TECHNICAL REPORT

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Gas cylinders — Guidance for design of composite cylinders —

Part 2: Bonfire test issues

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

Partie 2: Aspects concernant les essais à la flamme vive

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Contents

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).

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This document 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. Common fibres used in composite cylinders include glass, aramid, and carbon. Resin matrix materials are commonly epoxy or vinyl ester.

Composite cylinders are known to be exposed to the action of fire, ranging from radiant heating to full engulfment in the fire. Cylinder performance during exposure to fire might depend on the cylinder materials of construction, size of the fire, dimensions of the cylinder, its orientation, its contents, and the use of temperature or pressure activated relief devices.

Fire exposure tests are often included in composite cylinder standards, sometimes as a mandatory test and sometimes as an optional test. This document addresses issues related to composite cylinders exposed to fire, summarizes test requirements, and offers a new approach to qualifying cylinders with relief devices.

Gas cylinders — Guidance for design of composite cylinders —

Part 2:
Bonfire test issues

1 Scope

This document addresses the topic of safety and performance of composite cylinders in a fire situation. A statement of safety addresses the topics which should be understood in order to operate cylinders safely in service. The remainder of this document provides a basic level of understanding of these topics.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

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

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

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

4 Background

Composite cylinders began service in the 1950s, initially as rocket motor cases with glass fibre reinforcement. This led shortly to glass fibre pressure vessels with rubber liners, and then to glass fibre pressure vessels with metal liners. Metal liners were typically either aluminium or steel. Eventually, new structural fibres, such as aramid and carbon, came into use for reinforcing pressure vessels. Today, typical reinforcements are glass and carbon, either individually or together as a hybrid. Typical liner materials are steel, aluminium, or polymers, often high density polyethylene (HDPE) or a polyamide (PA).

Composite cylinders offer certain advantages, particularly light weight and corrosion resistance. However, there are some performance requirements that tax the abilities of composite cylinders. One of these is the ability to withstand exposure to fire conditions without rupture. Fire conditions might include both direct exposure to fire, and to the elevated temperatures resulting from a fire. Direct exposure might include localized flames, or an engulfing fire.

Sources for a fire could include discharge of flammable gases from nearby cylinders, spilled liquid fuel from motor vehicles, car fires, house or building fires, and grass or forest fires, to name a few. There is significant variation in the fire conditions that arise from each of these causes, and there are issues on reproducibility of any of these types of fires.

Composite cylinders might be able to withstand a certain level of fire exposure on their own. However, it is more common in certain applications to use a system approach that could include isolation from fire, insulation, pressure activated relief valves or devices, and/or thermally activated relief devices. However, there might be conditions where the risk of rupture is less than the risk and consequence of leakage, and a pressure relief device (PRD) or similar device would not be used. Individual cylinders might be tested without any type of protection, but it is also common for the cylinder to be tested as part of a system that contains some means of protection. Regardless, the cylinder should be representative of a production cylinder and the test should address hazards which might occur.

5 Statement of safety

Composite cylinders, and assemblies of composite cylinders, can be used safely in conditions where there might be exposure to fire conditions if there is an:

— understanding of composite materials, including the liner;

— understanding of fires;

— understanding of PRDs, if used;

— understanding of insulation, if used;

— understanding of valves and their failure mechanisms;

— understanding of venting;

— understanding of single cylinder vs. multiple cylinder systems;

— understanding of interaction of the above elements;

— optimized test, which is developed, based on above understandings.

Clause 6 addresses the elements of the statement of safety, and provides some understanding for each of the elements.

6 Components of fire testing

6.1 Composite materials

The reinforcement of a composite cylinder consists of reinforcing fibres in a resin matrix. There might be resins or additives in the resin that affect structural or thermal performance. There might also be external coatings that protect the composite, such as intumescents. When exposed to fire, intumescents form a char layer which has low conductivity and protects the underlying material. There might also be ablative layers, which could remove heat of the fire as they ablate.

Reinforcing fibres primarily include glass and carbon, and occasionally aramid. E-glass properties on matweb.com[1] show glass has a melting point of about 1 725 °C (3 137 °F), and therefore might soften or melt in a bonfire test, where temperatures might reach 1 960 °C (3 500 °F) which is the flame temperature of the combustion of natural gas in air. Kevlar®1) properties on matweb.com[2] show aramid fibres begin to lose strength above 425 °C (797 °F), and might decompose and burn at 500 °C (932 °F). Carbon fibre might oxidize in the fire and lose strength at temperatures of 600 °C (1 112 °F). The onset of pyrolysis, affecting organic materials such as epoxy resin, can be as low as 300 °C (572 °F).

Resins are typically epoxy or vinyl ester. These materials might burn in a fire. The resins might contain additives that are also attacked by fire, but some additives might be fire retardants.

A liner is generally used to prevent gas from leaking through the composite, and also serves as a winding mandrel for the composite. The liner is typically steel, aluminium alloy, HDPE, or PA. Polymer liners generally have a metallic end boss, either on one or both ends, centred on the longitudinal axis.

The composite reinforcement is wound in layers on top of the liner. The composite reinforcement typically ranges from 3,2 mm to 50 mm (0,13 in to 2 in) thick and is dependent upon factors such as vessel diameter, working pressure, and regulations. Curing of the laminate is achieved by cross-linking

1) Kevlar® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

of the resin, involving a combination of time and temperature. This time and temperature depends on the resin materials and the thickness of the laminate. These layers might be of a single material, multiple materials in a layer, or alternating layers of material. External insulation or protective layers might be wound onto the cylinder.

The thinner the laminate, the faster the degradation of the laminate in the fire, and the faster the gas inside is heated. A thicker laminate takes longer to fail, and longer to transfer heat through the wall. Due to cylinder geometry and winding, the structural composite is generally thickest in the cylindrical section and near the end bosses, and thinner in other sections of the pressure vessel such as the end domes.

Composite materials generally have a low thermal conductivity, and are often considered to be an insulating layer. Degradation or failure of the composite laminate can occur from three causes. First, the fibre might be directly reduced in strength by the fire. Second, the fire might burn resin out of the laminate. When the resin is removed from the laminate, the load is not efficiently transferred from inner layers to outer layers. This might cause the inner layers to be overstressed and fail. Third, there might be heat from the fire that increases pressure within the cylinder, and decreases the strength of the laminate, even though there is no direct flame contact. When directly exposed to a fire, charring and burnout of the resin is the primary factor in degradation of the composite. It is also possible for heat from the fire to be transferred to the liner, which in the case of polymer liners, might melt and allow the cylinder contents to vent.

Testing is generally conducted on full scale cylinders filled with the gas that the cylinder has been designed to contain and where appropriate equipped with the PRDs designed to protect the pressure vessel from bursting. There might be times when a full diameter, short length cylinder would provide an accurate measure of performance. It is generally accepted that similar sizes would have similar performance in a fire test, so a fire test is not always required with a change of design. However, studies have shown that time to burst in a fire is only the same if the composite materials, thickness, stresses, and winding sequences are the same, so good judgment should be used when qualifying new designs.

6.2 Fire

6.2.1 General

Fire exposure in service can be from a number of sources, including diesel fuel, kerosene, gasoline, propane, natural gas, hydrogen, tyres, wood, or other combustible materials. In some cases, fires involving cylinders containing flammable materials release their contents, which then adds to the fire. The flame temperature varies by fuel source, and can be affected by wind conditions and ambient temperatures. The size of the fire and length of time in the fire would depend on the amount of fuel for the fire and its distribution around the cylinder. In some cases, the cylinder might only be exposed to a heat flux, and not directly to a fire. Different applications might have different fire sources and risk levels.

At one extreme, the fire might be focussed on a very small area (such as with a propane torch). In this case, it might be unlikely that a PRD is activated. A localized fire might be caused by a small pool of liquid fuel, a burning tyre, or an engine fire. In this case, it is more likely that a PRD would be activated, but activation is not absolutely certain. If the relief device was not activated, a cylinder rupture would be likely. An engulfing or global fire would involve exposure of the entire cylinder. Newhouse and Webster[3] indicate that, in this case, activation of the PRD is virtually assured. If the cylinder was exposed to a heat flux, it might be at a temperature that would degrade the composite strength directly, in which case, a thermally activated PRD would likely be activated and release the contents safely. If the temperature was below the activation temperature of a thermally activated PRD, it might be possible for a pressure activated PRD to be triggered.

Test methods have been developed that reflect fires that might actually occur in service. However, such fires are not precise or particularly repeatable. Most standards use a somewhat localized fire, typically limited in length to 1,65 m. Some standards are developing tests with a more localized fire that acts for a given time, followed by exposure over a larger area. In some standards, localized fire is achieved by testing the cylinder in a vertical orientation. Fires generally continue until the cylinder is vented or the fuel is consumed. A fire would typically last 20 minutes or more. The length of time a fire burns, vs. the time for a PRD to activate, or the cylinder to rupture, are of particular interest to first responders.

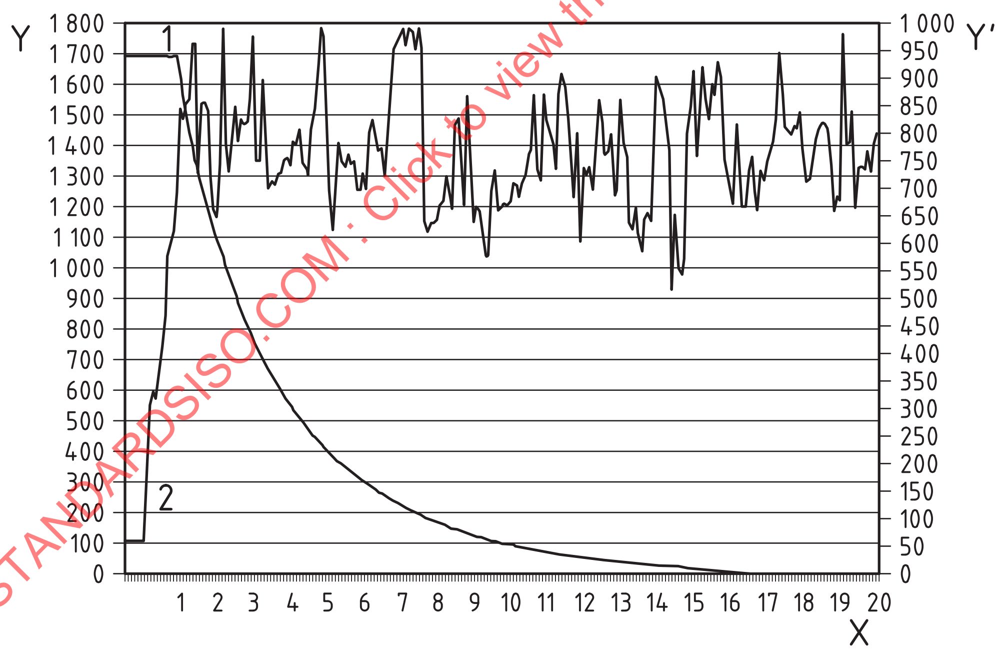
Fuels used in bonfire tests typically have included kerosene, diesel fuel, or kerosene soaked wood. More recently, natural gas or propane has been used in burners that are oriented to cover a given portion of the cylinder. Hydrogen/oxygen burners have also been used experimentally. The flow of gas can be controlled to give a range of thermal input and temperature level. Thermal input to the cylinder includes heat from convection and from radiation. Wind can affect real fires, and similarly those made with wood, kerosene, or diesel fuel. There will be flames that "lick" the surface of the cylinder, essentially moved back and forth by the wind. If natural gas or propane burners are used, the fire should be more controlled than would be the case in actual field service, that is, control the area of the cylinder in the fire is better achieved, including the height of flames, the evenness of the flames, and the total heat flux, and thereby a more consistent test is achieved. In some cases, these gaseous fuelled fires are conducted in tubes or sheltered areas, such that wind is not a factor.

The combustion temperatures of the different materials, as reported by Murphy[4] are given in Table 1.

Table 1 — Adiabatic flame temperature (burning a stoichiometric mixture of fuel)

Fuel	°C	°F
Gasoline	1 977	3 591
Diesel	2 054	3 729
Natural gas	1 884	3 423
Propane gas	1 990	3 614
Hydrogen gas	2 115	3 839

The effective temperature would be lower in the case that wind pushes the flame around on the surface of the cylinder. Figure 1 shows how measured diesel fuel flame temperature varies during one particular test.



Key

X minutes

Y degrees °F

Y′ PSIG

Figure 1 — Measured flame temperature vs. time

One advantage of using solid or liquid fuels is that the test set-up can be accomplished without too much set-up equipment being required. Also, fires in actual service would more likely be solid or liquid fuels, making this a more valid test. One advantage of using gaseous fuel is that the test is more repeatable, making the test more reliable as a predictor of performance in the field. If a cylinder ruptured during the test, there would be no need for environmental cleanup, while solid or liquid fuels might be spread around the test area and contaminate the soil.

6.2.2 Fire tests in standards

Table 2 lists some common standards that address fire testing, and how they define the fire. Further detail from these standards is provided in Annex A. The fire test is designed to demonstrate that finished cylinders, complete with the fire protection system (cylinder valve, PRDs and/or integral thermal insulation) specified in the design, prevents the rupture of the cylinder when tested under the specified fire conditions.

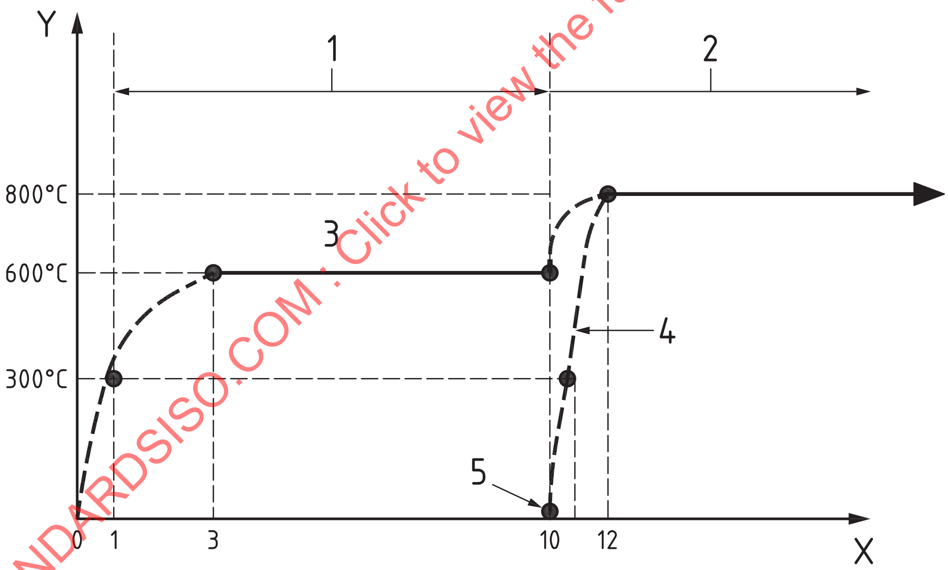
Table 2 — Examples of standards or reports that address fire testing

Item	Requirements/reference	ISO 11119[5]	ISO 11439[6]	EN 12245[7]	ANSI NGV2[8]	DOT FRP1[9]	DOT RPT HS 811 303[10]
Application	Transportable cylinder	X		X		X	
	Vehicle fuel container		X		X		X
Fire source	Any fuel with uniform, sufficient heat to maintain temperature	X	X		X		
	Wood or kerosene			X			
	Kerosene-soaked wood, gasoline, or JP-4 fuel					X	
	LPG (propane)						X
Fire size	1,65 m length × cylinder diameter	X	X		X		
	Total engulfment			X		X	
	250 mm length × cylinder diameter						X
Fire temperature	≥ 590 °C on cylinder surface	X	X				
	≥ 590 °C within 25 mm of cylinder surface			X			
	≥ 430 °C within 25 mm of cylinder surface				X		
	900 °C to 950 °C on cylinder surface						X
	Not specified					X	
Cylinder orientation	Horizontal	X	X		X		X
	Horizontal and vertical			X		X	
Cylinder contents	Intended contents; or air or nitrogen	X				X	
	Natural gas (or methane)		X		X		
	Air or nitrogen			X			
	Hydrogen						X
Fire protection device	Required		X		X	X	X

Table 2 *(continued)*

Item	Requirements/reference	ISO 11119[5]	ISO 11439[6]	EN 12245[7]	ANSI NGV2[8]	DOT FRP1[9]	DOT RPT HS 811 303[10]
	Not required	X		X			
Pressure	Service	X	X	X	X	X	X
	And 25 % of service if a thermally activated pressure relief device (TPRD) not used		X		X		
Test time with protection	Until vented	X	X	X	X	X	
	30 minutes or until vented						X
Test time with no PRD	Two minutes	X		X			

The standards listed above have a similar approach to fire testing. However, the case where multiple cylinders are being vented by a single PRD is generally not well covered in most standards. Standards might be updated to recognize the increased time to vent multiple cylinders, even if only one cylinder is actually in a fire. Standards being developed for hydrogen vehicle fuel containers, including SAE J2579, and the UN Global Technical Regulations for hydrogen fuel cell vehicles – ECE/TRANS/180/Add.13, have taken a modified approach to the fire test, beginning with a smaller, localized fire for the first 10 minutes of the test, then progressing to an engulfing fire, as reported by Scheffler[11]. Figure 2 shows the development of the fire from local to global.



Key

X minutes

Y minimum temperature

1 localized fire exposure

2 engulfing fire

3 localized area

4 engulfing region outside localized area (burner ramp rate)

5 ignite main burner

Figure 2 — Fire Test approach for hydrogen fuel containers

6.2.3 Standardized fire test

From these standards that address fire testing, it follows that a common approach is currently:

1) Cylinder preparation for fire test:

   a) The cylinder is pressurized with nitrogen or the intended gas at working pressure. Air is not recommended as a test gas. A test at 25 % of working pressure is recommended if the cylinder is protected by a pressure activated relief device, but is not required if a thermally activated relief device is used. Tests may be conducted at ambient temperatures between −7 °C and 43 °C (20 °F and 110 °F), but the container settled pressure is to be temperature compensated to 15 °C (60 °F). Some standards limit wind to 2,25 m/s to avoid problems with the flame.

   b) Metallic shielding of a minimum 0,4 mm (0,016 in) thickness is used to prevent direct flame impingement on cylinder valves, fittings, and/or PRDs. The metallic shielding is not to be in direct contact with the specified fire protection system (PRDs or cylinder valve).

   NOTE Some consideration has been given to removal of the shielding requirement, provided that fire is not directed onto the PRDs.

   c) Thermocouple location: At least three thermocouples are placed along the bottom of the cylinder under test not more than 0,75 m apart and within 25 mm (1 in) of the surface. Each thermocouple may be attached to a steel cube up to 25 mm (1 in) on a side. Thermocouples are protected from direct flame impingement by attaching to steel cubes as mentioned above or by metallic shielding of a minimum of 0,4 mm (0,016 in) thickness.

   NOTE The purpose of the 25 mm steel cube is to average out temperatures over time, i.e. to average over the time period while alternately being directly in the flame vs. in air.

   d) Cylinder internal pressure is monitored.

2) Cylinder orientation

   a) Cylinders that are mounted vertically may be tested in a vertical orientation.

   b) Cylinders less than or equal to 1,65 m (65 in) long should be horizontally oriented with a fire source below the centre of the long axis of the cylinder for the entire length of the cylinder.

   c) For cylinders of length greater than 1,65 m, the cylinder is to be positioned in accordance with the following procedure.

      i) If the cylinder is fitted with a PRD at one end, the fire source is to commence at the opposite end of the cylinder.

      ii) If the cylinder is fitted with PRDs at both ends, or at more than one location along the length of the cylinder, the centre of the fire source is to be centred midway between the pressure relief devices that are separated by the greatest horizontal distance.

3) Fire sources: The fire source can be any fuel provided it supplies uniform heat sufficient to maintain the specified temperature until the cylinder has vented. Gaseous fuel sources are recommended based on ease of control and avoidance of environmental contamination in the event of cylinder rupture. A uniform fire source of 1,65 m (65 in) length provides direct flame impingement on the container surface across its entire diameter. The bottom surface of the cylinder is to be about 0,10 m above the base of the fire.

4) Fire test requirements: Thermocouples and internal cylinder pressure are to be recorded at least every 30 seconds for the duration of the fire test. Fire test temperature is to be ≥ 590 °C (1 094 °F) as measured using at least three thermocouples. Within five minutes following fire ignition the temperature of two of the three thermocouples are to be ≥ 590 °C (1 094 °F) and two of the three thermocouples are to be ≥ 590 °C (1 094 °F) throughout the duration of the test. It is noted that the temperature is generally the only measure of the fire intensity; however, heat flux is also important as a measure of fire intensity, and consideration should be given to its use, particularly

as consideration to localized vs. engulfing fires. However, specification of the fire source, in addition to fire size, does give some measure of control over heat flux.

5) Fire test success: A successful fire test is one in which the cylinder vents its contents down to a pressure less than 7 bar through a PRD without bursting. In the event that complete venting occurs in less than five minutes, the minimum temperature requirements do not apply and the fire test is a success.

NOTE Some standards have not required venting, but instead require a fixed number of minutes in the fire without rupture. The number of minutes has ranged from two minutes to 20 minutes.

6) Fire test failure: If the cylinder bursts the fire test is a failure in the case where a PRD is used. If the cylinder bursts before the specified time limit the fire test is a failure in the case where a PRD is not used. Any failure during the test of a valve, fitting or tubing that is not part of the intended protection system design invalidates the result.

7) A single test is generally considered adequate for qualification, based in part on prior testing of similar cylinders. If a non-typical cylinder or PRD is used, consideration should be given to additional tests for characterization.

8) Design changes: It is generally accepted that a test should be conducted if a design change is likely to change the results of the test. For a bonfire test, such design changes include:

   a) Significant change in internal volume. This includes an increase in length of 20 % or more, or a change in diameter of 20 % or more.

   b) Significant change in pressure. This includes an increase in pressure of 20 % or more.

   c) If a new PRD is used.

   d) If the fibre type is changed. This includes changes between carbon, aramid, and glass fibre, but generally not for changes in manufacturer for the same type of fibre.

   e) If the liner material is changed. This includes changes between steel, aluminium, and polymer liners, but generally not for changes in supplier.

6.2.4 Considerations for future standardized fire tests

From recent developments, however, the following test approach issues should be considered:

— should the fire be localized, engulfing, or some combination based on application;

— should the size of the fire be tied to the size of the cylinder;

— should the cylinder be tested by itself, or in a package representative of the actual application.

Webster, 2010[10], reported:

The design of compressed hydrogen fuel systems for hydrogen vehicles has been largely based on the compressed natural gas (CNG) vehicle experience. In addition to installation requirements, the test procedures used to qualify on-board hydrogen fuel systems for service use were based upon the test protocol developed for the CNG industry.

Between 2000 and 2008, there have been over 20 failures of CNG cylinders onboard vehicles. The single largest cause of these failures (over 50 %) was fire. These CNG cylinder failures have occurred on OEM passenger vehicles (Ford Crown Victoria, Honda Civic), as well as on OEM transit buses (Heuliez, MAN Bus).

Note that the effect of localized fires is more pronounced on cylinders of longer length, as Thermally activated Pressure Relief Device (TPRD) locations are typically spaced far apart. Some of the fire failures could be attributed to slow reacting TPRD designs, but the majority of the failures were caused *by localized fire effects where the flame exposure was at a location on the cylinder remote from the TPRD location.*

Note that TPRDs do not tend to activate unless they are sufficiently exposed to a high heat source, or direct flame impingement.

All CNG or draft compressed hydrogen cylinder standards worldwide only specify a bonfire test of a cylinder where the fire source is a standard 1,65 m length. This fire length is derived from a US DOT fire test developed in the 1970s for application to composite air-breathing cylinders of relatively small size.

The Webster 2010 report[10] concluded that a localized fire test was required that would be severe enough (900 °C for 30 minutes in the same location of approximately 250 mm in length with a flame impinging on the cylinder surface) such that a cylinder design able to survive the test is safe for service even if there are small differences in repeatability. The burner design is specified and the fuel is propane. The cylinder is filled to its service, or working, pressure with the fuel under test (CNG, hydrogen). Cylinder orientation was also specified depending on the location and number of TPRDs used.

The surface temperature of 900 °C was decided based upon a review of several vehicle fire tests, as reported by Gambone, 2008[12]. None of the vehicle fire cases reviewed had a fire temperature that exceeded 900 °C for 30 minutes, therefore a fire of 900 °C intensity for a continuous 30 minutes likely exceeds any continuous source of heat in a vehicle fire.

One approach to assessing the consistency, and validity, of different fires might be to measure the depth of a resin char layer, or decomposition of a fibre, vs. time and vs. fuel use. This could be done with a standard specimen so that the only variable is the fire itself. Thermocouples should measure temperature of the outer surface and within the cylinder contents. Another approach might be to put thermocouples in a standard test specimen and monitor the temperature vs. time and fuel use for different fires, and also internal pressure vs. time using a standard contained gas, such as nitrogen. Thermocouples would be on the inner and outer surface of the composite, within the laminate, and within the cylinder contents. In fires fed by gas burners, the fuel delivery rate and fuel/air ratio would both be variables. Wind velocity would be limited or controlled in these studies.

It is recommended that the fire test be conducted with the gases to be contained, if known. Different gases have different temperature rise rate, pressure vs. temperature, flow characteristics through the PRD and vent piping, and flammability. It is recommended that air not be used as a test gas unless it is the intended content. Under some conditions, the air might react with the liner, creating an internal fire that would intensify under pressure and cause the vessel to rupture. If the contained gas is a toxic gas, it is generally recommended that a PRD not be used, so a fire test might not be appropriate, except to determine time for the cylinder to burst in a fire as part of a system risk analysis.

6.3 Pressure relief devices

A PRD is a device that, when activated, vents the contents of the cylinder, and cannot be reclosed. A pressure relief valve (PRV) is a device that, when activated, vents a portion of the contents, but can be reclosed once a certain lower pressure is reached. PRVs are generally not used on composite cylinders, because composite cylinders lose strength in a fire, and a PRV will not totally vent the cylinder, which could result in a rupture of the cylinder.

There are two fundamental types of PRDs, those that are pressure activated and those that are thermally activated. There are also hybrids that might need a combination of heat and pressure to activate.

Pressure activated PRDs generally use a rupture disk made of metal. The rupture disk is held in a carrier, and the carrier is installed in a valve or other component that is exposed to cylinder pressure. The rupture disk would have a burst pressure that is lower than the burst pressure of the cylinder. This would be true at any temperature, or any condition of fire exposure, to provide proper protection. However, this condition might be difficult to meet if the cylinder is not at full pressure, and the fire is sustained. In this case, the pressure might not reach the activation pressure of the rupture disk, yet the cylinder strength is continually degraded by the fire, so a burst is likely. Another issue with rupture disks is that, since they have a lower safety factor than the cylinder, they operate at a high stress level, and they are at risk of failing by cyclic fatigue.

Rupture disks have been allowed in some composite cylinder standards, particularly in applications where the cylinder is either full or empty. The thermal insulating properties of composite reinforcement limits the increase in internal pressure during a fire, in which case the use of pressure activated PRDs is not recommended. Pressure activated PRDs might be of value when working with liquefied gases such as propane. The use of rupture disks for composite cylinders is subject to further discussion, and including consideration of the application and related performance requirements. Some standards for some applications have not allowed the use of pressure activated PRDs. However, rupture disks have been used safely in some applications – for example, several million emergency breathing cylinders using rupture disks for protection have a safe service record.

There are several methods that may be used to design and manufacture a thermally activated PRD. The earliest method was to use fusible materials, specifically eutectic metal alloys. These thermally activated PRDs generally activate when triggered regardless of the pressure in the cylinder. This makes them a safer option than pressure activated PRDs if the application uses cylinders when they do not have full pressure. Care would be taken in the design of PRDs with fusible materials such that they do not extrude prior to being in a fire, and do not freeze shut once gas begins to flow when activated.

There are other materials that may be used in fusible PRDs besides eutectic alloys. Thermoplastic polymers would be an example. Glass globes, similar to those in fire sprinkling systems, are being used successfully. As temperature increases, a liquid inside the globe expands, breaking the globe and activating the gas release mechanism. Shape memory metals can be used to activate a gas release mechanism when a given temperature is reached. A gas release mechanism can be triggered if a pressurized gas is released from a fusible trigger. An ignitable device, such as a detonation (ignition) cord, can trigger a gas release mechanism. An electrical device, such as a thermocouple, can trigger a gas release mechanism. However, electrically powered sensors and PRDs are discouraged from use unless they have an uninterruptable supply of electrical power.

Other methods are expected to be developed over time. Any method should be suitable as long as it properly activates a mechanism that releases the cylinder's pressurized gas in a fire situation, and is sufficiently robust to handle the environmental conditions without degrading over the lifetime of the cylinder. Test methods should be developed to allow new PRD methodologies to be used, as they might be more effective and reliable.

A polymeric liner that melts and releases gas might be an acceptable pressure relief mechanism. However, it is necessary for the liner to reach its melting temperature before the composite is degraded sufficiently to rupture. This might be possible in some, but not all, applications.

Insulation, intumescent coatings, or heat deflectors may also be used to protect cylinders in a fire. While they might not release the contained gas, they can delay heat input to the cylinder and related damage to the composite, as reported by Webster, 2010[10]. The use of means to delay the effects of fire might be useful if the application or regulation puts a time limit on exposure to the fire, or allows a rupture after a specified time. If thermally activated PRDs are used in combination with methods to delay heat input, the heat should be allowed to flow to the PRDs with minimal restriction.

Combination PRDs are sometimes used where a pressure activated and thermally activated PRD are used together, either in series or parallel. An example of a series device would be a rupture disk backed by a fusible material. The fusible material might provide some structural support for the rupture disk, so that there is less cyclic fatigue over its life. The disk would not rupture until after the fusible material is activated. However, issues about venting partially charged cylinders would remain. A parallel device would be activated by either high pressure or high temperature. This would increase the opportunity to activate the PRD, but there would still be issues relating to fatigue life of the disk.

PRDs are often installed in one or both ends of a cylinder, particularly when the cylinder is of limited length. When longer cylinders are protected by discreet PRDs, it might be necessary to use a manifold and space the PRDs along its length. Some systems have multiple cylinders connected by pressurized manifolds, with one or more PRDs connected. When a PRD is activated, all of the cylinders on the manifold are vented. It is necessary to assure that all cylinders on the manifold can safely be vented through a single PRD before cylinder strength is degraded in the fire to the point where one might rupture. Care should be taken not to choke the flow when venting, either by having a small orifice to flow through, or by having an excessive length on a vent line, as this could prevent the cylinders from venting in a timely manner.

There are two fundamental modes in which a PRD can fail. A type 1 failure is when the device fails to operate when it should. A type 2 failure is when the device operates when it should not have. There are risks involved in either type of failure which should be considered when assembling a system. A subset of the type 1 failure is when the device begins to operate when it should, but fails to properly vent the cylinder, resulting in rupture. Examples of this include insufficient vent flow area, freezing of a eutectic that plugs the line after flow begins, or plugging of the flow area by contamination. The standards for the PRDs should have testing to reduce the risk of both types of failure of the PRD.

A 1997 report by Gambone[13] conducted a safety analysis using PRD performance statistics from the US, Canada, UK and Australia, revealed that NGV PRDs exhibit comparable-to-low failure rates when compared against other safety devices such as simple pressure relief valves and sprinkler heads. A comparison of NGV PRD reliability data to a reasonable level of expected safety (represented by the performance of all-steel cylinders manufactured by Faber), demonstrated that in the worst case PRDs are approximately two orders of magnitude less reliable than the cylinders they are designed to protect. Powertech Labs Inc., evaluated eight thermally activated PRDs and five series and parallel combination PRDs. Of these, only two thermally activated PRDs and none of the series and parallel combination PRDs met all of the requirements of the PRD-1[14] performance tests.

It is useful to consider reliability of the PRD to fail in either Type 1 or Type 2 mode when setting up a system with multiple cylinders and PRDs connected by a manifold, and how this relates to the reliability of the entire system. It is often the case that by minimizing the number of components, the overall reliability of the system can be improved.

It is also useful to consider risk with a PRD vs. risk without one. Composite cylinders are damaged in a fire, and would be expected to rupture in approximately five to 20 minutes, but possibly more or less. A PRD is essential if a rupture is to be avoided, unless other fire suppression systems are in use. Steel cylinders often last significantly longer in a fire, but even they are known to rupture if not equipped with a PRD. One step in understanding risk of not having a PRD on a cylinder is to know the distance within which a rupture might kill someone, or to have ear drums ruptured. These lethality/safety distances can be calculated.

Another factor in determining whether to use a PRD is to evaluate the toxicity of the contained gas. If the contained gas is highly toxic, the added risk of leakage through the PRD or the o-ring where it is installed, or the risk of a type 2 failure, might be greater than the risk of allowing the cylinder to rupture in a fire.

6.4 Venting

The PRD vents the contents of the cylinder when it is activated. The contents might be vented directly into the environment, or the gases might go through a vent line or vent manifold, generally depending on the application. Individual transportable cylinders would generally be vented directly. Cylinders in a tube trailer, or fuel containers on a CNG or H2 powered bus would generally go through vent tubing and be directed upwards, but some might direct gases sideways. Newhouse and Webster[3] reported that cylinders in bundles would be vented away from the bundle.

The choice of venting direction should include an assessment of whether the venting gas could catch fire, and what items could be ignited by the fire from venting. Depending on the amount of contained gas in the cylinder(s) being vented and the pressure at the exit of the vent, the flame plume could be significant. The characteristics of the plume, including diameter, length, and intensity of its flame, if present, would have some dependence on the vent nozzle, and whether there was mixing with air. While this is of interest, it is outside of the scope of a fire test, and if considered, would likely be in the PRD specification or a system specification.

One of the reasons for understanding, and perhaps standardizing, the venting process is for protection of first responders to the fire situation. Depending on direction of venting, which could be indicated on a vehicle or bundle, the first responder might choose to fight the initial fire or to stay back until venting occurs. They might decide to wait until all PRDs have activated or all cylinders have vented. First responders would also need to know that reseatable devices could open again at any time.

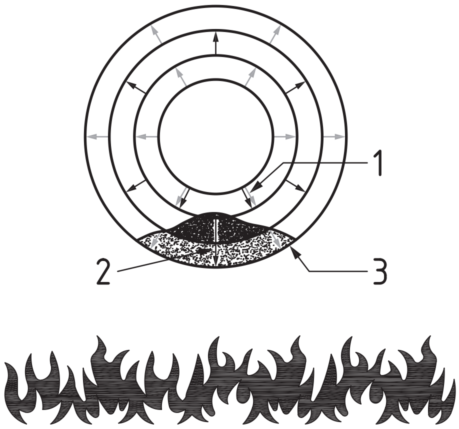
Vent manifolds should be protected against intrusion of water, which could cause corrosion or turn to ice. One obvious entry point for moisture is the end of the vent tube. However, any joint in the tubing that is not sealed could be an entry point. If a vent tube is cooled, such as if the bus enters a wash operation with water cooler than ambient, a relative vacuum can be generated within the tubing, and water vapour draw into the tube. Over time, this water vapour can condense and build up. If the water then froze, it could damage the tubing or the PRD, and it could prevent flow of gas through the vent tube. Vent manifolds should also be protected against intrusion of debris or insects, which have also been known to block vent lines.

The pressure capability of the vent line would be greater than the pressure of the venting gas to avoid rupture of the vent line. If the vent line is short and of a larger diameter, and the venting rate from the PRD is low, the vent line pressure might be very low. If the vent line is very long, sufficient to develop choked flow, or if the exit to the vent line reduces the flow, the pressure in the vent line might be equal to the pressure of the gas in the cylinder.

6.5 Interaction

The elements of the system, fire, composite, contained gas, PRD, and vent lines, interact. Understanding this interaction helps to understand safety and risk associated with the system. The contents of the cylinder increases in pressure as temperature rises, though in a more limited amount than for metal cylinders. The strength of the composite cylinder's reinforcement decreases with time of exposure to fire. The strength of the PRD decreases over time of exposure to the fire. The PRD activates when the right pressure or temperature is reached. The vent time varies according to the volume and type of gas to be released, and the characteristics of the vent line, including restrictions.

The fire would first increase the surface temperature of the composite cylinder, and heat is subsequently conducted into the laminate, and eventually into the contained gas, increasing its pressure. The conductivity of the composite is low, and heat transfer between the liner and contained gas is low, so the pressure increase is slow. Resin may be consumed by the fire, decreasing the radial modulus of the laminate, which reduces the strength contribution of the outer layers (see Figure 3). The temperature or fire may reduce the strength of the fibre itself. Glass fibre would melt, while aramid and carbon fibre would burn at some rate. It should be noted that these figures are intended solely to illustrate potential behaviour of a system during a fire event, and are not to be used as empirical data of any cylinder or PRD design.



Key

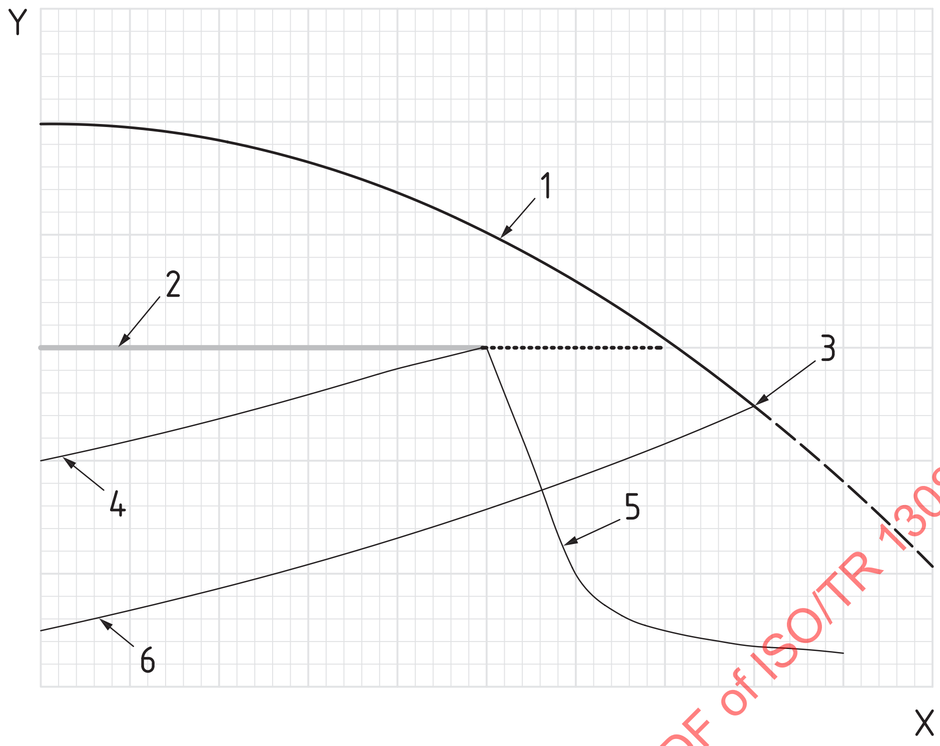
1 excessive load on inner layers resulting in rupture

2 damaged radial load path; load transfers to outer structural layers reduced

3 area affected by fire

Figure 3 — Effect of resin burning out of laminate

The following figures provide examples of interaction between fire, cylinder, and PRD components. Figure 4 illustrates pressure and strength of a temperature resistant cylinder, characteristic of steel, and a rupture disk in a fire. Figure 5 illustrates pressure and strength of a composite cylinder and a rupture disk in a fire. Figure 6 illustrates pressure and strength of a composite cylinder and a thermally activated PRD in a fire.



Key

X time

Y pressure

1 strength of steel cylinder in a fire

2 strength of rupture disk

3 cylinder rupture

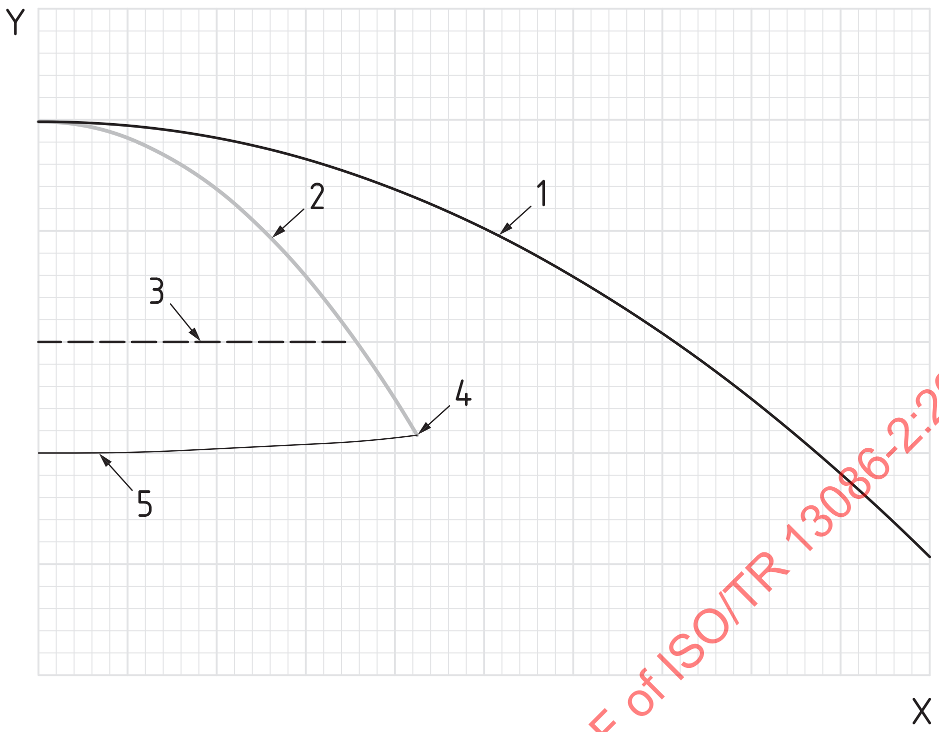
4 pressure rise, full fill

5 pressure drop after disk rupture

6 pressure rise, partial fill

Figure 4 — Pressure and strength of a steel cylinder and a rupture disk in a fire

It can be seen in Figure 4 that for a representative temperature resistant (e.g. steel) cylinder filled with gas at full pressure, could be protected from rupture in a fire by a rupture disk PRD, but a partially pressurized cylinder could rupture before the rupture disk PRD vents.



Key

X time

Y pressure

1 strength of steel cylinder in a fire

2 strength of composite cylinder in a fire

3 strength of rupture disk

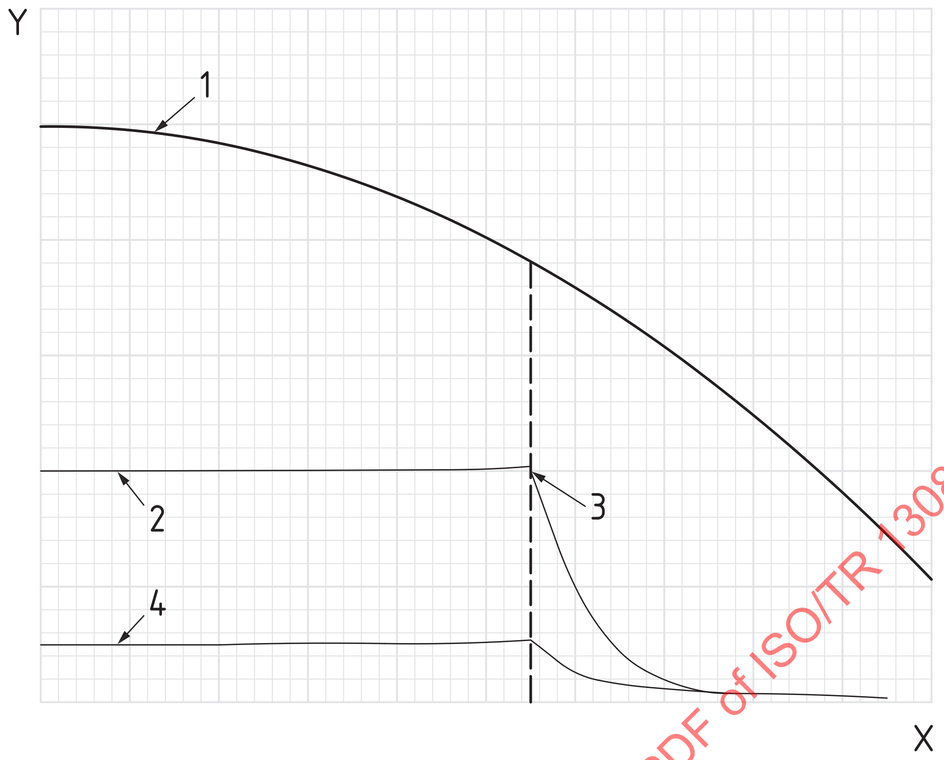
4 cylinder rupture

5 pressure rise, full fill

Figure 5 — Pressure and strength of a composite cylinder and rupture disk in a fire

It can be seen in Figure 5 that there is the potential that a composite cylinder protected by a rupture disk PRD could rupture whether it started at full pressure or partial pressure, specifically if the strength of the cylinder degrades too quickly in the fire or the internal pressure does not increase quickly enough so as to trigger the PRD before the cylinder fails.

The actual performance of a cylinder and PRD in a fire is a function of many factors. In part, the strength of the composite cylinder will depend on the specific composite materials utilized, the laminate wall thickness of the cylinder, and the temperature, heat output, and location of the fire. The time required for the internal pressure to increase to the rupture point of the burst disc will depend on the starting internal pressure, the water volume of the cylinder, the pressure rating of the burst disc, and the size and intensity of the fire. Because of this, the performance of a given cylinder and PRD configuration in a fire should always be validated through testing.



Key

X time

Y pressure

1 strength of composite cylinder in a fire

2 pressure rise, full fill

3 (T)PRD activates

4 pressure rise, partial fill

Figure 6 — Pressure and strength of a composite cylinder and thermally activated PRD in a fire

It can be seen in Figure 6 that a composite cylinder protected by a thermally activated PRD could be protected from rupture in a fire whether it started at full pressure or partial pressure.

It is necessary to have some margin for PRD activation vs. pressure, temperature and/or time in order to get reliability. Different pressure vs. time profiles might be needed for different cylinder types, fibre reinforcements, or application. These margins might affect first responder safety as well as people near the cylinder during operation. There are opportunities for research to understand degradation and margins. One way to get a first estimate of margins is to put a cylinder in a fire with no PRD, insulation, or coatings, and determine the time to burst.

Figures 4, 5 and 6 give some understanding of margins for a cylinder/PRD system. Other aspects to consider include the type and intensity of the fire, the type of PRD system, how temperature affects strength of components as well as their activation times, the time to vent a single cylinder vs. having multiple cylinders in a manifold vent through a single or multiple PRDs, full venting vs. choked vent flow, and the nominal pressure and volume of gas being vented. It should also be noted that under some conditions, a plug-type fusible PRD might have some re-freezing of the fusible materials following activation, which has some dependency on flow rate.

6.6 Availability of reports

Research performed by several organizations regarding hydrogen fuelled vehicles (HFV) found that many of the concerns related to vehicle safety of fuel storage systems in the hydrogen storage are similar to the compressed natural gas storage systems which can be found in reports by the United States (US) National Highway Traffic Safety Administration (NHTSA), including Flamberg, 2010[15]. A query of the United States' NHTSA databases ("Defect Investigations"[16]) contained over 45 000 records and of those records, since 1980, there were 3 185 "NHTSA Action Numbers", of which 11 investigations were related to CNG or CNG equipped vehicles. Six of the reported failures involved CNG cylinders and the other five reports involved leakage of CNG at crimped fittings, leakage at a regulator, and cylinder mounting bracket failures.

Reports on other field events may be obtained from other government agencies, standards developers, and from industry groups, including those involved with compressed gases and alternative fuel vehicles. Incidents include those where the PRD was not located in the same compartment as the cylinder, or where the PRD was otherwise not exposed to the fire. There have also been incidents where the vent rate was not sufficient after the PRD was activated.

6.7 Optimized test method using thermally activated pressure relief devices

6.7.1 Explanation of optimized test method

The traditional method of evaluating composite cylinder safety in a fire is to test the cylinder with its chosen PRD. When a design changes, particularly for longer cylinders or larger diameter cylinders, or anytime a new PRD is used, the fire test is run again. This testing is necessary based on how it is conducted, but can be onerous if there are several changes to PRDs used, or changes in manifolding or venting.

A new method for testing is presented in the following paragraphs that optimizes the test based on single component tests combined with analytical evaluation of system response. This method basically develops the “outer envelope” of acceptable performance of the cylinder, followed by testing of the PRD as a component, and evaluating the resulting system. The PRD to be used would be thermally activated.

The first step is to test a cylinder in a traditional manner in a fire. However, instead of using a traditional valve and thermally activated PRD, the cylinder should be fitted with a valve that can be operated remotely. The cylinder should be pressurized and put into the fire. The person conducting the test can start releasing pressure in the cylinder at the time they choose, and they can choose the rate of release of the contents. The intent is to maximize the envelope of the pressure vs. time chart without the cylinder rupturing. The pressure vs. time envelope thereby establishes the limits in which the cylinder can operate safely in a fire situation. A cylinder might be tested in a fire without opening the valve in order to determine the full time available before the cylinder ruptures.

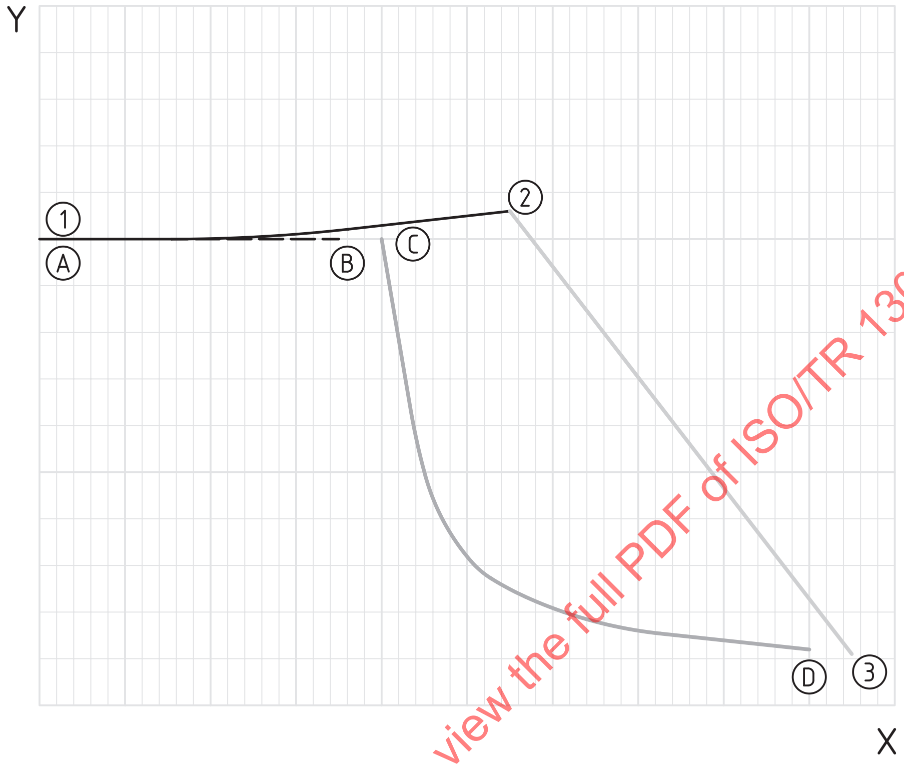
The second step is to test the PRD in a simulated fire to determine the activation time. A representative pressure should be seen by the PRD mechanism to confirm proper activation. Pressure might be provided by a small steel cylinder or pressure tube. Consideration would be given to the extent of exposure of the PRD to a fire, whether it will always be fully engulfed in flames, or whether it is some distance from the fire. This provides guidance to the system designer as to the proper spacing and location of PRDs.

The third step is to vent a cylinder, or multiple manifolded cylinders, through the activated PRD to determine the pressure vs. time to vent the cylinder(s). The PRD should include any vent lines that would normally be attached.

The fourth step is to combine the data from steps two and three, and compare the resulting figure with the pressure vs. time envelope developed in step one. If the figure generated from the data of steps two and three falls completely within the envelope generated by step one, the cylinder(s)/PRD combination is safe and can be put into service. If the figure falls outside the envelope generated by step one at any point, there is a risk of rupture that needs to be addressed. This risk might be removed by generation of a new envelope, or by using a different PRD, or by reducing the volume of gas needing to be released through the PRD.

The use of this test avoids the need to conduct a fire test on a cylinder every time a new PRD is used. It would also be a means to confirm acceptable safety, by checking different flow rates, if a different gas is to be contained. A new fire test would need to be conducted if there is a change in the reinforcing fibre, and might need to be conducted if there is a change in fibre manufacturer or change in other cylinder components. Figure 7 shows how a cylinder pressure vs. time envelope might be generated, and how the data from the second and third steps might be combined and compared with the safe envelope.

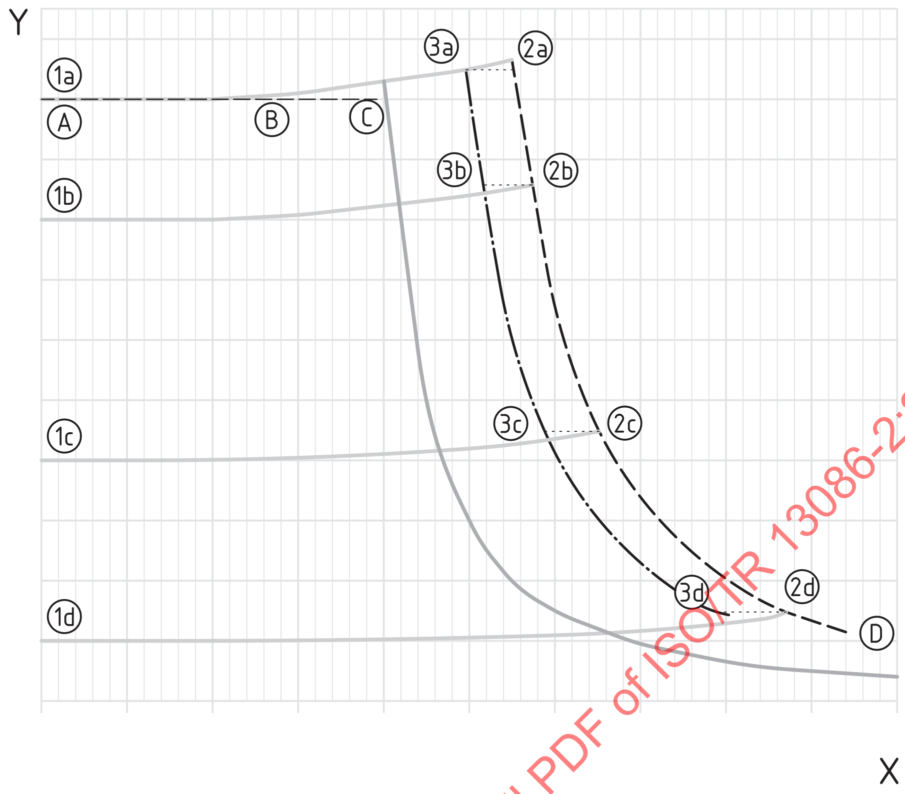
Consideration should be given to maintaining a time-based offset between the vent time from the cylinder test and the vent time from the PRD activation. For example, if the start of venting during the cylinder test was at three minutes, and a one minute margin was required, then venting in the PRD test would begin prior to two minutes of elapsed time, and the PRD test vent profile would remain one minute away from the cylinder vent profile until the contained pressure is less than 10 % of the working pressure.



Key

X	time
Y	pressure
(1)	pressurized cylinder is exposed to the test fire
(1)->(2)	internal pressure increases while the cylinder is exposed to the fire
(2)	vent valve is opened manually
(2)->(3)	pressure vs. time is established by controlling the vent valve
(3)	cylinder is vented
(A)	thermally activated PRD is introduced into the test fire
(B)	thermally activated PRD activates in the test fire
(C)	venting is initiated from the representative pressurized cylinder or cylinder assembly through a representative activated PRD and vent tube assembly
(D)	cylinder/cylinder assembly is vented
(A)->(B) and (C)->(D)	this data is generated separately, then added together (A time based safety margin should be added between point B and point C)
Test requirement: (A)->(B)+(C)->(D)	this line is entirely within the (1)->(2)->(3) line

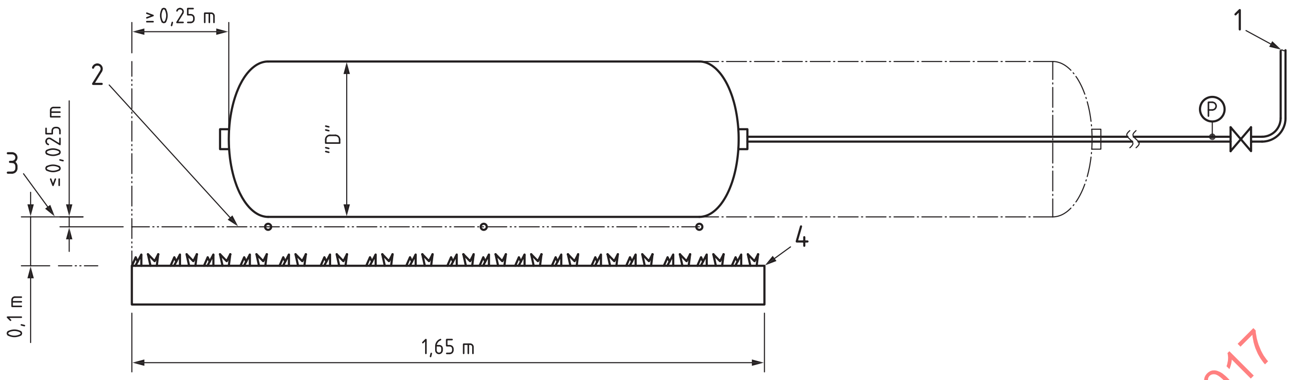
Figure 7 — Generation of a safety envelope and actual cylinder/PRD performance (Method 1)



Key

X	time
Y	pressure
(1a, 1b, 1c, 1d)	pressurized cylinder is exposed to the test fire
(1)->(2)	internal pressure increases while the cylinder is exposed to the fire
(2a, 2b, 2c, 2d)	cylinder ruptures
(2)->(3)	time offset margin
(3a)->(3b)->(3c)->(3d)	safety envelope
(A)	thermally activated PRD is introduced into the test fire
(B)	thermally activated PRD activates in the test fire
(C)	venting is initiated from the representative pressurized cylinder or cylinder assembly through a representative activated PRD and vent tube assembly
(D)	cylinder/cylinder assembly is vented
(A)->(B) and (C)->(D)	this data is generated separately, then added together
Test requirement: (A)->(B)+(C)->(D)	this line is entirely within the (1a)->(3a)-> (3b)->(3c)->(3d) line

Figure 8 — Generation of a safety envelope and actual cylinder/PRD performance (Method 2)



Key

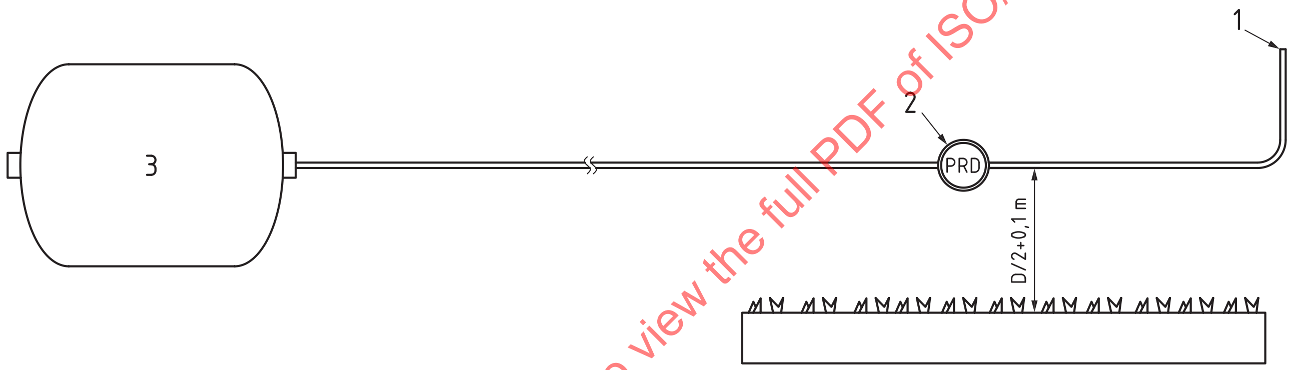
1 vent stack

2 line containing thermocouples

3 line representing lower surface of cylinder

4 fire source

Figure 9 — Standard fire set-up



Key

1 vent stack

2 thermally activated pressure relief system

3 gas source

Figure 10 — PRD fire set-up

6.7.2 Procedures for optimized test method

Following is a standardized test approach using this new test method. Annex B incorporates this approach into test requirements that could be used in a standard.

1) Cylinder preparation for fire test (see Figure 9)

   a) The cylinder is pressurized with the contained gas at working pressure. Tests may be conducted at ambient temperatures between −7 °C and 43 °C (20 °F and 110 °F), but the container settled pressure is to be temperature compensated to 15 °C (60 °F). Limit wind to 2,25 m/s to avoid problems with the flame.

   b) A valve is installed such that the valve may be opened, and the flow rate controlled, during the test.

   c) Metallic shielding or insulation of the valve and attached tubing components is allowed, but not required.

   d) Thermocouple location: At least three thermocouples are placed along the bottom of the cylinder under test not more than 0,75 m apart and within 25 mm (1 in) of the surface of the cylinder. Each thermocouple may be attached to a steel cube up to 25 mm (1 in) on a side.

Thermocouples are to be protected from direct flame impingement by attaching to steel cubes as mentioned above or by metallic shielding of a minimum of 0,4 mm (0,016 in) thickness.

NOTE The purpose of the 25 mm steel cube is to average out temperatures over time, i.e. to average over the time period while alternately being directly in the flame vs. in air.

e) Cylinder internal pressure is monitored and recorded vs. time.

2) Cylinder orientation

a) Cylinders that are mounted vertically may be tested in a vertical orientation.

b) Cylinders that are mounted horizontally and are less than or equal to 1,65 m (65 in) long should be horizontally oriented with a fire source below the centre of the long axis of the cylinder for the entire length of the cylinder.

c) For cylinders of length greater than 1,65 m, the cylinder is to be positioned horizontally such that one end is approximately 0,25 m inward from the edge of the fire.

3) Fire sources: The fire source can be any fuel provided it supplies uniform heat sufficient to maintain the specified temperature until the cylinder has vented. Gaseous fuel sources are recommended based on ease of control and avoidance of environmental contamination in the event of cylinder rupture. A uniform fire source of 1,65 m (65 in) length provides direct flame impingement on the container surface across its entire diameter. The bottom surface of the cylinder is to be about 0,10 m above the base of the fire.

4) Fire test requirements: Thermocouples are to be recorded at least every 30 seconds for the duration of the fire test. Internal cylinder pressure is to be recorded at least every 10 seconds. Fire test temperature is to be ≥ 590 °C (1 094 °F) as measured using at least three thermocouples. Within five minutes following fire ignition the temperature of two of the three thermocouples are to be ≥ 590 °C (1 094 °F) and two of the three thermocouples are to be ≥ 590 °C (1 094 °F) throughout the duration of the test.

5) Pressure vs. time: The valve may be opened at any time, and the flow rate changed vs. time, as long as the pressure vs. time is being recorded. Pressure vs. time is to be recorded until the pressure is less than 5 % of the working pressure.

a) Alternate procedure: The pressure vs. time record may be established by fire testing cylinders that are maintained at a given pressure until the cylinder ruptures. A minimum of four cylinders are required, with initial pressures being 100 % of working pressure (SP), 80 % of SP, 40 % of SP, and 5 % of SP. The test may be stopped after 30 minutes and no rupture has occurred. The time of rupture, or stoppage of the test, is to be noted.

6) PRD preparation for fire test (see Figure 10)

a) One thermally activated PRD is connected to a pressure source that contains gas pressurized to the working pressure of the intended application.

b) A second thermally activated PRD is connected to a pressure source that contains gas pressurized to 25 % of the working pressure of the intended application.

7) PRD orientation

a) Each PRD, tested separately, is to be centred over the fire.

b) The PRD is to be located a distance above the base of the fire equal to 1/2 the diameter of the largest cylinder to be protected, plus 0,1 m. If the PRD is intended to be located in a position other than the end boss, it should be located a distance above the base of the fire equivalent to what would be seen in service, but no closer than 0,1 m.

c) It is not necessary for the pressure source to be exposed to the fire.

8) PRD fire sources: The fire source can be any fuel provided it supplies uniform heat sufficient to maintain the specified temperature until the PRD has activated. Gaseous fuel sources are recommended based on ease of control. A uniform fire source of at least 0,3 m diameter, and no more than 0,6 m by 0,6 m, provides heating to the PRD.

9) PRD fire test requirements: Thermocouples are placed in the fire approximately 0,1 m from the bottom of the flame. Temperature is recorded at least every 30 seconds for the duration of the test. Fire test temperature is to be ≥ 590 °C (1 094 °F) as measured using at least three thermocouples. Within five minutes following fire ignition the temperature of two of the three thermocouples are to be ≥ 590 °C (1 094 °F) and two of the three thermocouples are to be ≥ 590 °C (1 094 °F) throughout the duration of the test.

10) PRD activation time: The activation time for the PRD is to be recorded, along with the pressure at time of activation, i.e. 25 % or 100 % of working pressure.

11) Vent time test

a) The two PRDs from the PRD fire test are checked for flow rate. The PRD offering the higher resistance to flow (i.e. the lower flow rate), is to be used for the vent time test.

b) A cylinder, tube, or assembly of same, representing the largest combined volume that will be protected by the PRD, are assembled and connected to a valve, and the valve connected to the selected PRD.

c) The outlet of the PRD is connected to a vent tube representative of the flow area, length, fittings, and orientation expected to be used in service.

d) The valve is opened, and the pressure vs. time recorded until the pressure drops below 5 % of working pressure

12) System evaluation (see Figure 7 and Figure 8)

a) Generate the system fire test safety envelope using one of the following.

i) Method 1

1) The pressure at the start of the fire test is plotted.

2) From that point, the pressure vs. time is plotted during the fire test, up to the point when the valve is opened.

3) The pressure vs. time is plotted during the fire test, from the point when the valve is opened to the point where the pressure is less than 5 % of the working pressure.

ii) Method 2

1) The pressure at the start of the fire test is plotted.

2) The pressure vs. time is plotted during the fire test, up to the point when the cylinder held at 100 % of working pressure ruptures.

3) The time point for rupture is plotted at the hold pressure for the cylinders held at 80 %, 40 %, and 5 % of working pressure.

4) A best-fit curve is plotted through the various rupture points.

b) Generate the venting plot as follows.

1) The pressure at the start of the fire test is plotted.

2) From that point, and maintaining pressure, add the time based safety margin.

3) From that point, and maintaining pressure, add the time for the PRD to activate.

4) From that point, plot the pressure vs. time from the venting test.

c) Compare the venting plot and the safety envelope to confirm the pressure is always below the safety envelope; consider a time offset, either as a fixed time offset of a percentage of the time to activate the PRD, in consideration of scatter in the activation time of the PRD, or, and/or consider multiple PRD tests be better characterize the scatter; if no PRD is to be used, a minimum time to rupture would be established in order to allow time to put the fire out or reach a safe distance.

13) Successful system test: A successful fire protection system test is one in which the profile from the venting plot, including the time based safety margin, is entirely within the system fire test safety envelope, to the point where the pressure is 10 % of the working pressure.

14) Failed system test: A failed fire protection system test is one in which the profile from the venting plot, including the time based safety margin, touches (except at the starting point), or is outside of the system fire test safety envelope, to the point where the pressure is 10 % of the working pressure.

15) A single test is generally considered adequate for qualification, based in part on prior testing of similar cylinders. If a non-typical cylinder or PRD is used, consideration should be given to additional tests for characterization.

16) Design changes: It is generally accepted that a test should be conducted if a design change is likely to change the results of the test. For a bonfire test, such design changes include:

a) If the total system volume increases, conduct a vent test and reconstruct the venting plot and system test evaluation.

b) Significant change in pressure. This includes an increase in pressure of 20 % or more.

c) If a new PRD is used, rerun the PRD fire testing and vent testing, and reconstruct the venting plot and system test evaluation.

d) If the fibre type is changed. This includes changes between carbon, aramid, and glass fibre, but generally not for changes in manufacturer for the same type of fibre. Rerun the cylinder fire test, and reconstruct the system fire test safety envelope and system test evaluation.

e) If the liner material is changed. This includes changes between steel, aluminium, and polymer liners, but generally not for changes in supplier. Rerun the cylinder fire test, and reconstruct the system fire test safety envelope and system test evaluation.

7 Summary

Clause 6 provides a basic understanding of the system elements involved in demonstrating cylinder performance and safety during a fire test. The current methods of fire testing have resulted in a high level of field safety in fires, but testing might need to be repeated with minor design changes. A new approach to system testing is presented that would give better understanding of safety margins and an easier path to qualifying new components and systems.

Based upon field failure data and testing of CNG vehicle fuel cylinders and hydrogen fuel system cylinders, care in designing systems is recommended so that localized exposure would not occur and the PRD would not be isolated from the cylinder. The alternative would be additional testing with localized fires.

Annex A
(informative)

Comparison of fire tests in standards and reports

Standard	Fire type(s)	Requirements	Comments
ISO 11119-3[5] Gas cylinders — Refillable composite gas cylinders and tubes. Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 L with non-load-sharing metallic or non-metallic liners. ISO 11119-3 applies to cylinders intended for transportation of compressed or liquefied gases.	Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified test temperatures until the cylinder is vented. A uniform fire source of 1,65 m length shall be used that is capable of enveloping the entire diameter of the cylinder and provide direct flame impingement on the cylinder surface across its entire diameter, when in the horizontal position.	Surface temperatures shall be monitored by thermocouples located along the bottom of the cylinder and spaced not more than 0,75 m apart and shielded from direct flame impingement with metallic shielding of a minimum 0,4 mm thickness. Thermocouple temperatures and the cylinder pressure shall be recorded at intervals of 30 s or less during the test. The fire source shall produce a temperature of at least 590 °C, measured within two minutes on the bottom surface of the cylinder. The timing of the fire test shall start when the thermocouple temperature reaches 590 °C and all thermocouples must register a temperature of at least 590 °C for the remainder of the test. For cylinders with a PRD, the cylinder shall be exposed to the fire until it has vented to a pressure less than 7 bar. For cylinders without PRDs, the cylinder shall not rupture within two minutes	3.22 working pressure - settled pressure of a compressed gas at a reference temperature of 15 °C in a full gas cylinder. For cylinders intended to be fitted with a specified pressure-relief devices the cylinders shall vent through the pressure-relief devices. For cylinders intended for liquefied gases a leak through the cylinder wall is acceptable.

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ISO 11439[6] Gas cylinders — High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles. This International Standard covers cylinders of any seamless steel, seamless aluminium alloy or non-metallic material construction, using any design or method of manufacture suitable for the specified service conditions. Cylinders covered by this International Standard are designated type 1, type 2, type 3 and type 4. Type 4 design - A fully wrapped cylinder with a non-load sharing liner and composite reinforcement on both the cylindrical part and dome ends.	Fire source Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified test temperatures until the cylinder is vented. For cylinders of length 1,65 m or less, the centre of the cylinder shall be positioned over the centre of the fire source. Immediately following ignition, the fire shall produce flame impingement on the surface of the cylinder along the 1,65 m length of the fire source and across the cylinder diameter width.	A.15.5 General test requirements The cylinder shall be pressurized to working pressure with natural gas and tested in the horizontal position at working pressure and, if a thermally activated PRD is not used, also at 25 % of working pressure. Working Pressure – 200 bar (2 900 psi) at 15 °C (59 °F). Max filling psi – 260 bar (3 770 psi) Fire test requirements. Within five min of ignition the temperature on at least one thermocouple shall indicate a temperature ≥ 590 °C. This minimum temperature shall be maintained for the remainder of the test. If the temperature of 590 °C is not reached within five min but the cylinder vents, through the PRD, within five min without rupturing, the test is considered successful. Any failure during the test of a valve, fitting or tubing that is not part of the intended protection system for the design shall invalidate the result.	The cylinder shall be placed horizontally with the cylinder bottom approximately 100 mm above the fire source. Metallic shielding of a minimum 0,4 mm thickness shall be used to prevent direct flame impingement on cylinder valves, fittings, and/or PRDs. The metallic shielding shall not be in direct contact with the specified fire protection system (PRDs or cylinder valve). Cylinder set-up For cylinders of length greater than 1,65 m: a) if the cylinder is fitted with a PRD at one end, the fire source shall commence at the opposite end of the cylinder; b) if the cylinder is fitted with PRDs at both ends, or at more than one location along the length of the cylinder, the centre of the fire source shall be centred midway between the pressure relief devices that are separated by the greatest horizontal distance; c) if the cylinder is additionally protected using thermal insulation, then two fire tests at service pressure shall be performed, one with the fire centred midway along the cylinder length, and the other with the fire commencing at one of the ends of a second cylinder.
EN 12245:2009 (E)[7] Transportable gas cylinders. The purpose of this European Standard is to provide a specification for the design, manufacture, inspection and testing of refillable, transportable fully wrapped composite cylinders.	5.2.12.1 Test 12 – Fire Resistance Test Fire source shall be created using wood or kerosene. NOTE Examples of Standards that contain directions to produce a suitable fire test are EN ISO 11439, CGA C14 1992 and EN 3-1. The fire shall be capable of enveloping the entire length of the cylinder and valve, but in no case shall the flames be allowed impinge directly on to the PRD.	Cylinder(s) shall be pressurized with either air or nitrogen to 2/3 test pressure. The fire shall be capable of producing a temperature of at least 590 °C, measured at no more than 25 mm below the cylinder within two min. Criteria 5.2.12.2 a) For cylinders fitted with a PRD, the cylinders shall vent through the PRD. For cylinders intended for liquefied gases, a leak from the cylinder wall is acceptable. b) For cylinders not intended to be fitted with a PRD, the cylinders shall not burst during a period of two min from the start of the test. Cylinders may leak through the cylinder wall.	Procedure: Two cylinders shall undergo test: a) one in horizontal position and b) one in vertical position. If the cylinder is too long to enable the fire to envelop the entire length of the cylinder in the vertical position, and the cylinder does not have a PRD on both ends, the vertical bonfire test can be replaced with a second horizontal bonfire test cylinders shall be fitted with a PRD (one of two types) see 5.2.12.1.

Standard	Fire type(s)	Requirements	Comments
ANSI NGV 2-2007[8] For Compressed Natural Gas Vehicle (NGV) Fuel Containers. This standard contains requirements for the material, design, manufacture and testing of serially produced, refillable Type NGV 2 containers intended only for the storage of compressed natural gas for vehicle operation. These containers are to be permanently attached to the vehicle. Type NGV 2 containers shall not be over 1 000 litres (35,4 ft3) water capacity. The information in this table is related to Type 4 containers, namely, resin impregnated continuous filament with a non-metallic liner.	Any fuel which provides uniform heat and sufficient temperature to meet the requirements. A uniform fire source of 1,65 m (65 in) length shall provide direct flame impingement on the container surface across its entire diameter. Immediately following ignition, the fire shall produce flame impingement on the surface of the container along the 1,65 m (65 in) length of the fire source and across the container diameter.	Containers shall be pressurized with natural gas or methane (Tests may be conducted at ambient temperatures between −7 °C and 43 °C (20 °F and 110 °F), but the container settled pressure shall be temperature compensated to 21 °C (70 °F) and tested in the horizontal position at both: a) The service pressure; b) 25 % of the service pressure (not required if a thermally activated device is used). Flame temperatures shall be monitored by at least three thermocouples suspended in the flame within 25 mm (1 in) of the surface. The thermocouples may be attached to steel cubes up to 25 mm (1 in) on a side. Thermocouple temperatures and the container pressure shall be recorded at least every 30 seconds during the test. Within five minutes of ignition the temperature at two of the three thermocouples shall average at least 430 °C (800 °F) over any one minute interval. This average temperature shall be maintained for the remaining duration of the test.	Acceptable results. The container shall vent through a PRD without bursting. In the event that complete venting occurs in less than five minutes, the minimum temperature requirements do not apply. NOTE Minor leakage from other components may occur during the test.