TECHNICAL
REPORT

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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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

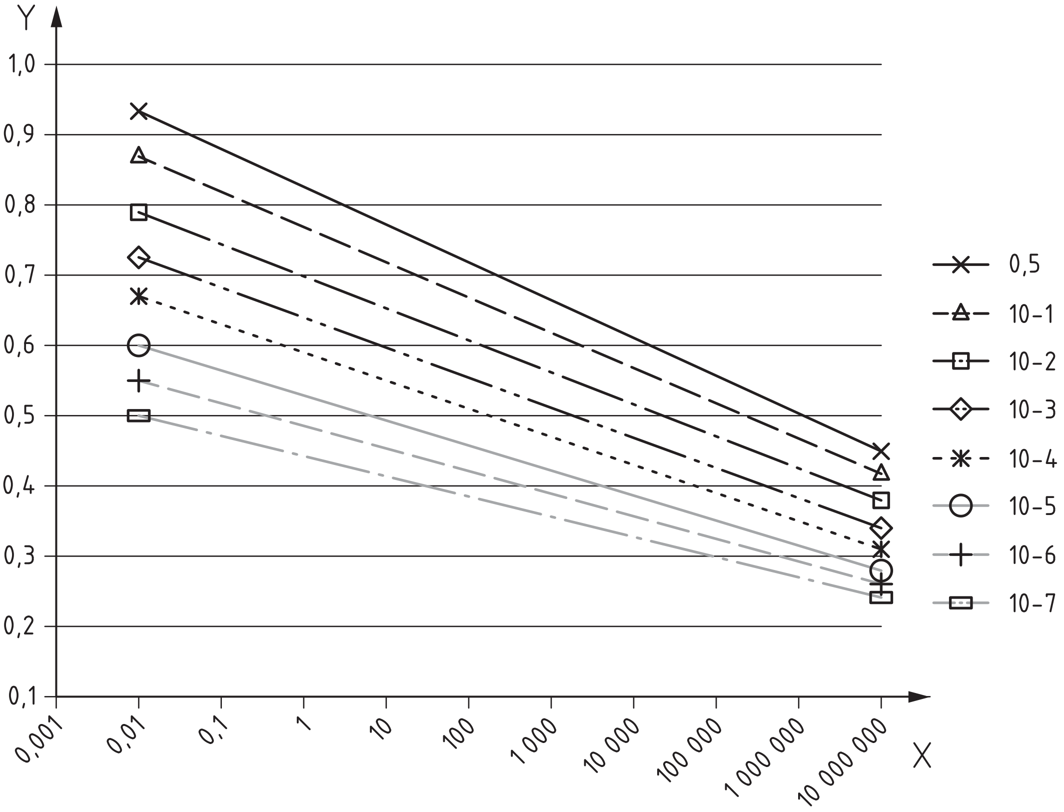
Test programs evaluating the stress rupture characteristics of glass, aramid, and carbon fibres were conducted [8][9][10][11][12][14]. These references discuss the background of the test programs, offer assessments of reliability, and discuss issues related to the results. Robinson [13] presents an analytical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



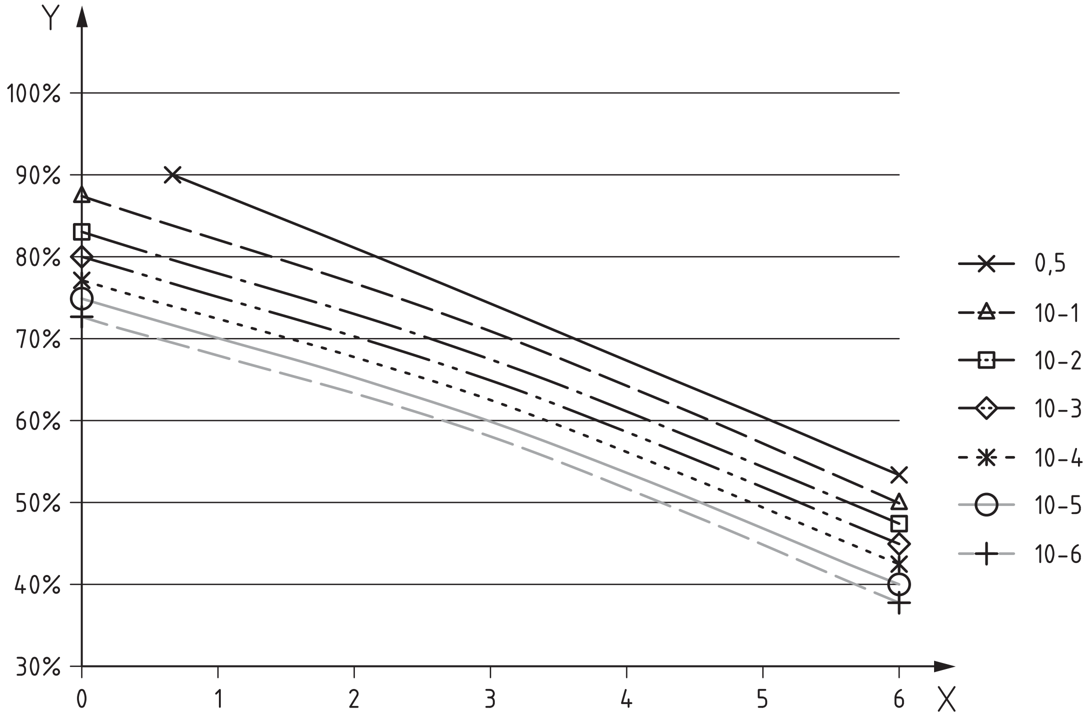
Key

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.



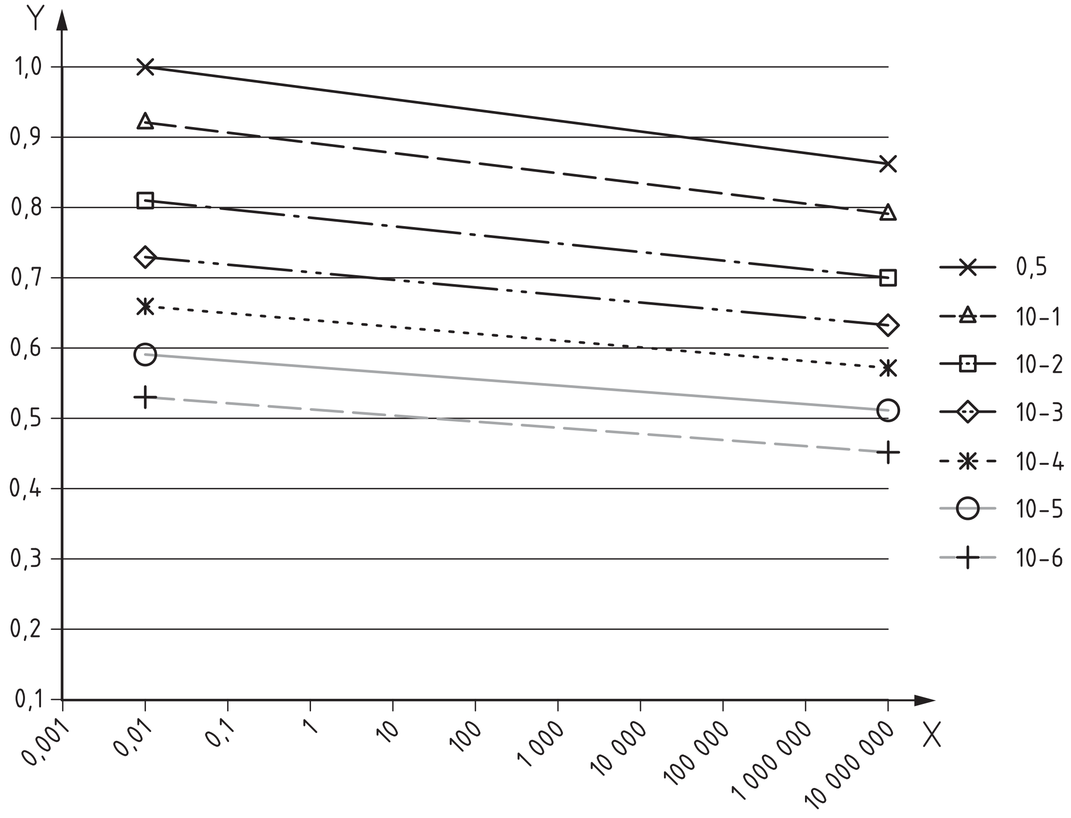
Key

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.



Key

X time, hours

Y load fraction of median strength

Figure 3 — Carbon Composite Strand Stress Rupture Design Chart

The stress ratios given in Table 1 are conservative based on the data presented in Figures 1, 2, and 3. These figures are based on the mean burst pressure of representative cylinders. The stress ratios are applied on the minimum burst pressure for a cylinder design. For normal distribution of burst pressure, this may result in mean burst pressure being 10 to 15 percent higher than the minimum required burst pressure.

At the reliability levels projected by this analysis, the incremental risk from one year to the next is close to linear. Therefore, if the cylinders were left in service for an extra year or two, the incremental risk is not significantly greater than for an earlier year. However, it is critical that cylinders be inspected on a regular basis, and damaged cylinders removed from service.

4.5 Stress rupture field experience

Laboratory testing and field experience have provided validation for the stress rupture studies and predictions provided above. There have been a very limited number of stress rupture failures in the field. The failures that have occurred have generally been as a result of either damage to the pressure vessel or overfilling.

There have been a limited number of glass cylinder failures in the field. However, most have been traced to field damage or quality problems during manufacture. A limited number of cylinders have failed on military aircraft. These cylinders had a lower stress ratio than used in commercial service, and the cylinders were left in service beyond their rated life. Their rupture times, given the number of cylinders in service, were in reasonable agreement with stress rupture predictions for glass fibre.

There was a study conducted at Lewis Research Center involving glass fibre reinforced cylinders with load-sharing aluminum liners that were in an outdoor environment, with full exposure to temperature extremes, −26 °C to 43 °C (−15 °F to 110 °F), and ultraviolet light, and periodic pressure cycles, which degraded the vessel strength [15]. One tank failed after 8,5 years.

No aramid fibre reinforced pressure vessels are known to have failed in service due to stress rupture.

A set of 10 aramid reinforced spherical pressure vessels were provided to NASA/Johnson Space Center for extended fatigue testing [16]. These vessels were being tested as “fleet leaders” in regards to similar vessels being used aboard the Space Shuttles. These vessels had been held at 50 percent of their average ultimate strength under elevated temperature conditions in Houston. One of the vessels held at elevated temperature failed in 1995, after about 12 years in test. Using an Arrhenius rate equation, with a doubling of activity for each 10 °C (18 °F) temperature rise above ambient, this correlates to a 700 year life at ambient temperature with a stress ratio of 2,0. This result is consistent with predictions from stress rupture models.

No carbon fibre reinforced pressure vessels are known to have failed in service due to stress rupture. Fleet leader testing programs are under consideration.

4.6 Other discussion

Hybrid construction, using more than one fibre, is allowed in standards. These are often classified as either load sharing, or non-load sharing hybrids. In a load sharing hybrid, both materials are able to meet the defined stress ratio requirements. Therefore, high reliability is assured. If one of the two materials does not meet stress ratio requirements, it is at risk of failing over time. Its load would then shift to the primary material over time, which could overload it and thereby cause it to fail. To avoid this, there must be enough of the primary material that it could meet its stress ratio requirements even if the other material were removed, thereby assuring high reliability.

The stress rupture studies evaluated the data using a Weibull distribution. Tests have been conducted at pressure levels from about 50 percent up to about 97 percent of the average ultimate strength. While it is possible to get failure of glass or aramid fibres at the lower end of this test range, the lowest load level for which carbon fibre stress rupture data has been generated is 80 percent. This is due to the superior stress rupture properties of carbon fibre, as tests at lower levels would require testing for times greater than the service life of the cylinders.

The use of higher pressure to accelerate stress rupture testing may be overly conservative in terms of the shape factor alpha (α) of the Weibull distribution [17]. Testing has indicated that the alpha factor for glass and aramid fibre increases as the load level decreases. With no data at a lower load level, the alpha used in the Weibull analysis of carbon fibre stress rupture has been maintained so as to yield conservative results.

Elevated temperature has also been used to accelerate testing. The Arrhenius rate equation relates molecular activity increase to temperature increase. Stress rupture was confirmed to be subject to the Arrhenius rate equation on aramid fibre by C.C. Chiao of LLNL, and is expected to apply similarly to glass and carbon fibre. Elevated temperature was used to accelerate testing in the NASA program [16] mentioned above.

The use of elevated temperature to accelerate testing must be done with some caution. If the strength of the fibre being tested is significantly affected by temperature, or if the temperature exceeds the glass transition temperature of the resin matrix, there must be additional efforts to correlate the accelerated testing to ambient results. This is also true if the elevated temperature causes thermal stresses in the composite, which particularly can occur when a metal liner is used.

4.7 Summary

There have been studies of stress ratios as they relate to reliability of composite reinforcing fibres as it relates to stress rupture. The results of these studies have been used to validate stress ratios used in several national and international standards. The safety record of cylinders built to the stress ratios given in Table 1, has been excellent, specifically as it relates to stress rupture, and consistent with what would be projected from the stress rupture studies. Although the stress ratios given in Table 1 have shown a safe service history, it is also necessary to conduct other performance based qualification tests to ensure that other requirements are met, such as damage tolerance and environmental capability.

5 Factors of safety related to test pressure

5.1 General

This clause addresses the use of a burst ratio that is a function of working pressure. The pressure ranges and burst ratios that are discussed are representative of those used for permanent gases, and is not intended to apply to liquefied gases.

As test pressure increases, the composite wall thickness increases, the cylinder is then more robust, and therefore better able to withstand impact and external damage and still function safely. The opportunity to reduce the burst ratio as the test pressure increases will be addressed.

> The following scale was considered for inclusion but not addressed in the revision of ISO 11119:2002, for which the rationale will be addressed:
>
> For cylinders with working pressure (P_w) below 350 bar the minimum burst pressure (P_b) shall be 2 times test pressure (P_h) (i.e. for $P_w \le 350$ bar $P_b = 2 \text{ x } P_h$ [$3 \times P_w$]).
>
> For cylinders with working pressure (P_w) between 350 bar and 499 bar the minimum burst pressure (P_b) shall be 1,8 times test pressure (P_h) (i.e. for $P_w > 350$ bar and $P_w < 500$ bar $P_b = 1{,}8 \times P_h$).
>
> For cylinders with working pressure (P_w) above 500 bar the minimum burst pressure (P_b) shall be 1,6 times test pressure (P_h) (i.e. for $P_w \ge 500$ bar $P_b = 1{,}6 \times P_h$).

Some composite cylinder performance is based directly on the stress in the fibre. Examples are burst pressure, cyclic fatigue of the composite, and stress rupture reliability. Other times, performance is more a function of composite wall thickness. Examples are flaw tolerance, drop/impact, gunfire/penetration, and bonfire.

Composite wall thickness is a function of diameter, test pressure, and safety factor, each contributing linearly to increased wall thickness. Of the items listed above that are more affected by thickness than pressure, it is likely because the performance criteria are likely affected by thickness at an exponent greater than 1 (i.e. t^2, t^3).

When considering the safety factor, the following should be taken into consideration:

a) is the safety factor adequate to address the burst pressure, cyclic fatigue requirements, and stress rupture requirements; and

b) is the safety factor adequate to address other requirements such as flaw tolerance, drop/impact, gunfire/penetration, and bonfire.

5.2 Burst

The requirement to meet burst pressure is determined by the specification. Any change as a function of test pressure or other criteria shall be simply stated.

5.3 Cyclic fatigue

The ability to meet cyclic fatigue life can be determined by testing. Based on laboratory studies of composite fatigue, and the requirements of most standards, there is generally margin on fatigue life. Considering the issue of composite fatigue, a reduction in burst ratio may be possible. However, there is evidence from fatigue testing that glass strength is reduced during cycle testing at a faster rate than for aramid (aromatic polyamide) or carbon fibre. The cyclic fatigue capability of metal liners will also be reduced as the burst ratio is reduced.

Therefore, considering both composite fatigue and liner fatigue, it is recommended that appropriate cyclic fatigue testing be required by the standard.

5.4 Stress rupture reliability

The requirement to address stress rupture reliability is addressed in Clause 4, Factors of safety related to stress rupture, of this Technical Report. Values are presented in Table 1 for minimum stress ratios to meet a reliability level of 0,999999 for the life of the cylinder. These values are 2,25 for carbon fibre, 3,0 for aramid fibre, and 3,5 for glass fibre.

Different fibres have different stress rupture characteristics, therefore different stress ratio values as shown in Table 1. Carbon fibre has the best stress rupture characteristics, and therefore the lowest stress ratio. Glass fibre has the poorest stress rupture characteristics, and therefore the highest stress ratio. Aramid fibre has intermediate stress rupture characteristics and stress ratio.

The particular question is for burst ratio ranging from $2 \times P_h$ ($3 \times P_w$) for $P_w \leq 350$ bar, $1{,}8 \times P_h$ ($2.7 \times P_w$) for P_w $350 < P_w < 500$ bar, $1{,}6 \times P_h$ ($2.4 \times P_w$) for $P_w \geq 500$ bar.

For carbon fibre, these burst ratio values will result in safe operation in regards to stress rupture reliability, as all values are above that needed for 0,999999 reliability (stress ratio = 2,25). The 0,999999 reliability (1 in 1,000,000) is based on a very conservative interpretation of Robinson's results [13] of the tests performed. Considering nominal versus minimum strength, and pressure versus time in some applications, may give a reliability of a given cylinder to failing in one year to be closer to 1 in 20,000,000,000.

For aramid fibre, the burst ratio value of $2 \times P_h$ ($3 \times P_w$) for $P_w \leq 350$ bar matches the stress ratio given in Table 1 (stress ratio = 3,0). The burst ratio values for the higher pressures are below the stress ratio given in Table 1.

For glass fibre, all burst ratio values are below the stress ratio value given in Table 1. At the lower pressure range, for cylinders with load sharing liners, the burst ratio of $3 \times P_w$ is reasonably consistent with the stress ratio value of $3{,}5 \times P_w$. At the higher pressure ranges, the reliability as regards stress rupture falls below the recommended level of 0,999999. At the highest pressure range, the projected reliability is only 0,999, resulting in the potential for 1 in 1000 cylinders failing by stress rupture during a normal lifetime. If there is any loss in strength due to other factors, such as environmental degradation or mechanical damage, the reliability would be lower (as would also be true for other fibres).

5.5 Damage tolerance

Flaw tolerance testing per ISO 11119 has been successfully completed on a carbon/glass hybrid composite reinforced cylinder designed with a stress ratio of 2,25 for the carbon fibre. Therefore, it is possible that such cylinders can pass this test at any of the burst values given. However, an all-carbon tank might not meet the burst requirement of $2 \times P_w$ with the flaw currently required. Performance of aramid or glass fibre reinforced cylinders designed to a lower burst ratio is not known for the flaw tolerance test.

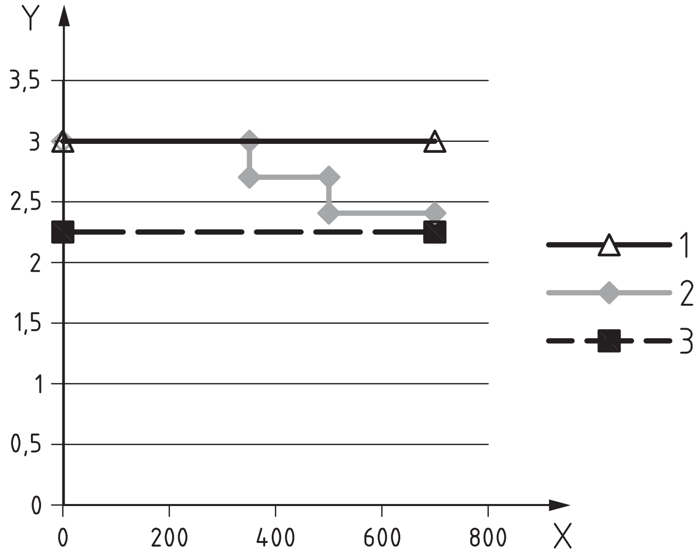
Drop/impact testing has been conducted successfully on cylinders designed for lower safety factors than currently allowed or being considered for inclusion in revisions of ISO 11119:2002. Therefore, there is a high likelihood that cylinders would be able to pass drop/impact testing with the burst ratios being considered.

Gunfire/penetration testing has shown that as wall thickness increases, be it due to increased diameter or increased pressure, the ability to pass the gunfire test increases. Obviously, the wall thickness will increase if the required safety factor is increased. However, carbon and aramid fibre reinforced cylinders often require either higher stress ratios or hybridized construction using a second fibre in order to meet gunfire requirements. Because glass fibre is typically tested at a higher burst ratio than is being considered for higher pressure, performance in this test at lower burst ratios is unknown.

Bonfire testing of composite cylinders has shown that quick response, thermally activated pressure relief devices offer the best protection for the cylinder against burst. The key factor is for the PRD to activate before the composite is degraded to the point the cylinder ruptures. Once a PRD activates, the pressure in the cylinder generally drops fairly rapidly, so there is little risk of rupture. Carbon fibre cylinders have been tested successfully at lower burst ratios being considered for inclusion in revisions of ISO 11119:2002, so there is a relatively low risk. Aramid and glass fibre cylinders are more likely to lose strength in a fire, so their performance at lower safety factors is not known.

Regardless which burst ratio is chosen, it is necessary to confirm performance of the cylinder by actually conducting the qualification tests as required. The discussion above regarding the ability of cylinders to meet qualification test requirements at a lower safety factor is informative, but cannot take the place of actual testing.

5.6 Evaluation of burst ratios



Key

X P_w, bar

Y safety factor

1 ISO 11119:2002 burst ratio

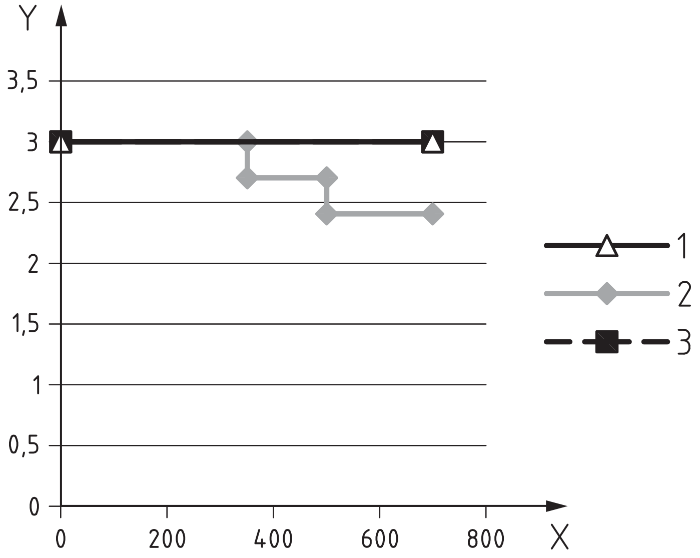
2 burst ratios under consideration

3 stress rupture-carbon

Figure 4 — Factor of Safety versus Pressure for Carbon Fibre

Figure 4 shows burst ratios being discussed for carbon fibre. Line 1 represents the current burst ratio requirements, $3 \times P_w$ ($2 \times P_h$). Line 2 represents the burst ratios under consideration. Line 3 represents the minimum stress ratio required to meet stress rupture requirements, 2,25 F.S. Line 1 and line 2 overlap up to 350 bar.

Since line 1 and line 2 are always above line 3, the risk of a stress rupture failure is less than 1 in 1,000,000. The burst ratios in ISO 11119 could be reduced to match line 3 without incurring significant risk of a stress rupture failure. However, all other qualification testing requirements must still be met. This could, depending on the design, require a higher burst ratio.



Key

X P_w, bar

Y safety factor

1 ISO 11119:2002 burst ratio

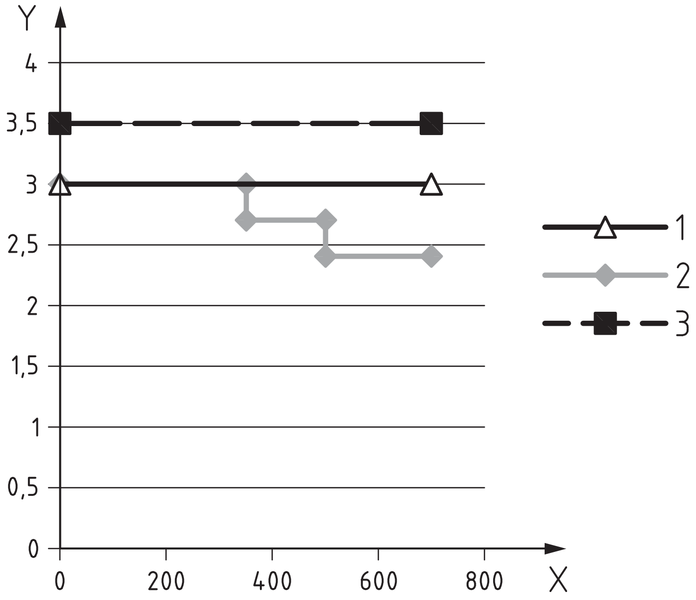
2 burst ratios under consideration

3 stress rupture-aramid

Figure 5 — Factor of Safety versus Pressure for Aramid Fibre

Figure 5 shows burst ratios being discussed for aramid fibre. Line 1 represents the current burst ratio requirements, $3 \times P_w$ ($2 \times P_h$). Line 2 represents the burst ratios under consideration. Line 3 represents the minimum stress ratio required to meet stress rupture requirements, 3,0 F.S. Line 1 and line 2 overlap up to 350 bar. Line 1 and line 3 overlap over the entire pressure range.

Where line 1 and line 2 are equal to line 3, the risk of a stress rupture failure is less than 1 in 1,000,000. The region where line 2 drops below line 3 reflects where the reliability related to stress rupture is lower than for the stress ratio given in Table 1. Again, all other qualification testing requirements must still be met. This could, depending on the design, require a higher burst ratio.



Key

X P_w, bar
Y safety factor
1 ISO 11119:2002 burst ratio
2 burst ratios under consideration
3 stress rupture-glass

Figure 6 — Factor of Safety versus Pressure for Glass Fibre

Figure 6 shows burst ratios being discussed for glass fibre. Line 1 represents the current burst ratio requirements, $3 \times P_w$ ($2 \times P_h$). Line 2 represents the burst ratios under consideration. Line 3 represents the minimum stress ratio required to meet stress rupture requirements, 3,5 F.S. Line 1 and line 2 overlap up to 350 bar.

Since line 1 and line 2 are always below line 3, the risk of a stress rupture failure is greater than 1 in 1,000,000. The region between line 1 and line 2 reflects a significant risk of stress rupture failure. It is recommended that the stress ratio requirement of 3,5 be maintained for glass fibre. A higher burst ratio might also be required to meet other qualification test requirements.

5.7 Summary

The possibility exists to reduce the burst ratio requirements in ISO 11119 below what is required in the current standard without significant additional risk, to the level of the stress ratio listed in Table 1 to meet a reliability requirement of 0,999999 for stress rupture, providing that other qualification test requirements are met. If the burst ratio is reduced so that the stress ratio requirements listed in Table 1 are not met, there is increased risk of stress rupture failure, which could be significant. Other performance requirements such as damage tolerance and bonfire resistance are affected by burst ratios. However, the relationship between burst ratio and these performance requirements have not been established, so it will still be necessary to conduct related qualification testing. It must be noted that additional explanation and supporting evidence would be required before the burst ratios proposed could be justified. Therefore, there is no basis at this time for implementing reductions in burst pressure based on increases in the test pressure.

6 Technical Report Summary

This Technical Report addresses topics related to stress rupture reliability, and evaluation of burst pressure as a function of test pressure. In Clause 4, stress rupture reliability data was presented as a function of stress ratio and reinforcing fibre. In Clause 5, specifying the burst ratio as a function of test pressure was discussed. Information in these topic areas is intended to offer guidance to working groups developing standards for cylinders that are developing standards for composite cylinders.

Annex A
(informative)

Verification of stress ratios using strain gauges

This annex describes a procedure that may be used to verify stress ratios by use of strain gauges.

a) The stress-strain relationship for fibres is always elastic, therefore, stress ratios and strain ratios are equal.

b) High elongation strain gauges are required.

c) Strain gauges should be orientated in the direction of the fibres on which they are mounted (i.e. with hoop fibre on the outside of the cylinder, mount gauges in the hoop direction).

d) **Method 1** (applies to cylinders that do not use high tension winding)

    1) Prior to autofrettage, apply strain gauges and calibrate.

    2) Measure strains at autofrettage, at zero pressure after autofrettage and at working and minimum burst pressure.

    3) Confirm that the strain at burst pressure divided by the strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at working pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

e) **Method 2** (applies to all cylinders)

    1) At zero pressure after winding and autofrettage, apply strain gauges and calibrate.

    2) Measure strains at zero, working and minimum burst pressures.

    3) At zero pressure, after strain measurements have been taken at the working and minimum burst pressures, and with strain gauges monitored, cut the cylinder section apart so that the region containing the strain gauge is approximately 125 mm long. Remove the liner without damaging the composite. Measure the strains after the liner is removed.

    4) Adjust the strain readings at zero, operating, and minimum burst pressures by the amount of strain measured at zero pressure with and without the liner.

    5) Confirm that the strain at burst pressure divided by strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at working pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

Bibliography

[1] ISO 11439:2000, *Gas cylinders — High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles*

[2] ISO 11119 (all parts):2002, *Gas cylinders of composite construction — Specification and test methods*

[3] ISO/TS 15869, *Gaseous hydrogen and hydrogen blends — Land vehicle fuel tanks*

[4] ANSI NGV2-2007, *American National Standard for Natural Gas Vehicle Containers*

[5] CSA B-51 Part 2, *Boiler, pressure vessel, and pressure piping code*

[6] UN ECE R110, *Compressed natural gas systems (CNG Systems)*

[7] KHK Technical Standard #9, *Fuel tanks*

[8] OUTWATER, J.O. and SEIBERT, W.J., Strength degradation of filament-wound pressure vessels, *Modern Plastics*, May 1964

[9] GLASER, R.E., MOORE, R.L., and CHIAO, T.T., Life Estimation of an S-Glass/Epoxy Composite Under Sustained Tensile Loading, *Composites Technology Review*, Spring 1983, Vol. 5, No. 1

[10] GLASER, R.E., MOORE, R.L., and CHIAO, T.T., Life Estimation of Aramid/Epoxy Composites Under Sustained Tension, *Composites Technology Review*, Spring 1984

[11] BABEL, H., VICKERS, B., and THOMAS, D., Sustained Load Behavior of Graphite Epoxy Metal-Lined Pressure Vessels for Long-Life Space Applications, AIAA 89-2644, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA July 10-12, 1989

[12] CHIAO, T.T., CHIAO, C.C., and SHERRY, R.J., Lifetimes of Fibre Composites Under Sustained Tensile Loading, Preprint UCRL-78367, Lawrence Livermore National Labs, November 17, 1976

[13] ROBINSON, E.Y., Design Prediction for Long-Term Stress Rupture Service of Composite Pressure Vessels, Aerospace Report No. ATR-92(2743)-1, The Aerospace Corporation, 1 December, 1991

[14] SHAFFER, JOHN, T., Stress Rupture of Carbon Fibre Composite Materials, 18th International SAMPE Technical Conference, October 7-9, 1986

[15] FADDOUL, JAMES, R., Ten Year-Environmental Test of Glass Fibre/Epoxy Pressure Vessels, Lewis Research Center, Cleveland Ohio, NASA TM 87058

[16] ECORD, GLENN, M., Stress Rupture Failure of a Kevlar Overwrapped Pressure Vessel During Stress Rupture Testing, Lyndon B. Johnson Space Center, EM2-96-006, February 6, 1996

[17] BABEL, HANK and GRIMES-LEDESMA, LORIE, Correspondence, Comments on factor of safety for fibre reinforced composite pressure vessels, 17 June 1999

[18] ASME Section X, Fiber-Reinforced Plastic Pressure Vessels, ASME Boiler & Pressure Vessel Code, 2010

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