TECHNICAL REPORT

ISO/TR 12391-1

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2001-12-15

Gas cylinders — Refillable seamless steel — Performance tests —

Part 1:
Philosophy, background and conclusions

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

Partie 1: Philosophie, historique et conclusions

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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

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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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

ISO/TR 12391-1 was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 3, *Cylinder design*.

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

— *Part 1: Philosophy, background and conclusions*

— *Part 2: Fracture performance tests — Monotonic burst tests*

— *Part 3: Fracture performance tests — Cyclical burst tests*

— *Part 4: Flawed cylinder cycle test*

Introduction

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

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

This part of ISO/TR 12391 presents the philosophy and background information developed by WG 14 to study the problems inherent with steel of higher tensile strength. It also states the conclusions of WG 14, which were included in ISO 9809-2.

Gas cylinders — Refillable seamless steel — Performance tests —

Part 1:
Philosophy, background and conclusions

1 Scope

This part of ISO/TR 12931 applies to seamless steel refillable cylinders of all sizes from 0,5 l up to and including 150 l water capacity produced of steel with tensile strength (R_m) greater than 1 100 MPa.

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

2 References

ISO 6406.1992, *Periodic inspection and testing of seamless steel gas cylinders*

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*

3 Terms and definitions

For the purposes of this part of ISO/TR 12391, the following terms and definitions apply.

3.1
flawed cylinder burst test
test conducted on a finished gas cylinder having a deep prescribed flaw machined into the exterior sidewall and failed by internal pressurization

NOTE Pressurization can be hydraulic, applied either monotonically or cyclical. The flaw depth is in the range of 75 % of the cylindrical wall thickness.

3.2
flawed cylinder cycle test
test conducted on a finished gas cylinder having a shallow prescribed flaw machined into the exterior sidewall and failed by cyclical internal pressurization

NOTE Pressurization is normally hydraulic. The flaw depth is 10 % of the cylindrical wall thickness.

3.3
fracture performance
type of crack growth at the instant of through-wall failure, either by stable crack arrest or a running crack rupture, i.e. leak or fracture

4 Symbols and abbreviations

4.1 Symbols

d = artificial flaw depth (mm),

D = nominal outside diameter of cylinder (mm),

l_o = length of artificial flaw (mm),

P_f = measured failure pressure (bar),

P_h = hydrostatic test pressure (bar),

P_s = calculated design working pressure (bar),

t_a = actual measured wall thickness at the location of the flaw (mm),

t_d = calculated minimum design wall thickness (mm),

R_e = actual measured value of yield strength (MPa),

R_m = actual measured value of tensile strength (MPa)

4.2 Abbreviations

CVN = charpy V-notch impact test

KIC = keyhole impact charpy

LBB = leak before break fracture performance

UTS = ultimate tensile strength

NOTE In ISO/TR 12391-2[1)] this term is to be defined as either “leak” or “fracture”.

5 Background

5.1 Participation

In 1989 ISO/TC 58/SC 3 formed a working group (WG 14) to study the potential need for controls in excess of those in ISO 9809-1 for the manufacture and testing of steel cylinders with tensile strengths greater than 1 100 MPa. Extensive technical considerations were essential to the development of an ISO standard for the production of a new generation of cylinders using higher tensile strengths to assure safe performance during their service life. A primary concern was the potential fatigue crack failure mechanism.

Seven member nations provided one or more technical members who had expertise in the technology of seamless steel gas cylinders. These countries and companies are listed in Table 1.

1) In preparation.

Table 1 — List of participating countries

Country	Company	Status
Austria	J. Heiser	Producer
France	Air Liquide	User
	Valmont	Producer
Germany	Mannesmann	Producer
Japan	JISC	Regulator
	Sumikin Kiko	Producer
Sweden	AGA	User
United Kingdom	Chesterfield	Producer
USA	Norris Cylinder Co.	Producer
	Praxair	User
	Pressed Steel Tank Co.	Producer
	Taylor Wharton	Producer
	U.S. DOT	Regulator
	National Institute of Science & Technology	Technology

5.2 Essential cylinder safety controls

The working group first studied and debated which physical attributes of cylinders would vary because of higher tensile strength and therefore affect critical safety performance of the cylinders. The need for additional manufacturing tests to control the envisioned critical attributes were then considered. Figure 1 is a flow chart of the analysis procedure.

5.3 Safety controls

Each member nation presented a review of their existing control system for steels of various tensile strengths which were generally categorized by R_m as:

— below 950 Mpa;

— 950 to 1 100 Mpa;

— greater than 1 100 MPa.

Table 2 lists existing controls, which affect fracture performance, presented by Austria, France, Sweden, United Kingdom and USA in 1989. It was noted that these basic controls were similar in all nations and used traditional metallurgical factors. In 1989 only Austria and the USA had developed specific controls for steel with a tensile strength above 1 100 MPa.

In addition to the data given in Table 2, various experts put forth other considerations. Austria presented a procedure for predicting burst versus leak in a cycle/fatigue test. France presented the classic French burst test with a statistical time-history along with impact test data. Sweden stated that an increase in Charpy values would normally be required to assure adequate toughness at the increased strength level. The United Kingdom presented a concept of a hydro-burst test measuring total energy and presented a paper on that concept. Germany investigated the “Battelle Concept” and pointed out that those equations were only valid where the material exhibits ductile fracture behaviour, and the calculations are not applicable to brittle fracture or mixed fracture mode. The USA presented a procedure applied since 1985 for cylinders with tensile strength over 1 100 MPa, and test data from two manufacturers for the “Leak-before-break” (LBB) test concept on a pre-flawed cylinder.

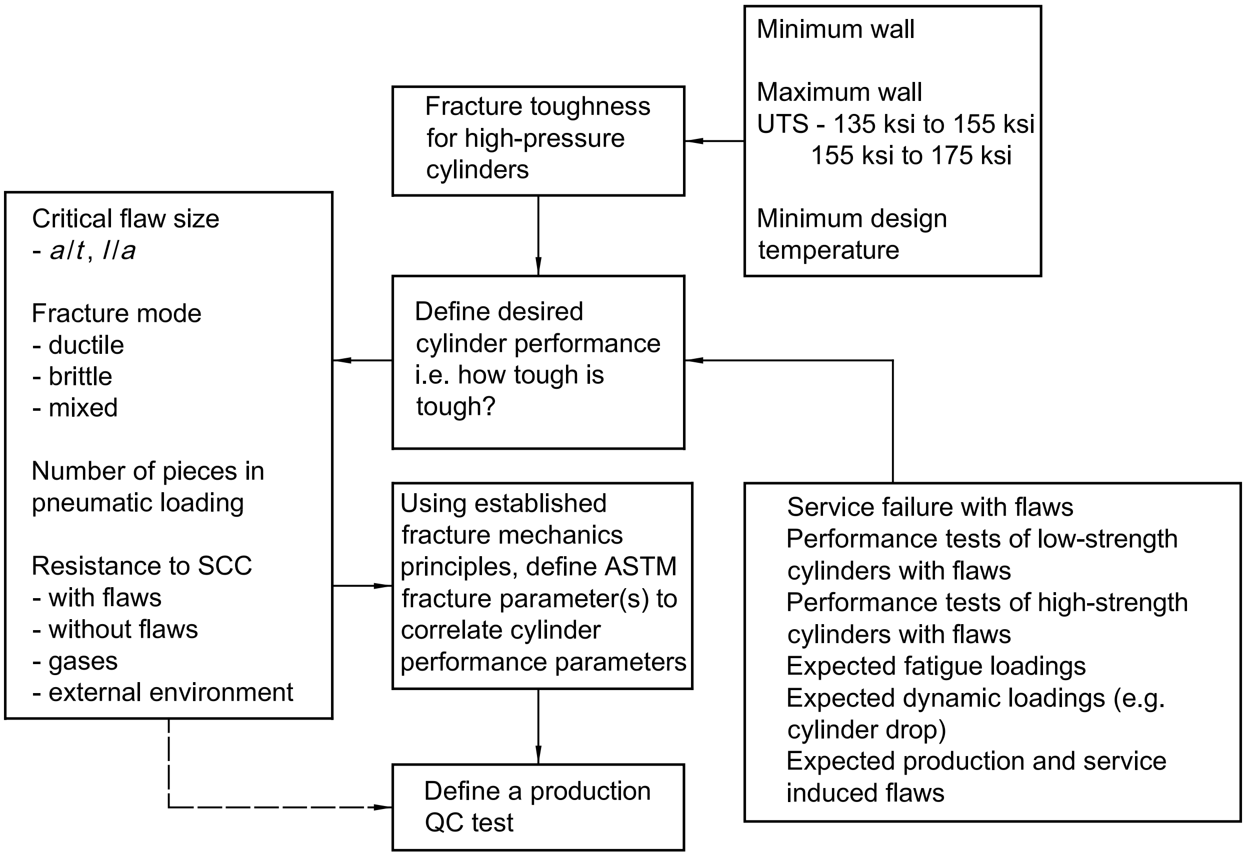


Figure 1 — Flow chart of issues, objectives and approach

It was concluded that the only significant change in cylinder performance at strength levels above 1 100 MPa would be the potential reduction in toughness because of the substantial increases in tensile strength. Consequently, it was agreed that the critical control factor required was "To develop toughness acceptance level and test procedures for steel used in the construction of seamless cylinders with tensile strength above 1 100 MPa to assure a fracture safe performance".

It was further agreed that current state-of-the-art control of fracture performance could be achieved by a flawed cylinder burst test and a Charpy V-notch test in the transverse direction at – 50 °C. An important consideration was to develop a test that tested the entire cylinder and not merely test samples taken from the cylinder wall.

At a later stage the work programme of WG 14 was extended to include a further test to control safe service performance and fatigue cycle life. As a consequence of this study, the flawed cylinder cycle test was adopted in ISO 9809-2.

Table 2 — Fracture control — Current practices — 1989

Control factor	Member nation and strength level											
	Sweden			France	Austria		UK			USA		
R_m (N/mm²)	< 950	950/1 100	> 1 100	All strengths	950/1 150	1 150	⩽ 1 030	⩽ 1 070	⩾ 1 100	⩽ 950 [a]	950/1 070	1 070/1 200
R_e/R_m	—	—	b	⩽ 0,9 for H_2 ⩽ 0,95 other	—	—	—	—	b	—	—	—
Elongation	14 %	14 % (ISO)	b	⩾ 16 % (5d gauge)	⩾ 14 % (ISO)	⩾ 12 % (ISO)	⩾ 14 % (ISO)	⩾ 14%	b	⩾ 20 % 2 in × 1,5 in gauge	⩾ 16 % 2 in × 1,5 in gauge	⩾ 12 % 2 in × 1,5 in gauge
Burst	P_b/P_h = NR	P_b/P_h ⩾ 1,6	b	P_b/P_h ⩾ 1,67	In accordance with ISO P_b = –	In accordance with ISO P_b = –	—	In accordance with ISO P_b = –	b	c	—	Flawed burst
Burst fracture appearance	NR	NR	b	Propagation into thicker section ⩽ 1,2 t	No limit on propagation length	No limit on propagation length	—	—	b	—	—	—
L/temperature	50/–50 °C	50/–50 °C	b	50/–20 °C	60/–20 °C	50/–20 °C	—	40/–20 °C	b	d	58/–18 °C	—
CVN (J/cm²) T/temperature	—	—	b	—	For t > 5mm 25/–20 °C	25/–20 °C	—	—	b	—	—	44/– 18 °C
KIC	—	—	b CVN <-->KIC	—	—	—	—	—	b	—	—	⩾ 85 Ksi

a USA limited R_m to 930 N/mm² for hydrogen and embrittling gases.

b No specific control.

c Burst test not required as production test; but US DOT requires maximum of 2,5 P_s (1,5 P_h) for standard 3A and 3AA.

d CVN not required as production test, however industry control limits are 51 J/cm², L at – 50 °C and average 102 J/cm², L at – 50 °C.

6 Considerations of fracture performance

6.1 General

WG 14 members conducted a series of tests on cylinders of different tensile strength levels. These included:

— all strength ranges of existing cylinders;

— existing cylinders re-heat treated to higher strength levels;

— cylinders with a tensile strength greater than 1 100 MPa.

Each cylinder test was to include:

— the flawed cylinder burst test;

— CVN impact tests transverse at – 50 °C;

— a standard tensile test.

Figure 2 shows the standardized test data report required to be used by each participant. By standardizing both the test methods and the required data collection report, the results of the tests performed at various locations were suitable for compilation, comparison and analysis.

A basic premise in studying the flawed cylinder burst test was that testing a finished cylinder under service stress conditions instead of testing samples extracted from a cylinder would be a far superior method to stimulate potential in-service failure due to cyclic fatigue.

Thirteen member companies performed the standardized tests and submitted the data via the standard report. More than 500 individual tests were performed and reported. The data resides in a "Data Bank" at National Institute of Science and Technology (NIST), Washington, DC, USA and is to be discussed in detail in ISO/TR 12391-2.

6.2 Fracture performance test programme

The intent of the test programme was to determine if the flawed cylinder burst test was adequate, as the primary control, to reliably predict fracture performance of steel cylinders, and to evaluate the Charpy V-notch impact test as a secondary control. Another test programme was conducted to evaluate fatigue cycle life of cylinders that were damaged externally during use.

The standardized test programme was designed to determine fracture initiation with leak or fracture performance, as a function of pressure and initial flaw size for a range of tensile strengths, wall thicknesses, and service pressures.

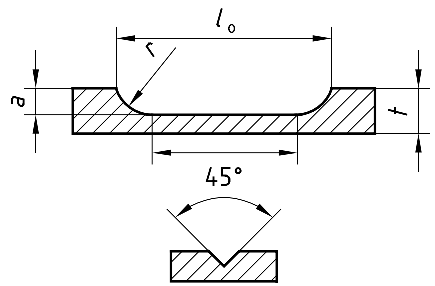
The extensive test data were analysed and reported both individually and collectively and were discussed and reviewed in detail over twelve meetings of WG 14. Data and analysis are discussed in clause 8 in order to demonstrate the procedures used to analyse the test as a control procedure. Actual test data and analysis is to be covered in ISO/TR 12391-2.

WG 14 concluded that data from participants are sufficiently consistent to demonstrate that the flawed cylinder burst test provides a major means to assess fracture performance of cylinders and reliably predicts fracture initiation, and that the Charpy V-notch impact test, conducted transverse to the major cylinder axis at – 50 °C, can be used in conjunction with the flawed cylinder burst test as a manufacturing control test system.

Report form for common cylinder data base

ISO/SC 3/WG 14 Fracture performance “Flawed Cylinder” Test report **Date submitted**____________

1.0	Cylinder description			1.7	Material type		
1.1	O.D.	230	mm		Cr-Mo	X	
1.2	Volume	50	l		C-Mn		
1.3	P_h	300	bar		Alloy		
1.4	Design t	4,5	mm		High C		
1.5	R_g	min.	max.	1.8	Design		
	MPa	1 100	1 160		Specification	X	
1.6	Type MFG				Experimental		
	Tube			2.0	Test details		
	Plate			2.1	Tested by	ABC	
	Billet	X		2.2	Test date	11/89, 3/90	
				2.3	Flawed cycle		Cutter: Standard CVN milling cutter
				2.4	Flawed burst	X	70 mm dia. 45°
				2.5	Specimen size tensile	ISO	Other dia. (mm) 80
				2.6	Specimen size impact	10 × 5,0	Other tip radius



Cycl. tests				Mechanical properties			Impact — CVN			Test results							Other data (if needed)			Comments
							Avg. 3 specimens			t	Flaw size		Failure data				Kt_{IC}	Sulfur	t_{avg} @ flaw circle	
				Tensile	Yield	Elong.	Temp.	Long.	Trans.	At flaw	Lenght	Depth	Pressure	Number of cycles	Mode					
L	#	#	#	MPa	MPa	%	(°C)	J/cm²	J/cm²	mm	nt	% t	bar	cycles	LBB	Frac.				
H	0	4	0	1 154A	1 087A	14,3	20	91	46	4,8	8,3	83,3	285	—	X					
							– 50	—	26											
H	0	4	1	1 122A	1 054A	15,3	20	103	68	4,8	7,0	93,8	280	—	X					
							– 50	—	42											
H	0	4	2	1 135A	1 072A	15,2	20	96	53	5,0	10,0	90,9	265	—	X					
							– 50	—	39											
H	0	4	3	1 128A	1 060A	14,4	20	97	55	5,0	10,0	85,0	273	—	X					
							– 50	—	38											
H	0	4	4	1 135A	1 070A	14,0	20	95	53	5,0	10,0	80,0	267	—	X					
							– 50	—	38											
H	0	4	5	1 112A	1 042A	15,6	20	105	56	5,0	10,0	75,0	295	—		X				
							– 50	—	46											
H	0	4	6	1 136a	1 063a	14,0	20	93	56	5,1	10,0	70,6	312	—		X				
							– 50	—	36											
H	0	4	7	1 117a	1 052a	15,3	20	99	57	5,2	10,0	76,9	290	—		X				
							– 50	—	38											
H	0	4	8	1 124a	1 060A	14,4	20	102	61	5,1	10,0	71,6	320	—		X				
							– 50	—	43											
H	0	4	9	1 127A	1 059A	14,0	20	103	59	5,1	10,0	67,6	345	—		X				
							– 50	—	44											

Figure 2 — Sample of standardized test report

7 Flawed cylinder burst test procedure

This test is required as both a design approval test and a production lot test in 9.2.5 of ISO 9809-2:2000. The following are the important requirements developed by WG 14 to finalize the test procedure. The intent is:

— to test a complete cylinder;

— to machine a standard exterior surface flaw;

NOTE 1 Production of a standard internal flaw is not practical; tests showed that use of an exterior flaw on “thin walls” is reliable.

— to machine the flaw by a standard CVN cutter and require a flaw to be about 10 × wall thickness in length; such cutters are available worldwide;

NOTE 2 Fatigue cracks are assumed to be ellipsoidal in shape with a 2:1 length to depth ratio. Specifying a flaw of considerably greater length represents an additional safety factor to compensate for variables such as exterior flaw and notch versus crack.

— to machine the flaw at a location of probable maximum stress under gas loading; i.e. longitudinal flaw at mid-length and at thinnest wall at mid-length;

— to machine the flaw depth so that failure of the remaining ligament would occur at not less than the wall stress at service pressure based on the actual wall thickness at the crack location;

NOTE 3 The intent is that failure of the ligament occur at or above the maximum wall stress, which would develop if the cylinder was being filled with gas. Retesting is allowed if ligament failure occurs below service pressure, i.e. retest with a less deep flaw.

— To pressurize hydrostatically, either monotonically or cyclical;

NOTE 4 The stress required to fracture the ligament will not vary with the type of pressurizing medium and therefore water can be used, which is more efficient, simplifies the test and is safer at the test site. Tests conducted using nitrogen gas demonstrated this fact.

— to demonstrate that a growing fatigue crack in a finished cylinder would fail by leakage and not by a running crack (fracture);

NOTE 5 Measurement of the length of the failure crack on the external surface was desired for a practical manufacturing lot acceptance test and so, in the definition a visual external extension beyond the machined notch in the longitudinal direction is allowed because of physical distortion at the notch ends.

8 Considerations of fatigue cycle test

8.1 General

When cylinders of the high strength type were placed into service there were concerns about the effect of damage on cycle life during use. WG 14 was assigned to consider this matter in conjunction with the fracture performance work. WG 14 observed that an ultrasonic inspection was required for each cylinder at the time of manufacture, and that the flaw detection sensitivity of that inspection was limited to 5 % of wall thickness. Therefore, flaws developed by service abuse would not be of concern unless the flaws were deeper than 5 % of the wall thickness.

It was observed that during periodic inspection, defects such as “cuts and gouges” are acceptable provided the depth does not exceed 10 % of the wall thickness (see ISO 6406). It was considered necessary to further investigate cylinders of higher tensile strength with such flaws in order to guarantee safe service conditions. In view of these facts, WG 14 concluded that a simulated exterior surface flaw of the same type as used for the flawed cylinder burst test, but with a smaller depth, would be appropriate for evaluation of the effect of service induced flaws on fatigue cycle life.

WG 14 agreed that a test programme of fatigue cycle life would be conducted on both 200 bar and 300 bar cylinders (i.e. R_m of 950 MPa and 1 100 MPa respectively) with flaw depths of 5 % and 10 % of wall thickness. Cylinders from the first series of tests did not fail at the 5 % machined flaw but failed elsewhere at normal manufacturing irregularities. Therefore testing artificial flaws at 5 % wall depth was abandoned. Seven cylinder manufacturers conducted standardized flawed cylinder cycle tests with a machined flaw depth of 10 % of wall thickness and a length of approximately 10 × wall thickness.

For additional technical collaboration, a study was made entitled "*Theoretical Study of Comparative Cycle Life of Cylinders of Two Steel Strength Levels*" using the cylinder fatigue test data submitted by various WG 14 members. The theoretical study included work at Powertec Laboratory entitled "*Fatigue Crack Growth Calculations for a High Pressure Steel Cylinder*", in which calculations included the effect of crack-tip blunting produced by application of the hydrostatic retest pressure periodically. These studies were used as background on fatigue cycle life for establishing acceptance criteria.

For specifying the acceptance criteria in ISO 9809-2 it was taken into consideration that some cylinders can be filled rather frequently (e.g. once per day). The cycle life of a cylinder having an acceptable defect at manufacture, as mentioned above, shall therefore withstand an average of 3 500 cycles within a ten year re-testing period (i.e. 350 fills × 10 years). In addition, for the purpose of this testing it was assumed that the absolute maximum developed pressure in a cylinder can be up to test pressure. Therefore, this pressure level was chosen for the flawed cylinder cycle test.

8.2 Flawed cylinder cycle test

Part 2 of ISO/TR 12391 is intended to provide the results of the test programme carried out to evaluate the cycle life of steel cylinders with tensile strength greater than 1 100 MPa. In view of the known reduction in cycle life as tensile strength increases, this test was added to ISO 9809-2 as a design approval test. The procedure is specified in 9.2.6 of ISO 9809-2:2000.

9 Discussion of test data

9.1 Flawed cylinder burst test

The test data and detailed analysis thereof are contained in ISO/TR 12391-2. The following discussion is provided to demonstrate the philosophy and conclusions of the work by WG 14.

Several hundred flawed cylinder burst tests were conducted. The cylinders were of the five tensile strength categories given in Table 3.

Group A represent low strength cylinders in use since 1910. Groups B and C represent existing cylinders which have been in use since about 1950 and provide a comparison of proven fracture safe performance. Group D represents ISO 9809-2 cylinders. Group E are experimental cylinders to demonstrate effects of steel metallurgical improvements on Group D cylinders.

Table 3 — Flawed cylinder burst tests

Material group	**Ultimate tensile strength category** (UTS)
A	UTS < 750 MPa
B	750 MPa ⩽ UTS < 950 MPa
C	950 MPa ⩽ UTS < 1 080 MPa
D	1 080 MPa ⩽ UTS < 1 210 MPa
E	UTS > 1 210 MPa

The basic philosophy of this test and the test procedure were gradually refined as data was obtained, studied and discussed. A starting philosophy was that the maximum probable filling pressure at the instant of fatigue break-through would be the pressure reached during filling, (P_s), that the probable site of break-through would occur at the actual minimum thickness probably at mid-length (t_a), that the stress at service pressure (P_s) could be calculated per the ISO design formula and that P_s could be adjusted by the ratio of design thickness to actual thickness; or ($P_s \times t_a/t_d$). The data were plotted for various lengths of the standard machined flaws.

The data were also plotted without the t_a/t_d adjustment. Comparison showed that adjustment for actual thickness significantly improved the prediction of failure pressure. The goal was to have P_f/P_s equal to or greater than 1, i.e. failure greater than service pressure. It was considered important, philosophically, to require failure by leakage and not by fracture at or above filling pressure, which is the maximum pressure when personnel are near the cylinder. It was also considered appropriate, technically, to require proof of LBB performance at pressures where the stress would be in the fully elastic range. Failure at a pressure well above P_s may not be fully elastic, but would be in the plastic range.

Examination of the data showed that the desired LBB (fracture) performance was achieved with current design cylinders at a crack length of 10 × design wall thickness. The data showed equivalent performance for cylinder designs with R_m greater than 1 100 MPa. The data also shows that cylinders with a thinner wall exhibited greater toughness by this measurement, just as theory predicts. This further validated the proposed test. The fact that toughness varies with wall thickness, because of quench effectiveness, is the reason for limiting the upper value for wall thickness because this test series did not include cylinders with t_d greater than 12 mm. A series of tests by France proved that cylinder diameter did not affect the P_f/P_s failure ratio.

The calculated P_s is the maximum working pressure that can be marked on finished cylinders in accordance with ISO 9809-1 and ISO 9809-2 and is based on the guaranteed minimum tensile strength, diameter and wall thickness with calculation by the ISO design formula.

It should be noted that a cyclic fatigue crack has a normal elliptical shape where length is twice the depth. Requiring no fracture within 10 % flaw length provides a significant additional factor of safety. An interesting corollary report from France concerning sulfur content and special calcium inclusion shape control treatment demonstrated the improvement in CVN impact values by controls specified for steels with R_m greater than 1 100 MPa, see Figure 3. Sulfur content in the range of 0,005 % instead of the previous specified limit of 0,045 % resulted in, a 50 % increase in CVN values. The calcium inclusion shape control resulted in a further increase of 100 %. These two metallurgical controls were incorporated into ISO 9809-2, and provide assurance that the fracture toughness will be enhanced over current designs such as specified ISO 9809-1.

9.2 Charpy V-notch impact test

The Charpy V-notch impact test was in common use for testing steel gas cylinders at the time of manufacture and was required by national specifications in several countries. Therefore, CVN tests were conducted on the test cylinders to compare CVN results with the flawed cylinder burst test. The data showed that CVN tests transverse to the longitudinal axis conducted at – 50 °C were indicative of fracture performance. It was found that when such CVN results exceeded certain values the cylinders would pass the flawed cylinder burst test. Likewise, when the CVN results were below those values, the cylinders would not pass the flawed cylinder burst test.

In view of these findings, ISO 9809-2 requires the flawed cylinder burst test for prototype design testing and allows use of either that test or Charpy V-notch, transverse at – 50 °C for production lot control.

9.3 Flawed cylinder cycle test

Seven companies conducted the series of tests on 200 bar and 300 bar cylinders with machined flaws. The results of this test programme are given in ISO/TR 12391-2.

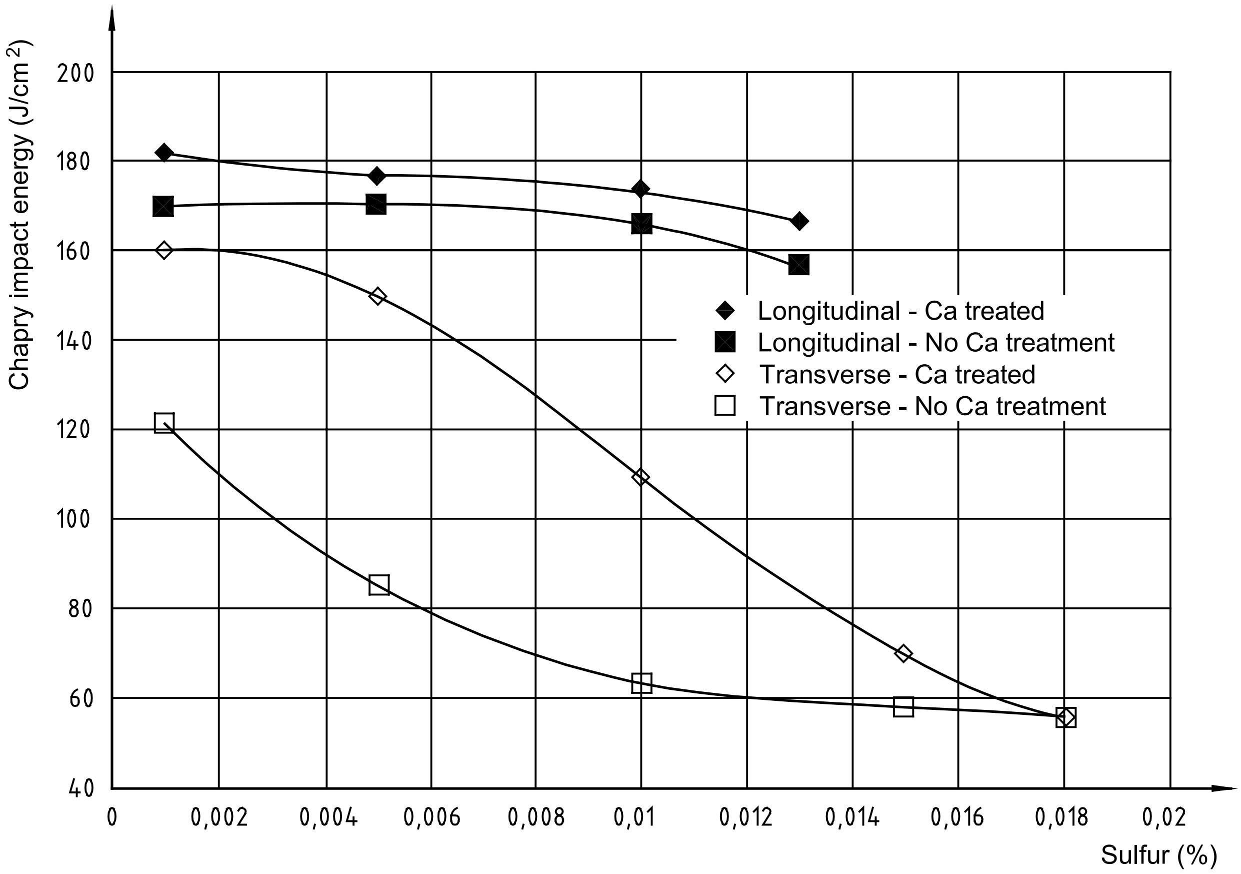


Figure 3 — Charpy impact versus sulfur content

Bibliography

NOTE The following is a list of "Reference papers" prepared by members of WG 14. Most of these papers were not published for general distribution but were for Working Group use. This is not a complete list of all of the analysis papers but is representative of the extensive efforts expended on these new technological developments. Copies of these reports may be obtained from the listed source for those interested in further study of thus subject.

[1] U.S. *Experience with High-Strength Steel Cylinder Design Using* $K1_c$ *(J) Properties*, M. Rana, Union Carbide Industrial Gases, Inc., October 1989, unpublished

[2] *Investigations into the Hydraulic Burst Test as a Means of Assessing Toughness Properties of Seamless Steel Gas Cylinders*, J. Walters, Chesterfield Cylinder Company, October 24, 1990, unpublished

[3] *Proposal for a Gas Cylinder Fracture Toughness Test*, J. Walters, Chesterfield Cylinder Company, October 1990, unpublished

[4] *Results of flawed burst tests*, C. Düren and G. Junker, Mannesmann Röhrenwerke, June 26, 1991, unpublished

[5] Supplement to above Report, October 1991, unpublished

[6] *ISO Data Analysis Graphs using Minimum Specified UTS and Minimum Specified Wall for B, C and D Materials*, M. Rana, Union Carbide Industrial Gases, Inc., Sept. 24, 1991, unpublished

[7] *Effect of Hydrostatic Retest on the Fatigue Behavior of a Steel Gas Cylinder*, G. Bhuyan, A. Akhtar and C. Webster, Powertec Labs., Inc. Transactions of the ASME, Nov. 1991, Vol. 113,556

[8] *Fatigue Crack Growth Calculations for an ISO HP Steel Cylinder*, G. Bhuyan, Jan. 14, 1992, unpublished

[9] *A Case Study in relation to European Standardization — Safety concept for Seamless Steel Gas Cylinders*, H. Brühl-Schreiner, K. Busch, C. Düren and K. Markhoff, Vulkan-Verlag, May, 1992

[10] *Flawed Cylinder Cycle Test — Fatigue Data*, M. Rana, June 9, 1992, unpublished

[11] *Toughness Requirements and Determination in High Strength Steel Gas Cylinders*, J. Walters, Chesterfield Cylinders Limited, October 5, 1992, unpublished (ECMTG Paper No. 76/92)

[12] *Data Analysis of Flawed Cylinder Burst Test Failure and Ratios and Fracture Area*, A. Mallen, Norris Cylinder Company, Dec. 22, 1992 and Feb. 10, 1993, unpublished

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