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

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).

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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.

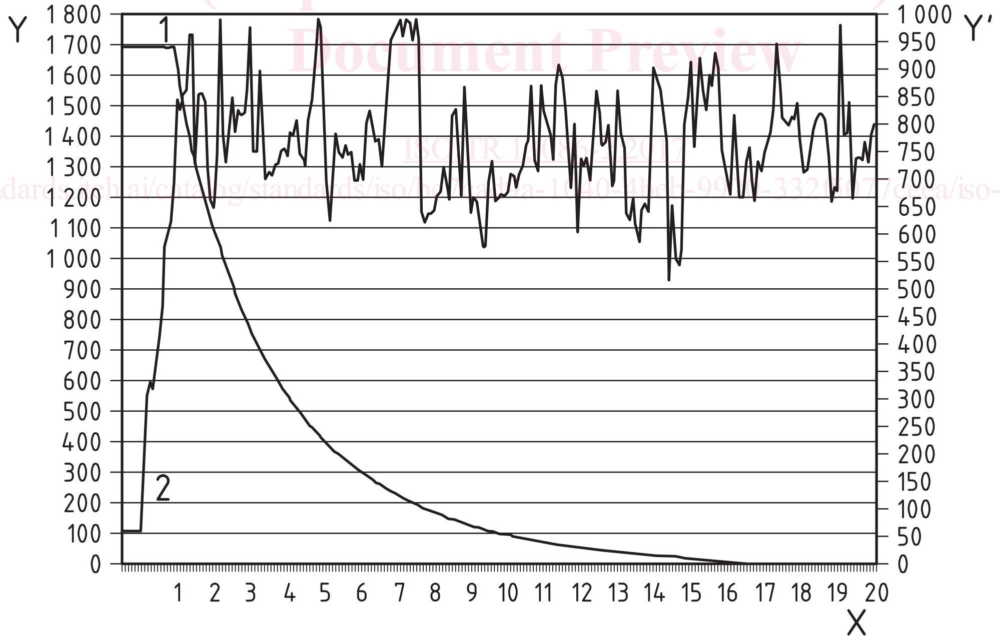
Fuels used in bonfire tests typically have included kerosene, diesel fuel, or kerosene soaked wood. More recently, natural gas or propane has been used in burners that are oriented to cover a given portion of the cylinder. Hydrogen/oxygen burners have also been used experimentally. The flow of gas can 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.

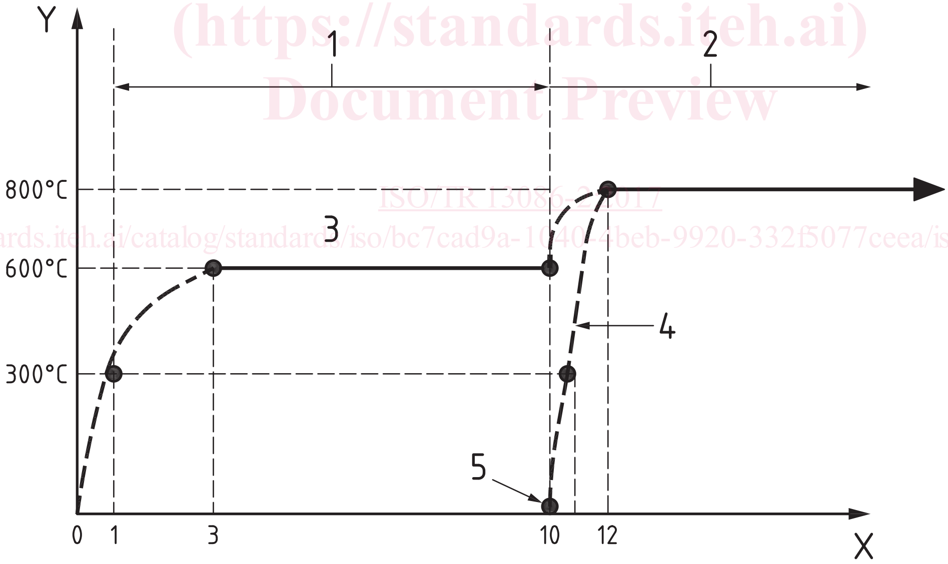
Table 2 — Examples of standards or reports that address fire testing

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