TECHNICAL REPORT

ISO/TR 13086-1

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Gas cylinders — Guidance for design of composite cylinders —

Part 1: Stress rupture of fibres and burst ratios related to test pressure

Bouteilles à gaz — Directives pour la conception des bouteilles en matière composite —

Partie 1: Fracture sous contrainte des fibres et indice d'éclatement relatifs à la pression d'essai

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Foreword

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

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

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

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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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

ISO/TR 13086-1 was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 3, *Cylinder design*.

Introduction

Composite reinforced cylinders have been used in commercial service for about 40 years. In the first years of use, glass fibres were the reinforcement of choice. Design guidelines, including safety factors, were established when these cylinders were first developed.

Additional fibres for reinforcing composite cylinders have become available in following years, including aramid and carbon. Different design configurations have been established over the years, including hoop wrapped, full wrapped with a metal liner, and full wrapped with a non-metallic liner. Different applications have developed, including breathing cylinders, emergency inflation cylinders, fuel tanks for vehicles powered by compressed natural gas or hydrogen, accumulators, and many other uses.

Standards for these composite cylinders have developed in different ways. Some are design based, others are performance based. Some were developed for a single fibre or application. Some of these have remained static, while others evolved as materials and designs changed. Other standards were developed with a broad scope of materials and applications. Safety factors have been treated differently in these different standards.

The entire industry, including manufacturers, customers, and regulatory bodies, would benefit from a cohesive foundation of the technical issues from which safety factors for composite cylinders are developed, so that a consistent approach to safety factors is taken in composite cylinder standards. The elements of foundation currently exist, but need to be collected and organized for maximum benefit. This foundation will also serve as a base for evaluating new materials, designs, and applications that develop in the future.

A foundation of the technical issues supporting safety factors for composite cylinders will be built under this part of ISO/TR 13086. Elements involving the composite cylinder materials, designs, and applications will be incorporated. This Technical Report will be updated with additional topics periodically and can be referenced in the development of standards for composite cylinders.

Gas cylinders — Guidance for design of composite cylinders —

Part 1: Stress rupture of fibres and burst ratios related to test pressure

1 Scope

This part of ISO/TR 13086 gives guidance for the design of composite cylinders, relating to stress rupture reliability and burst ratio as a function of test pressure. Related issues, such as cyclic fatigue of the liner and composite, damage tolerance, environmental exposure, and life extension will be addressed in subsequent parts.

The topics covered by this part of ISO/TR 13086 are to support the development and revision of standards for fibre composite reinforced pressurized cylinders.

2 Normative reference

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10286:2007, *Gas cylinders — Terminology*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10286:2007, Annex A, and the following apply.

3.1
autofrettage pressure
pressure to which a metal lined composite pressure vessel is taken, prior to the test pressure cycle, in order to yield the liner, and therefore establish a compressive stress in the liner at zero pressure

3.2
burst ratio
the ratio of the minimum required burst pressure and the working pressure

3.3
stress ratio
the ratio of the minimum strength of the fibre, as determined through burst testing of a pressure cylinder, divided by the stress in the fibre at working pressure

3.4
stress rupture
phenomenon by which a reinforcing fibre can fail under an applied tensile load over time, and is dependent on the stress level

NOTE Temperature level can affect stress rupture as predicted by the Arrhenius rate equation. Resin properties can affect stress rupture. If the temperature level of the resin exceeds its glass transition temperature, this can also affect stress rupture.

4 Factors of safety related to stress rupture

4.1 General

This clause addresses stress rupture and related reliability for composite cylinder reinforcements, including glass, aramid (aromatic polyamide), and carbon fibres. Stress rupture is directly related to stress in the fibre. Stress in the fibre is related to pressure in the cylinder, but not necessarily linearly.

Stress rupture, which is the possibility that the reinforcing fibre fail under continuous loading, will be addressed as a function of the reinforcing fibre, including glass, aramid (aromatic polyamide), and carbon fibres. Reliability versus time under load will be addressed.

The term “safety factor” has more than one meaning. It is often used to be the ratio of the burst pressure to the working pressure or to the maximum expected operating pressure. It may also be used as the ratio between any ultimate failure level compared with an operating level, such as with cyclic fatigue of a liner or of the composite reinforcement.

4.2 Stress ratio

The term “stress ratio” is often used with composite pressure vessels to address a fibre characteristic known as stress rupture. Stress ratio is the ratio of the minimum strength of the fibre, as determined through burst testing of a pressure cylinder, divided by the stress in the fibre at working pressure.

Stress ratio has more validity than a burst ratio in predicting reliability associated with stress rupture. The difference in the ratios occurs because in composite cylinders with metallic liners, the load sharing between the composite and liner is not linear with pressure. In these vessels, the stress ratio, and therefore reliability prediction, can be affected by variables including the liner and fibre modulus of elasticity, liner and fibre thickness, liner yield strength, and autofrettage pressure.

As an example, consider a Type 3 cylinder with a load sharing liner. The cylinder is first subjected to an autofrettage cycle, which yields the liner, and puts it in compression at zero pressure. The composite, therefore, will have some pre-load that is added to the stress at working pressure. As the cylinder is taken up to burst pressure, the liner yields above the autofrettage pressure, therefore the composite takes a higher percentage of the added load. The end result is that stress ratio and burst ratio will not be equal. Calculation of stress versus load is necessary in order to meet stress ratio requirements. Note that for a cylinder with a non-loadsharing liner, the stress ratio and burst ratio are equal.

Stresses may be calculated by finite element analysis that incorporates material non-linearities, or by closed form analysis that accounts for material non-linearities. Alternatively, strains can be verified using strain gages on the composite in accordance with the guidelines in ISO 11439:2000, Annex G [1]. See Annex A.

Table 1 lists stress ratios commonly used in newer composite standards that consider stress rupture reliability for the various reinforcing materials and configurations used in the cylinder standards. These stress ratios are intended to provide a reliability of 0,999999 over the cylinder lifetime; that is, less than 1 failure in 1,000,000 cylinder lifetimes. Other standards may use higher stress ratios or safety factors, in part to address damage tolerance, environment, or unknown issues.

Table 1 — Fibre Stress Ratios to achieve 0,999999 reliability

Fibre Material	Hoop Wrapped, Metal Lined (Type 2)	Fully Wrapped, Metal Lined (Type 3)	Fully Wrapped, Non-metal Lined (Type 4)
Glass	2,65	3,50	3,50
Aramid	2,25	3,00	3,00
Carbon	2,25	2,25	2,25

NOTE 1 Values of 2,35, 2,35, and 2,75 are used on carbon, aramid, and glass respectively for Type 2 cylinders in standards for CNG where settled temperature is 15 °C.

NOTE 2 Values of 2,35, 3,1, and 3,65 are used on carbon, aramid, and glass, respectively, for Types 3 and 4 in some standards for CNG where settled temperature is 15 °C.

NOTE 3 Values of 2,00 are used for carbon for Types 2, 3, and 4 in ISO/TS 15869 for pressures greater than or equal to 350 bar.

Standards that use these stress ratios include ISO 11439, ECE R-110, ISO/TS 15869, ANSI/CSA NGV2, CSA B-51 Part 2, ASME Section X Class III, and KHK Technical Standard #9.

4.3 Field experience and background

Metal pressure vessels have historically had a 2,25-2,5 burst ratio for high pressure transportable cylinders. Burst ratios in this range addressed margins for overfilling, temperature compensation during fill, material variability, and strength loss due to corrosion.

As glass reinforcing fibres were being introduced for use in pressure vessels, stress rupture was investigated. A higher stress ratio was required for glass fibre reinforced cylinders in order to provide adequate reliability and avoid stress rupture.

A higher stress ratio for glass fibre solved the problem with stress rupture, and the resultant thicker wall also provided good damage tolerance and durability. Several million glass fibre reinforced cylinders with the higher stress ratio are in service worldwide and have an excellent safety record.

When aramid fibres were introduced, they were used in cylinders almost immediately because of their lower weight. Today, the characteristics of aramid fibres are well understood, and lower stress ratios than glass are accepted and appropriate for many applications.

The use of carbon fibre as a reinforcing material for composite pressure vessels grew significantly in the early 1990's, and it was recognized that carbon fibre had superior stress rupture characteristics, allowing safe reductions in stress ratios.

However, specifying a stress ratio only addresses stress rupture and cyclic fatigue of the reinforcing materials. It is also necessary to specify testing which reflects the environment to which the pressure vessel is exposed. The environmental conditions should address temperature extremes, fluid and chemical exposure, and mechanical damage, at a minimum.

4.4 Stress rupture test programs

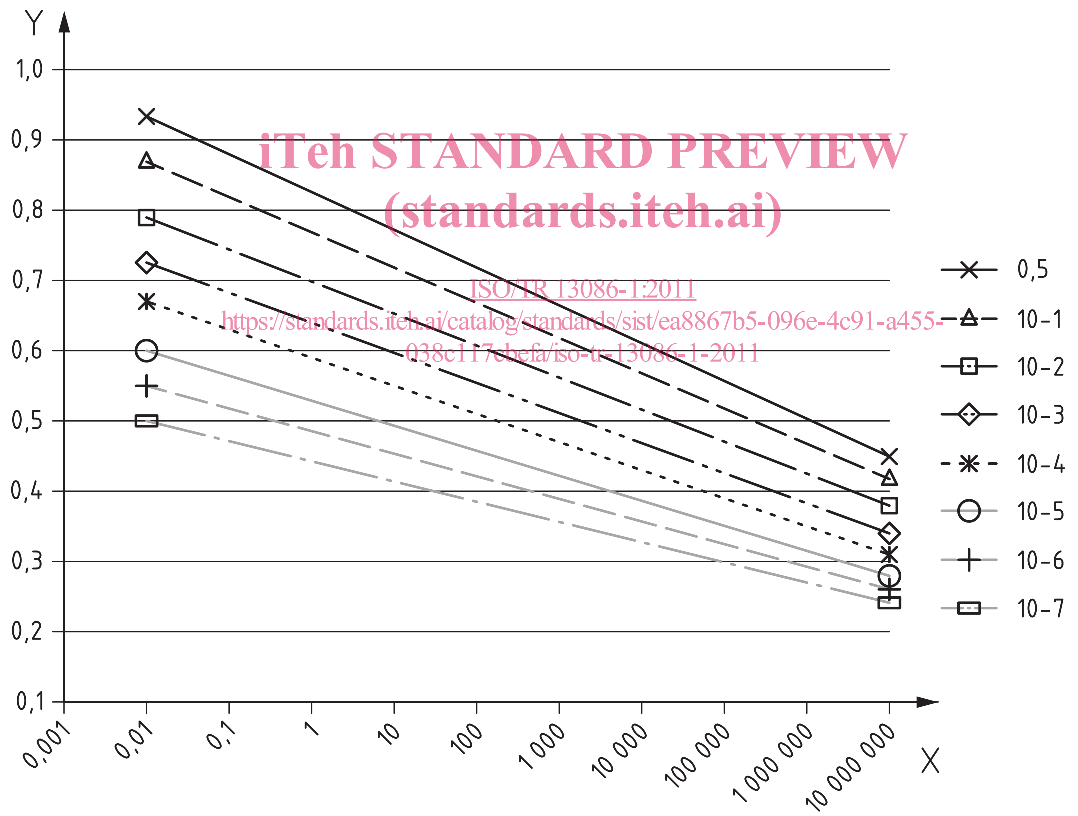
Test programs evaluating the stress rupture characteristics of glass, aramid, and carbon fibres were conducted [8][9][10][11][12][14]. These references discuss the background of the test programs, offer assessments of reliability, and discuss issues related to the results. Robinson [13] presents an analytical basis for comparing the reliability of the various fibres.

The reliability for glass, aramid, and carbon fibres, when used at the stress ratios given in Table 1, will all be greater than 0,999999 over the lifetime specified for composite pressure vessels (15-30 years) when held at the rated working pressure (see Figures 1, 2, and 3). The risk of a pressure vessel failing due to stress rupture is less than 1 in a million over its lifetime.

It is seen that carbon fibre is far superior to glass fibre in stress rupture using Robinson's evaluation. If the fibres were stressed to 80 % of their average ultimate strength, glass fibre would have a typical lifetime of about 1 hour, while carbon fibre would have a typical lifetime of over 1 million years. The stress rupture reliability for carbon fibres can be equal to or greater than that for glass or aramid fibre even at a lower stress ratio.

These fibres behave differently because they are fundamentally different materials. Glass is a super-cooled liquid, and is subject to creep flow and surface cracking. Aramid fibre is a long chain polymer, which can be stretched and broken under load. Carbon fibre is more crystalline in nature, and is relatively insensitive to creep or surface cracking.

Investigators of stress rupture characteristics of glass fibre include Outwater [8] and Glaser, Moore, and Chiao [9]. The data presented by Outwater was of relatively short duration. The data presented by Glaser, Moore, and Chiao of Lawrence Livermore National Laboratory (LLNL) was gathered over a longer period of time on impregnated strands under constant load. This study was interrupted after about 10 years by an earthquake, and there was some evidence of UV light influence on the specimens later in the study. Robinson [13] evaluated the data from LLNL with results as shown in Figure 1.



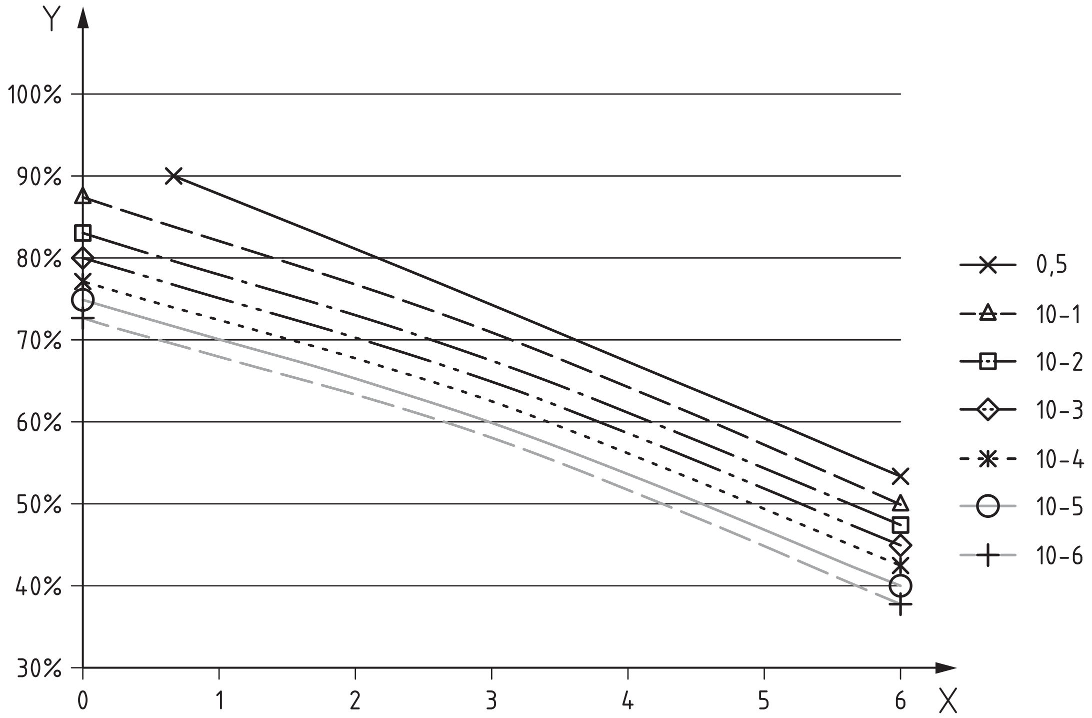
Key

X time, hours

Y load fraction of median strength

Figure 1 — Glass Composite Strand Stress Rupture Design Chart

Investigators of stress rupture characteristics of aramid fibre include Glaser, Moore, and Chiao [10]. This data included some specimens that were influenced by UV light, and some that were kept in darkness. Both strands and pressure vessels were included in the testing program. Figure 2 shows that the stress rupture characteristics of aramid fibre are better than those of glass fibre.



Key

X estimated lifetime, Log (h)

Y UTS %

Figure 2 — Maximum likelihood estimates of lifetimes of aramid/epoxy for vessels, with quantile probabilities

Investigators of stress rupture characteristics of carbon fibre include Shaffer [14], Babel, Vickers, and Thomas [11], and Chiao, Chiao, and Sherry [12]. Robinson [13] evaluated the data from Shaffer with results as shown in Figure 3. The data from Shaffer is conservative to the extent that the tests were conducted at elevated temperature, which would accelerate the stress rupture phenomenon. Figure 3 shows that the stress rupture characteristics of carbon fibre are superior to those of glass and aramid fibre.

