure pressure that caused a leak and the lowest failure pressure that caused a fracture at the specified flaw length. In addition to the uncertainties in the measured failure pressure P_f, the leak-fracture boundary depends on how close together the measured leak pressure and fracture pressure are for the specific flaw length. In some of the test series, sufficient tests were conducted so that the value of the P_f for a cylinder that leaked and the P_f for a cylinder that fractured are close together and this boundary can be estimated quite accurately. The uncertainty in defining the leak-fracture boundary will vary for each test series and can only be evaluated on a case by case basis. The uncertainty in the definition of the leak-fracture boundary can often be reduced by repeating the tests until the difference between the highest failure pressure at which a leak occurs and the lowest pressure at which a fracture occurs is minimized. No general value of the uncertainty for defining the leak-fracture boundary that can be used for all cylinder tests can be established.

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1) Discontinued in 1997; replaced by E1737, *Test Method for J-Integral Characterization of Fracture Toughness* discontinued in 1998; replaced by E1820-01, *Standard Test Method for Measurement of Fracture Toughness*.

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