TECHNICAL REPORT

# ISO/TR 13086-5

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# Gas cylinders — Information for design of composite cylinders —

## Part 5: Impact testing of composite cylinders

*Bouteilles à gaz — Informations relatives à la conception des bouteilles en matière composite —*

*Partie 5: Essais d'impact sur bouteilles en matière composite*



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# Contents

Page





 

# Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 3, *Cylinder design*.

A list of all parts in the ISO/TR 13086 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

# Introduction

This document considers how impact testing is carried out, why it is done in particular ways and the relevance of various aspects (e.g. a cylinder drop, a flying element through the air, from what direction, size, shape, weight, impact velocity, etc.; does the cylinder “fail” safe or blow into fragments with associated pressure wave?).

This document only addresses cylinders, as a definition of all the associated equipment and its interaction with the cylinders is difficult to assess. The designer can conduct some system level impact tests, including drop, to assess valves, pressure release devices and other attached components.

It is recognized that there are differences between cylinders/tubes that are for general use (without any requirements related to packaging and protection in service) and cylinders/tubes permanently mounted in frames (which offer some differences in loading and protection). Impact testing of an assembly can be different from testing a single, freestanding cylinder/tube.

This document addresses transportable cylinders, vehicle fuel containers and cylinders permanently mounted in frames. It applies to all sizes of cylinders, and to carbon, aramid and glass fibre reinforcements.

Drop testing of smaller cylinders is a requirement in some regulations, codes and standards. For serial production of automotive cylinders, an adequate returnable packing material/method to protect the cylinder during production and until mounted in the vehicle can be used. However, the drop of a cylinder demonstrates a general resistance to impact, which improves safety.

In addition to providing an understanding of the background, an overview is provided of some standard approaches to conducting tests.

# Gas cylinders — Information for design of composite cylinders —

## Part 5:
## Impact testing of composite cylinders



## 1 Scope

This document provides information for the design of composite cylinders related to impact testing and service experience with impact, including:

— low energy impact, which can result from events that can occur during handling or working around cylinders;

— high energy impact, which can result from accidents during transportation, or impact by large objects with velocity;

— drop impact, which can result from handling, where cylinders are dropped or tipped over; and

— high velocity impact, which can result from high energy impact by a small object, such as gunfire, and demonstrates non-shatterability of the cylinder or tube.

Where appropriate, field experience relevant to testing requirements is provided.

NOTE Unless otherwise stated, the word "cylinder" refers to both cylinders and tubes.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *Gas cylinders — Vocabulary*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10286 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

## 4 Low energy impact

### 4.1 General

Low energy impacts can occur during normal service. Examples of this include dropping tools on the cylinder, being hit by road debris, some bouncing when initiating or ending a lift by a crane, hoist, or forklift, being hit by a forklift, or similar incidents. In some cases, low energy impact can leave visual evidence of the impact or can require a cylinder to be removed from service.

## 4.2 Visible indications

Some impacts can be from contact with sharp objects, in which case there would likely be some visual indication of surface damage, such as a cut or surface indentation. Other impacts can be from blunt objects, which can result in some surface crazing, and either surface indentations or internal delamination, or both, without necessarily leaving visible damage. Glass fibre composite reinforcement with a translucent resin is more likely to show visible damage due to impact. Acoustic Emission Testing (AET) or Modal Acoustic Emission (MAE) can be appropriate to assess damage if there is no visible damage.

Low energy impact can cause some reduction in strength, but it is unlikely to result in a rupture when the impact occurs or before the opportunity for inspection. Guidance on these issues is provided in standards on visual inspection (see Clause 9).

## 4.3 Concepts in standards

### 4.3.1 General

There are some common low energy impact levels that are used in standards, including 30 J, 488 J and 1 200 J. These energy levels are based on typical events that can occur in service. Information related to low energy impact testing is provided in Annex A.

### 4.3.2 30 J impact level

The 30 J impact level is based on impact from road debris, such as one that can impact a natural gas or hydrogen fuel container mounted below a vehicle. The debris can, for example, be dislodged as a wheel passes over it. This impact level is used in a test from an EU standard for liquid fuel containers (i.e. gasoline or diesel), and subsequently applied to gaseous fuel containers. Impacts that can reach this energy level, would, for example, include a granite stone about 40 mm in diameter hitting at about 95 km/h, or a cube of steel about 22 mm on a side hitting at about 95 km/h. This level of impact is often considered as a means of evaluating protective coatings and is generally applied prior to chemical exposure testing.

### 4.3.3 488 J impact level

The 488 J impact level is based on the energy from dropping a man-portable cylinder weighing about 27,3 kg from a height of about 1,8 m. This is viewed as the highest combination of weight and height that can occur during transportation or installation by an individual. Such a drop can occur on any part of the cylinder.

The 488 J energy level reasonably represents energy of a similar cylinder falling off a loading dock or the bed of a transport vehicle. However, the energy level varies with the size of the cylinder. The impact is unlikely to occur axially on the end boss in such a fall. Accordingly, as cylinder size increases, the 488 J energy level is maintained on the end and is intended to be representative of other loads that can occur during handling, such as being hit by a forklift, or hitting an object while being transported by a forklift.

The 488 J energy level has been effective as a means of assuring impact resistance in the field based on safe responses to most incidents. There has also been some interest in testing to an impact energy level that is higher, but still less than the energy level of a high velocity impact.

### 4.3.4 1 200 J impact level

The 1 200 J impact level, by one account, addresses a stone of approximately 650 g kicked up by or falling off a vehicle travelling at 110 km/h in one direction, and impacting a cylinder going the opposite direction at 110 k/h. Such a stone would be approximately 80 mm to 90 mm in diameter, while a cube of steel with the same weight would be about 44 mm on a side. While this scenario is not as likely as the two energy levels discussed above, the energy level represents an impact that can occur in service.



Transported cylinders generally have some protection from road debris, including the truck bed and side walls.

#### 4.3.5 Consequences

Some standards have adopted both the 488 J and 1 200 J impact levels, where passing the 488 J impact is mandatory, and a warning label is applied if the 1 200 J impact results are not successful.

Some possible consequences of low energy impacts, following subsequent pressure cycling, include crack growth, delamination, and liner leakage. While strength can be compromised by impacts, it does not necessarily result in rupture of the cylinder.

While cracks can grow during pressure cycling, the pressure cycling can also serve to blunt some of the stress concentration that results from the impact. In testing of cylinders with cut flaws, including deep cut flaws, a full lifetime of cycles was applied, and in some cases, the burst pressure was higher after cycling than without cycling[13]. However, the performance of the cylinder after an impact depends on factors such as the fibre type, fibre stress ratio, and construction. Performance dispersion within a production batch can also affect the evaluation of cylinder performance drop due to impacts.

An impact can also result in delamination within the wall. If the construction is exclusively continuous fibres, delamination between layers is not necessarily of consequence. In some cases, an intentional delamination between layers has been part of a design as a means of improving cyclic fatigue life. However, if localized reinforcements are included, such as dome caps or cloth inserts, and the localized reinforcements delaminate from the wound layers, the structural response of the laminate can be altered, and strength can be compromised.

An impact that causes cuts or broken fibres reduces the local stiffness of the laminate. This results in greater local deformation during pressure cycling, which results in lower fatigue life in a metal liner, and possibly leading to leakage of the cylinder contents.

### 4.4 Test concepts

The 30 J impact is generally applied in a test via a pendulum with a defined impacting mass and pivot arm length. An alternative can be a weight dropped from a given height. Caution is advised when using other methods to catch the impactor after the first impact, to avoid multiple impacts. The 488 J impact is often applied to transportable cylinders in the form of a drop test, but can also be conducted using a pendulum or dropped weight. The 1 200 J impact is also generally applied by a pendulum, but can also be applied using a dropped weight or by an impactor in a horizontal orientation that is powered by a pressurized gas.

The impact is based on equivalent energy, but consideration can be given to differences in momentum. Using the example of the 30 J impact, the momentum of the stone or steel cube would be the same, about 2,24 N·s. For a typical 30 J impact test, the mass is a steel pyramid of 15 kg, which would result in an impact velocity of about 1,41 m/s, and a momentum of 21,2 N·s, or about 10 times that of the possible field event. At this point, testing is based on energy, but it would be useful to understand how momentum influences results.

The cylinder is subject to pressure testing following the impact. Most current standards require pressure cycling. The upper cycle pressure generally is the working pressure. The number of cycles is generally reflective of the number of pressure cycles that occur between inspections, although several standards require the same number of cycles as the original cycle test. Some standards consider the test successful if the cycling is completed without a rupture of the cylinder. Other standards generally burst the cylinder after cycling, with a minimum pressure that can be, for example, 80 % of the original design burst pressure.

# 5 High energy impact (accidents)

## 5.1 General

High energy impact can occur due to accidents for a vehicle transporting a cylinder, or using it as a fuel container that can in some cases involve other vehicles. Examples of this include a single vehicle hitting a bridge or other structure, dropping a cylinder that is being transported, or a similar incident. A vehicle transporting a cylinder can be hit by another vehicle, such as an automobile, truck, or train, where it is possible for the cylinder to be hit directly or caused to be ejected from the transporting vehicle. A tube trailer, battery vehicle, or vehicle transporting a multiple element gas container (MEGC) can run off the road and roll over. Prevention of roll-overs or other road accidents can be considered when designing the tube trailer, battery vehicle, or MEGC. High energy impact can also result from misuse of the cylinder.

## 5.2 Visible indications

High energy impact generally gives visual evidence of the impact if the cylinder physically contacts another component. If there is visual evidence, it is likely to be rejected on this basis. Impact with a sharp or small diameter component is more likely to show evidence of impact. If there is a known impact, it is generally considered that the cylinder can be removed from service.

Impact with a flat component at high energy is also likely to show some indication of damage. In some cases, impact from a flat component results in resin crazing and a noticeable loss in composite properties, such as can be detected when the composite wall is tapped with a coin. It is also possible for an impact with a relatively flat component to cause reversal of curvature of a cylinder, fracturing the inner layers, without necessarily showing significant damage on the outer surface.

Cylinders have also been known to rupture during an impact event. At very high levels of energy, the difference between a rupture and a progressive failure releasing gas can be negligible. However, it is possible that a high energy impact by a relatively small structure will only result in a hole in the cylinder and a release of contained gas.

The characteristics of the impacting body, of how impact energy is distributed into the composite wall, and characteristics of the wall itself, affect results. Consideration of non-dimensional terms helps to understand how laminate damage can occur. Comparing items such as diameter of the impacting body to the wall thickness or cylinder diameter can show likelihood of penetration of the wall. Looking at the load over the affected area, compared with the transverse compressive strength or the shear strength of the laminate can show likelihood of penetration versus laminate crushing.

## 5.3 Design influence

Comparing the total energy of impact to reserve strength of the laminate, i.e. the difference between energy contained at burst pressure versus energy contained when impacted, can give insight as to whether the impact will result in simple damage, penetration, or rupture.

The location of a cylinder in a vehicle during an impact event has an effect on how much damage the cylinder receives. Energy is absorbed by either the vehicle or the frame, or both, during the event, which can offer some protection for the cylinder.

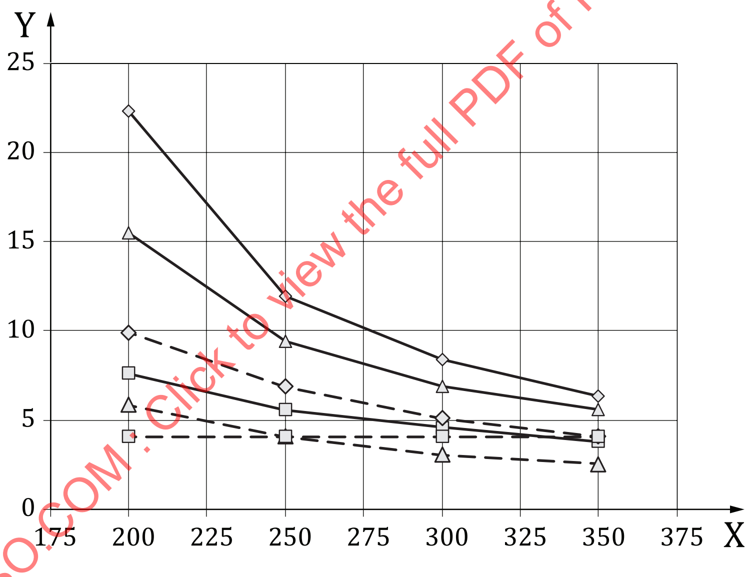
If the accident is such that the impact loading is only on a frame or container, and from the frame or container into the cylinder through the end bosses, it is possible that there is no visible damage, or even no damage, to the cylinder. In this case, AET or MAE can be required to assess if there is, in fact, any damage sustained by the cylinder in the accident. If it can be confirmed that there is no damage, the cylinder can safely remain in service.

The frame, container, or bundle structure is likely to absorb some of the energy through deflection or deformation, providing additional protection for the cylinders. A standard that addresses both cylinder design and frame design can offer information on design and testing that considers interaction of the cylinder and frame. The designer of the packaging would be aware of potential impact threats, and at a minimum conduct a failure modes and effects analysis (FMEA) to address possible concerns.

The pressure in the cylinder affects the level of damage incurred and the consequences. Pressure adds stress to the composite reinforcement, but it also stabilizes the wall, limiting deformation when impacted. Figure 1 shows cylinders with three diameters, each designed for four different service pressures, with a radial load in the cylinder applied at zero pressure and service pressure.

Figure 1 shows that deflection is greater for unpressurized cylinders than pressurized cylinders, as the pressure resists the impact load. Figure 1 also shows that larger diameter cylinders deflect less under load, for a determined stress level, given that the wall is thicker if the service pressure is the same. When pressurized after an impact at low pressure, the cylinder is more likely to have a lower burst pressure than a cylinder impacted at a higher pressure, given the greater deflection, and greater risk of damaged internal fibres, due to the impact loading.

The cylinder has an associated design margin of safety that allows some absorption of impact energy without rupture. The combination of pressurization and design margin limits risk of rupture. If there is a lower pressure in the cylinder, there is greater risk of damage, but the margin of safety is higher, and the contained energy is lower. Therefore, even with high damage risk, the safety risk is acceptable due to the reduced energy content. In any case, a cylinder with suspected damage would either be inspected or removed from service, or both.




**Key**

| | | | |
|---|---|---|---|
| —◇— | 254 mm, no pressure | X | service pressure (bar[1]) |
| —△— | 508 mm, no pressure | Y | max displacement (mm) |
| —□— | 1016 mm, no pressure | | |
| -◇- | 254 mm, service pressure | | |
| -△- | 508 mm, service pressure | | |
| -□- | 1016 mm, service pressure | | |

1) 1 bar = 0,1 MPa = 105 Pa; 1 MPa = 1 N/mm

**Figure 1 — Wall deflection under load versus diameter and contained pressure**

The gas contents, i.e. whether it is compressed gas or liquified gas, have some influence on results of an accident. If the vehicle carrying the cylinder is moving, the contained mass affects the dynamic response of the cylinder and any framing. Depending on the level of the impact, the contained mass can also limit deformation of the wall.

The cylinder construction also affects the level of damage incurred. A thicker wall is generally regarded as more impact resistant. Lower strength materials result in a thicker wall. Glass fibre requires a higher stress ratio, or safety factor, than carbon fibre, so a cylinder with glass fibre reinforcement is generally regarded as more impact resistant.

The cylindrical section of the cylinder or tube is nominally the thickest part. The domes are generally thinner, with the thinnest part adjacent to the cylindrical section, and increasing in thickness moving towards the end boss.

Some cylinders are made using hybrid material construction, for example, using both carbon fibre and glass fibre. This gains the advantage of the improved stress rupture characteristics of the carbon fibre, and the advantage of a thicker wall by adding the glass fibre. Some hybrid construction intermixes the carbon and glass fibres while winding, while others use interspersed layers of carbon and glass. Still others use carbon fibre on the inside layers, and glass fibres on outer layers. Using fibres with different modulus of elasticity also has some benefits with structural dynamics during high energy impact.

The impact energy in one impact incident was calculated to be in the range of 80 000 J to 100 000 J. The energy level can be lower than this in some incidents, but it can be higher in others. As with low energy impacts, a consideration of different momentum levels would be of interest.

High energy impact testing is generally not included in qualification testing of cylinders and tubes. High energy impact is not common in the field, and the impact levels and means of application are varied. These factors make it difficult to develop a meaningful test. However, the designer can consider some impact testing outside the scope of the standards. This would serve to build knowledge on the impact energy threshold leading to cylinder performance drop and corresponding damage criteria, for the definition of adequate pre-fill (pass/fail) inspection criteria. Regardless of specific application, the maximum impact energy is likely the same for any cylinder that is used in transportation.

The current impact tests, including drop, low energy impact, and high velocity impact, are considered sufficient to address impact resistance of cylinders and tubes, such that a higher energy impact test is not necessary. This is supported by field experience, given that in addition to the low level of incidence, the consequences of these impact have not been such that a new qualification test is necessary.

Examples of known impact incidents are given in Clause 10.



## 6 Drop impact

### 6.1 General

Dropping of cylinders and tubes can occur during transportation, handling, and use. These drops can occur in virtually any orientation, horizontal, vertical, or at an angle, although the orientation can be somewhat controlled by the size and use of the cylinder.

A cylinder that is horizontal on a loading dock or transport truck can roll straight off the dock or truck bed, resulting in a horizontal drop. If it rolls off where one end extends off the dock or truck bed before the other, i.e. rolls off at an angle, then it is likely to be at an angle when it impacts the ground. A drop on the end of a cylinder is most likely when carried by hand.

### 6.2 Test scenarios

The height of the drop is derived from likely scenarios in service. A drop height of 1,8 m is generally used to reflect the maximum height of a loading dock or truck bed. This would also apply to a smaller cylinder carried by hand. As cylinder size increases, the likelihood of impacting from a drop on the end of the cylinder decreases. The vertical drop can be limited in energy or be replaced by a defined impact on the end of the cylinder or tube.

Similarly, larger tubes are not likely to be transported or moved without the use of either handling equipment or a cradle, or both, or support frame. In this case, the drop test can be replaced by an impact test.

Cylinders are generally drop tested on a flat and level concrete surface. Drop testing in horizontal and vertical orientations is relatively straightforward. A cylinder is required to bounce on the ground as part of the horizontal test until it comes to rest. Damage is generally across the length of the cylinder, but can be concentrated on the ends or localized build-up locations. A cylinder is required to bounce on the ground as part of the vertical test until it comes to rest, but it is permissible to prevent the cylinder from toppling over. Toppling brings an uncertainty to the vertical test, and tests areas outside of the boss area. The 45° drop test is intended to address such areas. For large cylinders and tubes, it can be necessary to adjust the angle of the cylinder to maintain the centre of gravity and a minimum distance from the lower end to the ground. It is important to verify the angle prior to the drop.

## 6.3 Design influences

The 45° drop test (see Figure 2) tends to load mostly near the tangent area between the dome and the cylindrical portion or the cylinder, or near areas where build-ups are applied. The 45° drop introduces a rotational energy component into the test. When the first end hits the ground, the centre of gravity is still moving downward. The rotational component from bounce of the first end can result in a higher impact loading of the second end than the first end.

**Figure 2 — 45° drop test**



The impact energy depends on the mass of the cylinder, which is affected by its size, the materials of construction, and the wall thickness. Response to the impact depends on the energy level, materials of construction, and design features. Some cylinders use integral foam or foam covers in the dome area to provide protection against drop impact. Other cylinders can use a build-up area in the cylinder so that impact is reacted in that area. Higher safety margins or hybrid construction can be used to improve performance.

There is some issue with reproducibility of drop tests. Precision in establishing the orientation of the cylinder and precision in release of the cylinder without imparting spin are key factors. It is necessary to exercise caution with these issues to reduce scatter. Even with the reproducibility issue, this test has been effective as a test for demonstrating impact resistance.

The test is conducted without internal pressure, so there is no resulting stabilization of the wall during the test. Experience has shown that dropping a cylinder when empty is more severe than when the cylinder is pressurized. Annex C provides information related to drop testing of high-pressure cylinders.

Testing of small cylinders is sometimes conducted with water to simulate load and response of cylinders containing liquified gases such as propane. However, this is not necessarily representative of the proper weight, and it does not reflect that liquified gases would have pressure that would stabilize the cylinder wall in a drop test, unless some pressure is added for the test. Annex B provides information related to drop testing of low-pressure cylinders used for liquified gases.

Conformable containers are being developed for use in containing compressed natural gas or hydrogen gas for use as a vehicle fuel. Carrying out a drop test in sufficient orientations ensures that the container is impact resistant regardless of orientation.

# 7 High velocity impact

## 7.1 General

The high velocity impact test is often called the gunfire test. It serves two purposes:

a) assurance that the cylinder will not rupture when hit by a bullet of similar calibre and energy level; and

b) assurance that the cylinder will not rupture when subjected to penetrating impact at high velocity of similar energy level.

This is one of the few impact tests that are conducted under pressure during qualification. Pressure during testing is necessary for high velocity impact, as it tests for non-shatterability under pressure.

A high velocity impact (gunfire) test was historically used on metal cylinders to confirm that ductility was sufficient that they did not shatter and rupture during a high velocity impact. The high velocity impact test was later applied to composite cylinders to similarly demonstrate they did not shatter and rupture. Annex D provides information related to high velocity impact testing.

## 7.2 Test parameters

The test is generally conducted using a 7,62 mm (30 calibre) AP (armour piercing) bullet (see Figure 3). The cartridge is generally 51 mm long, with a nominal muzzle velocity of 850 m/s. Actual muzzle velocity depends on specific cartridge, barrel length, and other factors. The bullet has an energy of about 3 500 J. Armour piercing rounds are used to ensure penetration and improve repeatability. Other hardened bullets can be used, noting that the key factor is the capability to penetrate the cylinder wall. If softer bullets are used, they would likely spread on impact, increasing the impact diameter, but decreasing the likelihood of penetration. The intent is to demonstrate the cylinder does not rupture when the wall is penetrated. It is generally not specified whether the bullet exits, or is captured by, the cylinder.

Military applications often use larger calibre bullets or cuboid impactors with higher energy levels, but commercial applications generally use the bullets and energy levels discussed above.



**Figure 3 — Cartridge and bullet for high velocity impact (gunfire) test**

The gunfire test originally defined the path of the bullet to be 45° to the perpendicular axis of the cylinder (see Figure 4). More recently, the path of the bullet has been defined as perpendicular to the longitudinal axis of the cylinder. This change has been made because it is more likely for the bullet to penetrate as cylinder wall thickness increases, the bullet is less likely to ricochet, and it is easier to set up the test.

**Figure 4 — Gunfire test at an angle of 45°**

## 7.3 Test results analysis

One factor in cylinder performance in this test is the dynamic response of the cylinder to the impact. When the bullet hits, it deforms the shell, setting up stress and deformation waves in the cylinder. Some of these waves are in-plane, others are out-of-plane. The construction of the cylinder, particularly the fibre material, hybridization, wind angles, and thickness would affect these stress and deformation waves. If the bullet penetrates the first wall, then hits the second wall such that the stress is additive, the probability of the cylinder failing can be higher. This can be a basis to shoot the bullet at an angle other than perpendicular to the axis.

As the wall thickness increases, which can be due to higher pressure or larger diameter, it becomes more resistant to penetration, and is unlikely to hit the second wall with enough energy to be concerned about the path of the bullet. Initially, when a bullet failed to penetrate the cylinder wall, multiple bullets at one point were used to penetrate the wall, or a higher energy/calibre bullet was used. Experience has shown that if the initial bullet did not penetrate, the cylinder would pass the test if more bullets or higher energy/calibre bullet were used. Therefore, the criterion has been updated such that if the bullet does not penetrate the cylinder, the test is deemed to be passed.

If the bullet does not penetrate the cylinder wall, the test setup would include a means to safely vent the pressurized gas.

Historically there were some instances where very small cylinders were tested. The 7,62 mm bullet was large compared with the diameter, such that enough of the cylinder wall was destroyed by the bullet for the cylinder to be cut in half, which does not address the issue of rupture/not shattering. In such cases, when the diameter is less than 120 mm, the round is reduced to 5,6 mm (22 calibre).

There has been some consideration for replacing the bullet, fired by a rifle, with a mechanism that fires a bullet from an industrial test fixture instead of a rifle, or penetrates the cylinder with a rod of the same diameter as the bullet and at the same energy level. Such a mechanism would not be considered a firearm, even if fired using gunpowder. However, the rod can also be energized pneumatically, hydraulically, or mechanically. Consideration can be given to whether the momentum of the bullet is significant, and needs to be matched. Annex E provides information related to a bullet impactor or a mechanical impactor that can be used in place of a bullet fired from a gun.

## 8 Failure considerations

The modes of failure of the cylinder and effects of failure would be considered when evaluating the application and developing the operational controls. If failure occurs, the two likely failure modes would be leak or rupture. Protection of the cylinder from impacts, and inspection after suspected impacts, are a starting point for avoiding failures.

Consequences of a leak include:

— failure of the cylinder and associated system to function;

— overpressure in a closed room that can blow out windows, a door, or a roof if the leak is large;

— asphyxiation if the cylinder contents displace available oxygen in a room;

— fire or explosion if the cylinder contents are either flammable or oxidizing; or

— death if the cylinder contents are toxic.

Consequences of a rupture include:

— failure of the cylinder and associated system to function;

— overpressure in a closed room that can blow out windows, a door, or a roof;

— asphyxiation if the cylinder contents displace available oxygen in a room;

— property damage or injury from a shock wave;

— property damage or injury if the pressure release causes the cylinder to become a projectile;



— property damage or injury if the pressure release causes an external element to become a projectile, or causes the external element to impact another structure or a person;

— fire if the contents are either oxidizing or flammable and react with contents of the room;

— deflagration if the contents are oxidizing and react with the liner, or if the contents are either oxidizing or flammable and react with contents of the room (detonation is unlikely due to lack of time for mixing); or

— death if the cylinder contents are toxic.

There are some analysis models that use a point source of equivalent energy [14][15], sometimes known as a TNT model, to predict blast effects in the event of a rupture. However, it appears the point source blast model does not accurately predict pressure in the near field when evaluating the rupture of a composite cylinder following impact. Cain[16] states that pressure vessel burst overpressures cannot be computed using TNT equivalence except in the far field, and that in the near field the TNT equivalence result is higher than the actual. Field events discussed in Clause 10 also indicate the model for blast effects based on a point source is overly conservative.

The blast model is overly conservative in part because a point source, e.g. trinitrotoluene (TNT), releases energy "instantaneously", while a composite cylinder would release energy at a lower rate, avoiding a shock wave. Some factors to consider:

— composite cylinders have reserve strength (factor of safety) and robustness, while a point source has nothing to restrain the expansion of the energy,

— from the initial failure point, gas flows at a limited rate, and the shock wave is reduced or non-existent,

— for the initial failure point to grow larger, energy is absorbed as the composite reinforcement breaks, and time for the failure to progress is required,

— as time to fail increases, the peak of a shock wave, if it occurs, is reduced significantly, and structures mitigate shock waves.

Overpressure due to gas expansion is present, even though the blast effects of a composite cylinder does not approach that predicted by a point source model.

## 9 Inspection and examination

Visual inspection is a traditional means for inspecting cylinders for damage. Visual inspection identifies damage due to impact to the extent that there are resulting cuts, abrasions, indentations, or similar markings. Standards on visual inspection generally include methods such as tap testing, where sub-surface damage can be identified. Visual inspection can also identify damage resulting from conditions other than impact, which is outside of the scope of this document.

Visual inspection on cylinders and tubes that are permanently mounted on a vehicle or in a frame is generally done in situ. The risk of damage from removing a cylinder, and subsequent re-installation, is deemed to be greater than the risk of missing damage. If damage is seen, then the cylinder is generally either removed for more extensive examination or replacement, or both.

Visual inspection is covered in ISO 11623, ISO 19078 and the future ISO 23802.

There can be visual indications associated with the cylinder that would indicate potential for impact damage. This can include damage indicator coatings applied to the cylinders, and protective enclosures that would deform or otherwise indicate if an impact had occurred.

Ultrasonic inspection can be used to find delaminations within the composite walls or cracks within the laminate or liner.

Holography or shearography can be used to show local damage caused by impact. These methods would identify local changes to strain intensity due to impact damage, by superimposing images with no loading and very low loading.

Digital image correlation (DIC) can be used to show local changes to strain intensity due to impact damage, by comparing images of a cylinder when unpressurized and when fully pressurized.

Acoustic emission (AT) can be used to detect impact damage where fibre breakage during pressurization can be detected as an indication of impact damage. However, it can be difficult to distinguish impact damage from fibre or resin failures due to other causes. Traditional AET relies on parametric features of the transient waveform (e.g. amplitude, counts, rise time, etc.) and but can have some limitations [17][18]. ISO 23876 addresses this issue.

MAE provides a broader sensor range to detect fibre or resin failure, and identify in-plane and out-of-plane waves to more fully characterize damage that can have occurred during an impact event. This method has been used extensively to address possibility of impact during a life extension programme [19] and to evaluate end-of-life composite fuel containers, some of which have been subjected to impact damage and examined with MAE [20]. Related information can be found in ISO/TS 19016.

## 10 Field incidents

### 10.1 Bridge hit

In one incident, natural gas fuel containers were mounted on the top of a bus that hit a railroad bridge with about 15 cm of interference (see Figure 5). The cylinders were rated for 240 bar at 21 C, and contained about 200 bar at the time of the incident.1) The bus was travelling at a speed of about 75 km/h. The outer protective glass layer was damaged, and about four layers of structural composite, hybrid carbon and glass, were sheared off over a limited area. Results of a burst test on the container showed a loss in strength of only about 5 % from that of the lot sample burst test, and that it met the burst requirement for a new tank. This incident gives confidence that the general impact test requirements of standards result in a robust cylinder.

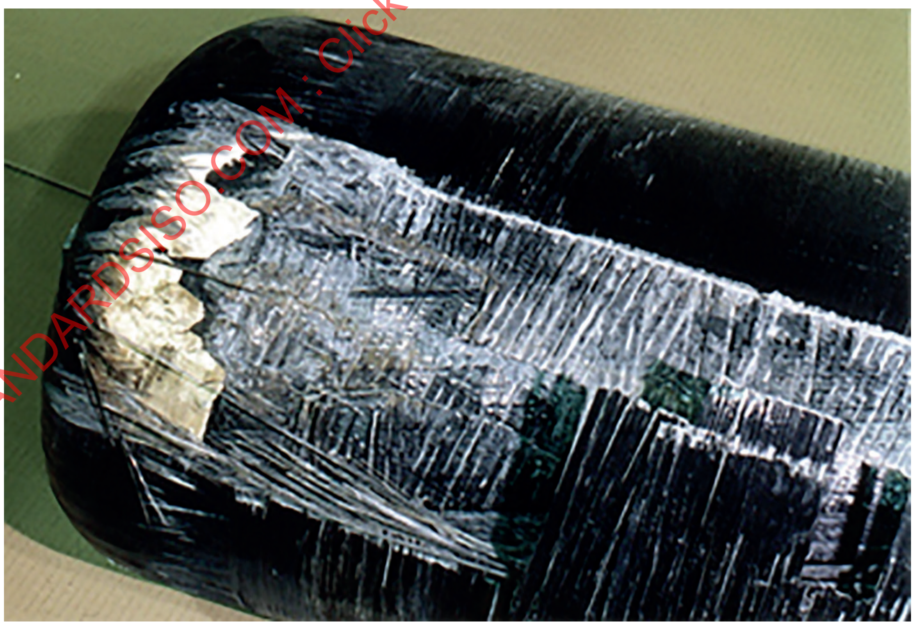


**Figure 5 — Cylinder from bridge hit**



1) 1 bar = 0,1 MPa = 105 Pa; 1 MPa = 1 N/$mm^2$

## 10.2 Rollovers

There are several incidents of tube trailers tipping over or rolling over (see Figure 6). The frame absorbs the impact and transmits the load to the tubes through the end bosses. MAE has been used in these cases, and most tubes have returned to service once cleared by the MAE inspection. In one incident, a tube was condemned by both visual inspection and MAE inspection. The tube was subsequently subjected to a burst test, and it passed the requirement for a new tube. This gives confidence that visual inspection and MAE inspection will find a defect that would result in significant loss in strength of a cylinder or tube. It also gives confidence that large tubes are robust, and that when tubes are mounted in frames, the load from incidents is transferred to the tube in a generally safe manner.

**Figure 6 — Tube trailer tip over**



## 10.3 Rollover with penetration

In one incident of a tube trailer tipping over, a 100 mm × 100 mm steel tube impacted the dome with sufficient energy to penetrate the dome. The gas was released, but the cylinder did not rupture, and the driver was not injured by the gas pressure. This incident shows that with sufficient energy, a cylinder or tube can be penetrated, and the contents released. It also adds confidence in the high velocity impact test as a measure of cylinder robustness, and that in the event of lack of penetration of a bullet in qualification testing, the cylinder will be safe at higher energy penetrations.

## 10.4 Vehicle collision

A vehicle with the CNG fuel container in the trunk, impacted by a heavy-duty truck, received significant damage with no leakage or rupture (see Figure 7). This incident gives confidence that the general impact test requirements of standards result in a robust cylinder.


**Figure 7 — Vehicle impact involving CNG fuel container**

## 10.5 Forklift impact

A truck with natural gas fuel containers mounted behind the cab was in an incident where the cargo, a forklift, was not properly secured such that in a severe braking condition, the forklift slid forward, and a forklift time impacted a fuel container with an energy of about 80 000 J to 100 000 J. The fuel container ruptured (see Figure 8). The driver was severely injured due to being crushed during the event. The passenger was not seriously injured and returned to work shortly. This incident shows that with sufficient impact energy, a cylinder or tube can rupture. It also shows that the event can cause serious injury due to physical impact from a component that moves due to the pressure wave. Given that the passenger was within the “death zone” predicted by a “point source” blast model, yet the passenger did not die or even suffer lung damage, this incident confirms that the point source blast model is overly conservative and not appropriate for predicting results of a cylinder rupture due to impact.

**Figure 8 — Fuel container ruptured by impact**

### 10.6 Other incidents

The above incidents represent some of the most severe incidents that have happened involving composite cylinders and tubes. There have been many other incidents that have not been presented, as there were virtually no consequences of these incidents other than removal of the cylinders from service.

## 11 Impact projects

There are projects that have addressed impact on composite cylinders, such as "Pre-normative research on resistance to mechanical impact of composite overwrapped pressure vessels" (HyPactor)[21]. Many of these are focused on analysis of impact on composite cylinders as opposed to reporting on field events and correlating to analysis.

## 12 Discussion

The impact tests discussed above are covered in standards on composite cylinders (see Bibliography). These impact tests have been effective in assessment and qualification of impact resistant cylinders. It is also appropriate to conduct FMEA and hazard and operability study (HAZOP) analysis to address possible impact scenarios that can occur depending on the application. This would include consideration of acceleration loading typically seen in transportation on both the cylinder and its mounting hardware, and is typically 1 g vertically up, 2 g vertically down, ± 2 g laterally, and +2/-1 g in the direction of travel. Acceleration loading can reach ± 8 g in an accident. The mounting of a cylinder, and the vehicle itself, can reduce the shock and acceleration loading below that can be seen by the vehicle itself.

The impact tests discussed above can be followed by additional testing such as pressure cycles or a burst test. The pressure cycles can be tied to the expected cycles per year times the number of years between inspections. The burst test can allow a slight reduction in strength, while still allowing safe service until the next inspection. However, cylinders with visible damage would be removed from service immediately for more detailed inspection or destruction.

## 13 Summary

The impact tests typically used in standards on composite cylinders have been presented, along with background on their origins and requirements. Parameters for each test are included in appendices. These test parameters are common to several standards.

Failure modes and effects are presented. Leak and rupture are the two likely failure modes, and the possible consequences are presented.

Inspection methods are presented and standards that are commonly used for inspection are listed in the Bibliography.

Field incidents are presented. Some incidents show that cylinders qualified using the impact tests described here demonstrate a high level of impact resistance. Other incidents show that there are events with high enough energy that result in penetration and/or rupture of the cylinder. It is not practical to address these very-high-energy events in qualification.

The current impact tests are appropriate and sufficient based on overall performance of composite cylinders in the field.

# Annex A
(informative)

# Low energy impact testing

## A.1 30 J impact

The impact body is made of steel and has the shape of a pyramid with equilateral triangle faces and a square base, the summit and the edges being rounded to a radius of 3 mm. The centre of percussion of the pendulum coincides with the centre of gravity of the pyramid; its distance from the axis of rotation of the pendulum is 1 m. The total mass of the pendulum referred to its centre of percussion is 15 kg. The energy of the pendulum at the moment of impact is not less than 30 N·m and as close to that value as possible.

During pendulum impact, the cylinder is held in position by the end bosses or by the intended mounting brackets. The cylinder is unpressurized during impact testing.

## A.2 488 J and 1 200 J impact

### A.2.1 Procedure

For Type 2 tubes, one empty tube, and if necessary, a second empty tube, are subjected to two impacts:

— one at the tube sidewall midway between the ends;

— one at the termination of the overwrap near the domes (e.g. within 10 mm).

For Type 3 and 4 tubes, one empty tube, and if necessary a second empty tube, are subjected to two impacts:

— one at the tube sidewall midway between the ends;

— one at an angle of 45° to strike the shoulder of the tube (mid arc length at the dome).

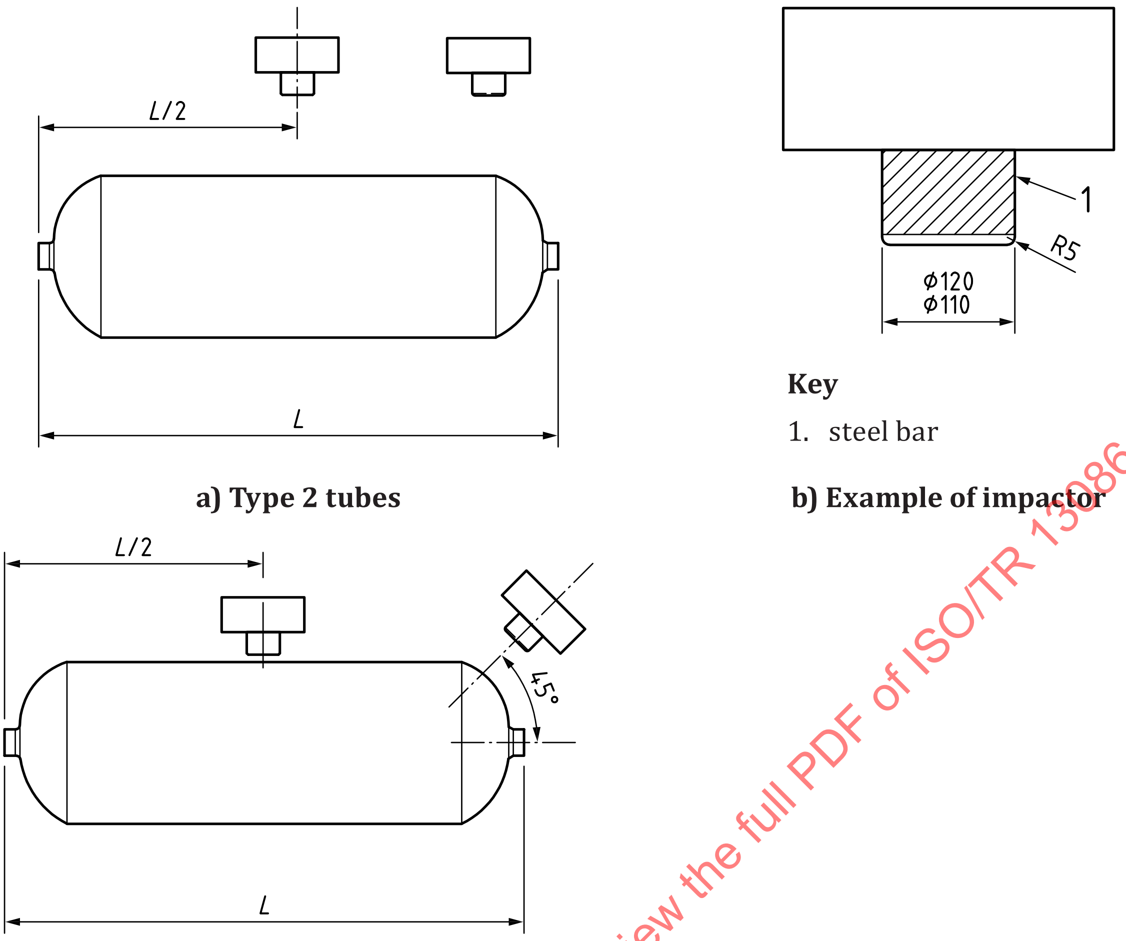
See Figure A.1.

The impact can be conducted by dropping a suitable weight or by a pendulum impact. The tube is secured to ensure it does not move during the impact. The impactor is made from a steel bar and has a diameter of between 110 mm and 120 mm.

— First test: An impactor with a potential energy of 1 200 J strikes the tube at the positions identified above.

— Second test (if necessary): An impactor with a potential energy of 488 J strikes the tube at the positions identified above.

The tube is then subjected to the ambient cycle test.




Key

1. steel bar

a) Type 2 tubes

b) Example of impactor

C) Type 3 and Type 4 tubes

**Figure A.1 — Blunt impact test procedure**

### A.2.2 Criteria

The tubes must withstand 3 000 pressurization cycles at maximum developed pressure $p_{max}$ without failure by burst or leakage. The test continues for additional cycles representing its specified lifetime, or until the tube fails by leakage, whichever is the sooner. In either case the tube is deemed to have passed the test. However, if failure during this second part of the test is by burst, then the tube is deemed to have failed the test.

A tube passing the test at an energy level of 1 200 J is identified as achieving impact resistance level 2, which is reported in the qualification report and on the label. If the tube does not pass the blunt impact test at this level, a second tube is tested at an energy level of 488 J. A tube passing the test at an energy level of 488 J is identified as achieving impact resistance level 1, which is reported on the qualification report and on the label. A tube that does not pass at an energy level of 488 J is not approved.



# Annex B
(informative)

## Drop impact testing (low pressure liquified gas, up to 50 l)

Two cylinders are filled with water to 50 % capacity and fitted with a steel or aluminium plug with diameter no greater than the neck diameter, to protect threads and sealing surfaces. It is recommended that the cylinder be pressurized to 15 bar with nitrogen during the test.[2)]

Both cylinders are dropped twice, in each of the five positions shown in Figure B.1, from a height of 1,2 m, on to a smooth concrete surface or a protective steel plate of a minimum of 10 mm thickness. The drop surface is sufficiently flat so that the difference in level between any two points on the surface is no more than 2 mm.

One cylinder is subjected to a burst test. The burst pressure, $p_b$, is equal to or greater than 100 % of the minimum burst level required in the burst test.

The other cylinder is subjected to a pressure cycling test. The cylinder meets the cycle life requirements for a new cylinder.

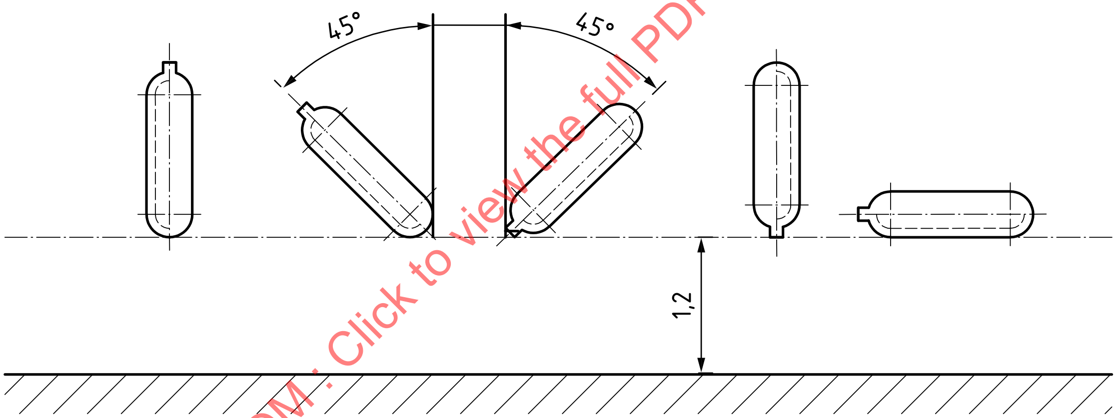



**Figure B.1 — Drop test**

2) 1 bar = 0,1 MPa = 105 Pa; 1 MPa = 1 N/mm$^2$