

LPG stored at the wildland–urban interface: recent events and the effects of jet fires and BLEVE

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ABSTRACT

Background. Jet fires and boiling liquid expanding vapour explosions (BLEVEs) are potential events when a vessel containing liquefied petroleum gas (LPG) is exposed to fire. Events involving domestic LPG tanks have occurred at wildland–urban interface areas in Portugal, the USA, Spain and Greece. **Aims.** Evaluation of the pressure relief device (PRD), the type of cylinder and the effects of jet fires and BLEVEs. **Methods.** LPG cylinders manufactured with steel and composite materials were exposed to fire. Hydrostatic tests were carried out to compare the burst pressure without fire influence. Fourteen accidents that occurred during wildfires are described. **Key results.** The presence of a PRD and the right choice of type of cylinder as well as cylinder location may avert major accidents. The jet fires and fireball radiation are also described, as well as the maximum distance reached by cylinder fragments. **Conclusions.** The tests showed that the burst pressure in the test of a cylinder without PRD under fire was significantly lower when compared with the hydrostatic tests. **Implications.** Lastly, recommendations to avoid accidents are made.

Keywords: accident, BLEVE, explosion, forest fire, fragmentation, gas, jet fire, LPG cylinders, pressure relief device, wildfire, wildland–urban interface fires.

Introduction

Wildland fires are frequent events in several parts of the world, namely in the USA, Canada, Australia and in the European Mediterranean basin. Wildfires are one of the most devastating environmental hazards in Portugal, causing severe socio-economic and environmental consequences, as well as fatalities (Pinto *et al.* 2017; Oliveira *et al.* 2020; Ribeiro *et al.* 2020; Viegas *et al.* 2021; Barbosa *et al.* 2022a). These fires are becoming more frequent and larger owing to climate change, sometimes affecting areas that did not burn previously (Baum 1999; Oliveira *et al.* 2020; Pastor *et al.* 2020). Portugal and Greece, in 2017 and 2018 respectively, suffered fires that caused more than 200 fatalities, mostly among civilians (Tedim *et al.* 2018; Oliveira *et al.* 2020; Pastor *et al.* 2020; Ribeiro *et al.* 2020; Viegas *et al.* 2021).

Liquefied petroleum gas (LPG) cylinders are widely used in Portugal for different purposes including cooking, heating water and to create a warmer environment within houses (Heymes *et al.* 2013; Scarponi *et al.* 2020). As the majority of rural and wildland–urban interface (WUI) areas do not have piped gas, LPG cylinders are used. When a wildfire occurs nearby, the cylinders become a hazard for people because of the large amount of energy stored, as they can trigger major accidents. Several accidents caused by forest fires have been recorded in Portugal, the USA, Spain and Greece, and others, related to LPG vessels of different sizes (Bartholomew 2016; Viegas *et al.* 2017, 2019; Caballero *et al.* 2019; Scarponi *et al.* 2020; Barbosa *et al.* 2022a). Fourteen accidents or incidents closely related to wildfires, and showing that LPG reservoirs can become unsafe when a WUI fire occurs, are described in the present work in the next section.

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There are different types of cylinders used to store LPG manufactured under European Standards (European Committee for Standardization 2010, 2011, 2017). For this reason, a high-quality process is applied during manufacture to avoid accidents. However, they are not manufactured for use under fire exposure. The cylinders manufactured with steel comply with European standard EN 1442, which allows a volume expansion capacity of 20%. However, cylinders manufactured with composites under European standard EN 12245:2009: +A1 do not have this volume expansion capacity. Thus, they have a pressure relief device (PRD) coupled to them, opening at lower pressures when compared with a PRD coupled to a steel cylinder.

In Portugal, composite cylinders are only traded filled with butane, whereas steel cylinders are traded having butane or propane. The valves coupled to a cylinder are chosen under European Standard EN 15995. Some traders sell the LPG cylinder filled with propane without a PRD. Thus, it can become a great hazard when a fire occurs. All cylinders filled with butane are traded with PRDs because they are aimed for domestic use.

Regarding the materials, steel cylinders are completely made of metal, whereas the composite ones are manufactured with three layers of different overlapping materials. The outer layer is made of polyethylene, and contains brand stamps and carrying handles. The middle layer is a composite liner made with braided filaments of fibreglass and polypropylene. The inner layer is a thin coat made of steel. Hence, there is a great difference in material properties when comparing both types of cylinders.

Propane gas has a higher vapour pressure than butane. At room temperature, a cylinder filled with propane can be at a pressure approximately four times higher than a butane cylinder. The higher pressure makes a propane cylinder more dangerous than a butane cylinder. When exposed to fire-induced heating, there will be a faster pressure increase rate that may jeopardise the surroundings. There are few papers describing experimental tests with LPG cylinders exposed to fire (Stawczyk 2003; Heymes *et al.* 2013; Tschirschwitz *et al.* 2017, 2018; Barbosa *et al.* 2022a). However, these works did not evaluate the PRD action. Recently, a protective device to minimise the effects of fire on a gas cylinder was proposed (Barbosa *et al.* 2022a).

Heating an LPG cylinder can cause serious events: for instance, it may trigger a boiling liquid expanding vapour explosion (BLEVE). The BLEVE occurs in pressurised vessels, which can cause severe damage to people and infrastructure. It is quite often associated with fires because the majority of cases happened due to radiation, engulfment, or flame impingement. However, a BLEVE can also happen owing to overfilling, impact on tank's surface, manufacturing defects and corrosion (Crowl and Louvar 2002; Abbasi and Abbasi 2007). The heat flux leads to high wall temperatures, weakening the wall (Heymes *et al.* 2013). Furthermore, once the vessel is exposed to, engulfed by or impinged by fire,

cylinder failure can happen quickly. The wall region in contact with the vapour phase has a higher temperature than the wall region wet by the liquefied phase. Thus, this leads to a hot spot and the structure becomes unstable and prone to bursting (Manu *et al.* 2009). The main BLEVE effects are thermal radiation from a fireball (when the fluid is combustible), fragments projected and overpressure, all of which jeopardise the surroundings (Baum 1999; Roberts *et al.* 2000; Planas-Cuchi *et al.* 2004; Casal and Salla 2006; Hemmatian *et al.* 2017a, 2017b). BLEVEs may be avoided if the cylinders have a PRD coupled, given the fact that the valve may prevent a large pressure increase. However, in a few cases, when the heat dose is high, a BLEVE can still happen. If the PRD works, instead of an explosion, a less dangerous event – a jet fire – may occur. However, either event can trigger a domino effect (Landucci *et al.* 2017).

There are many predictive methods to estimate the energy, flame shape and effects associated with a BLEVE or a jet fire (Planas-Cuchi *et al.* 2004; van den Bosch and Weterings 2005; Casal and Salla 2006; Casal 2008; Hemmatian *et al.* 2017a, 2017b). An important review of BLEVE and its mechanism, effects and predictive models was made by Abbasi and Abbasi (2007). For jet fires, recent papers have discussed the best geometry to fit the flame shape, for instance an ellipse, a cylinder, a conical frustum, cylinders with different intensities of surface emissive power, or horizontal and vertical jets (van den Bosch and Weterings 2005; Casal 2008; Palacios and Casal 2011; Palacios *et al.* 2012, 2020; Bradley *et al.* 2016).

Recent accidents and incidents with gas storage that occurred during WUI fires

In this section, recent LPG-related accidents and incidents that occurred during WUI fires are presented. In Table 1, the 14 cases mentioned in this work are listed. The cases are also briefly presented.

Cases 1 and 2: wildfire in Funchal, Portugal, August 2016

In August 2016, adverse weather conditions caused by an anticyclone in the northeast of the Iberian Peninsula and a depression in Morocco led the Madeira Islands to have extreme values of temperature and relative humidity between 5 and 10 August. In the south of Madeira, the air humidity reached 10–20% and temperatures $\sim 38^{\circ}\text{C}$. On 9 August, the most extreme weather conditions were registered: the wind reached 35 km h^{-1} with wind gusts of 80 km h^{-1} ; the minimum temperature registered was 29.6°C , which is 3.7°C higher than the last highest value registered in 1976 (IPMA 2016; Caballero *et al.* 2019).

On 8 August, at $\sim 3:30\text{ pm}$, an ignition occurred in a forest close to the WUI area. The local conditions of high

Table 1. A summary of recent accidents and incidents related to LPG during WUI fires.

Case	Fatalities	Type	Effect	Year
1	–	Cylinder	Burst – windows and door were found broken	2016
2	–	Cylinder	Four cylinders impinged by fire	2016
3	1	Cylinder	Burst – the explosion destroyed part of the house	2017
4	–	Cylinder	Two cylinders – first one burst and fragments hit the second one causing a jet fire	2017
5	1	Cylinder	Burst – the kitchen and its roof were destroyed	2017
6	–	Cylinder	Burst – a large part of the house was destroyed	2017
7	–	Cylinder	21 cylinders – some burst	2017
8	–	Tank	Jet fire	2016
9	–	Tank	Jet fire	2016
10	–	Tank	A jet fire may have happened	2018
11	–	Cylinder	An explosion may have happened	2018
12	–	Cylinder	Five cylinders impinged by fire	2018
13	–	Cylinder	Burst – the structure collapsed	2015
14	–	Tank	Jet fire	2016

temperatures, low humidity and strong wind increased fire spread to WUI areas, and ultimately, to urban areas. The fire spread initially uphill through the forest zone, coming downhill afterwards owing to the prevailing wind direction. These extreme conditions exposed houses, the water treatment plant and a five-star hotel to fire. On 9 August, 36 houses burned, 600 habitants and the João de Almada Hospital were evacuated and three fatalities occurred.

In two houses, LPG cylinders were directly affected by the fire. Non-natural fuels and forest fuels in the surroundings of the house contributed to the cylinder's fire impingement.

In the first house (Case 1), the cylinder burst. Damage from the BLEVE was found in the door and windows.

In the second house (Case 2), four LPG cylinders were impinged by flames. The house was destroyed by the fire, but a BLEVE did not happen.

No fatalities related to LPG cylinders were registered for Cases 1 and 2.

Cases 3 and 4: Pedrógão Grande fire complex, Portugal, June 2017

The Pedrógão Grande wildfire was a large fire in Portugal, possibly the second worst in Portuguese history. It caused 65 fatalities and ~200 injuries, and 45 328 ha were burned. This large wildfire was caused by at least two different ignitions on the same day, 17 June, at ~2:30 and 3:30 pm (local time), respectively in Escalos and Regadas. On 17 June, the Portuguese Institute for Sea and Atmosphere (IPMA) registered 80% of the Portuguese territory as having dry conditions. Accumulated precipitation was close to the lowest in the period records (1970–2017). The Fire Weather

Index (FWI) was 26, which means a very high risk (Viegas *et al.* 2017; Ribeiro *et al.* 2020).

Case 3

In the early morning of 18 June, a blind person who lived alone in a house in Balsa did not realise that the fire had ignited in an annex of the house where a gas cylinder was kept. The subsequent explosion destroyed that part of the house where the person lived and, ultimately, also killed her.

Case 4

In the fire zone, near Louriceira, there was a motorhome that was used for summer vacation by a tourist. On 20 June, the fire reached the motorhome at ~5 pm. An explosion was heard by firefighters who were nearby, who also saw dense smoke spreading upwards. A save-and-rescue team was sent but they soon realised that a cylinder burst had happened. Inside the motorhome were two mobile LPG cylinders. The first cylinder burst and fragmented. The second one was hit by the burst, which created a hole in cylinder's surface, causing LPG release and burning until the cylinder was empty (Viegas *et al.* 2017).

Cases 5–7: October wildfire, Portugal, October 2017

Owing to the long dry season, the same cited in Case 3, combined with Hurricane Ophelia (Level 2–3 on the Saffir–Simphson scale), which caused powerful winds (50 km h⁻¹), many ignitions occurred on 15 October, leading to fast fire spread in multiple locations. October 2017 was the warmest since 1931 and the driest since 1997. In

24 h, 220 000 ha burned. On this day, a moisture content of 10% in fine forest fuels was recorded and, in some places, values close to 5% were found. The dry season, powerful winds and low moisture content triggered a large wildfire, resulting in the largest burned area recorded in Portugal. The FWI was 82 (maximum risk) and 532 ignitions were registered on 15 October. This wildfire caused 51 fatalities (Viegas *et al.* 2017, 2019).

Cases 5, 6 and 7 happened during the October wildfire.

Case 5

In Oliveira do Hospital, a house on a hill was reached by a fire spreading very fast uphill. The house had walls built of stone. The kitchen and its roof were totally destroyed, and only the stone walls were left standing. After visiting the house ruins, a cylinder burst was suggested by the research team as the cause for the great destruction. A fatality that happened in this house may have been related to the burst (Viegas *et al.* 2019).

Case 6

At ~4 pm, the wildfire reached a small village called Vale do Laço. Citizens and firefighters were trying to save themselves, their houses and their belongings. A house nearby, situated on a slope and close to forest fuels, was affected by the wildfire. There were two brothers living there. At ~8 pm, in the aftermath of the fire, firefighters and habitants mentioned a suggestion made to the two brothers to leave and go into town. However, the brothers had declined this advice and remained at home. They later observed smoke coming from the attic, probably caused by an ember from some rekindling that entered through an open window. They tried to extinguish it but unsuccessfully, which led to one fatality. On the day after, during the fire aftermath, an LPG cylinder burst, destroying a large part of the house but fortunately without causing casualties (Viegas *et al.* 2019).

Case 7

In Oliveira do Hospital, a warehouse was severely damaged by fire; 21 LPG cylinders with a volume of approximately 0.026 m³ each were found. This cylinder size is usually the domestic size. It can be filled with up to 13 kg of LPG in the case of butane or up to 11 kg of propane. Thus, up to 271 kg of LPG was stored, and this very large amount of energy caused great concern and damage to the surrounding structures when the various cylinders exploded. In this case, only the destruction of the infrastructure was observed (Viegas *et al.* 2019).

Cases 8 and 9: Benitatxell fire, Spain, September 2016

This fire was a consequence of arson, on a day with a temperature of 35°C, relative humidity below 25% and

wind gusts of 52 km h⁻¹. During this fire, ~1400 people were evacuated, 470 received medical care and 200 structures were affected by fires, but only three structures were severely damaged. The burned area was 898 ha (Caballero *et al.* 2019; Vacca *et al.* 2020; Rodríguez-García *et al.* 2022).

Two LPG tanks near forest fuels were affected by the fire. In both cases, jet fires were recorded, both from LPG tanks equipped with PRDs that were able to prevent a BLEVE (Caballero *et al.* 2019; Scarponi *et al.* 2020).

Cases 10 and 11: Mati fire, Greece, July 2018

This wildfire is cited as the most lethal natural disaster in the history of the modern Greek state. The wildfire broke out in the forest surroundings of the Ntaou region on Peneli Mountain, approximately 20 km northeast of Athens. On 23 July, the temperature was nearly 40°C, relative air humidity was 19% and wind gusts were up to 100 km h⁻¹. The fire caused 100 fatalities, 200 people were injured and 998 structures were destroyed. (Caballero *et al.* 2019; Molina-Terrén *et al.* 2019; Efthimiou *et al.* 2020; Vacca *et al.* 2020; Palmos *et al.* 2021)

During this fire, several explosions were reported and at least two LPG-related cases were registered. The first (Case 10) is related to an LPG tank of at least 1 m³ exposed to fire. Case 11 was related to a mobile cylinder. Both vessels were found seriously damaged (Caballero *et al.* 2019).

Case 12: Llutxent, Spain, August 2018

This fire began on 6 August on a slope in the municipality of Llutxent. The ignition was caused by a thunderstorm and five fires were registered at the same time. The burned area was 3270 ha, 163 people were evacuated, 50 structures were affected and 10 houses were destroyed. The fire was completely extinguished by 13 August and no fatalities were reported (Caballero *et al.* 2019).

Five LPG mobile cylinders were burned during the fire and were found on a porch. BLEVEs and jet fire were not reported.

Case 13: Quinta do Colaço fire, Portugal, August 2015

This fire occurred during the summer of 2015, in the District of Coimbra, reaching the municipalities of Almalaguês, Ceira, Semide and Rio de Vide. The burned area was 5500 ha. A total of 722 civil protection agents and firefighters worked to suppress the fire, while they kept receiving new alert calls. The fire broke out in Quinta do Colaço at 00:42 pm. Unfortunately, at 4:13 pm, air support reported another seven spot fires, which were suppressed by seven fire trucks (Almeida 2015).

A small building on a hill, probably used as a workshop and close to trees, was affected by fire. Gas cylinders were

inside the building. In principle, those cylinders were used to do metallurgic work using acetylene and oxygen. One of these cylinders burst, and it was not possible to identify the fluid that was stored. The remaining cylinders were found burned but they did not burst. The small building collapsed after the exposure to the fire and BLEVE (Almeida 2015).

Case 14: Calabasas fire, California, USA, June 2016

During the summer of 2016, a brush fire occurred, threatening thousands of homes in Calabasas, California. The burned area was ~208 ha. Owing to the fire, mandatory evacuations at Calabasas Highlands, Eddingham and Adamsville, and voluntary evacuations in adjacent areas, forced approximately 5000 people to leave their homes. The fast-moving wildfire swept through the hills in Calabasas and reached a preschool complex, burning outbuildings and heating a propane storage tank that caused a jet fire (Bartholomew 2016; Weber 2016; Scarponi et al. 2020).

Experimental methodology

The cylinders tested in our experiments are the same as those traded in Portugal, without modification to the manufacturers' adjusted settings. The steel cylinder volume is 0.026 m³ containing 11 kg of propane, whereas the composite cylinder has 0.024 m³ filled with 12 kg of butane. Traders sell the cylinders 95% full and with approximately 95% gas purity.

Hydrostatic tests

Before the field tests with LPG cylinders, eight hydrostatic tests (HTs) were carried out to evaluate the burst pressure without fire and to compare the burst pressure with fire (Table 2) – four tests using a steel cylinder and four using a composite cylinder. The HTs were carried out inside a safe chamber by pumping water into the vessels. As water was pumped, the pressure data were registered. The HT was

Table 2. Summary of hydrostatic tests.

Ref.	Test	Type
1	HT1	Steel
2	HT2	
3	HT3	
4	HT4	
5	HT5	Composite
6	HT6	
7	HT7	
8	HT8	

considered concluded when the pressure decreased abruptly, resulting from vessel rupture.

Field tests

The tests were carried out in a quarry in Miranda do Corvo, Coimbra, Portugal, with the support of local firefighters and following all safety requirements for these types of tests.

The LPG cylinders were placed in a horizontal position, lying over a support structure manufactured with steel and placed over forest fuels (Fig. 1). The support used was 50 cm in height, and it was firmly fixed to the ground. The cylinder was tied through its handles using a steel cable to avoid movement when a jet fire occurred.

The experiments' aim was to understand the extreme behaviour of cylinders, namely the assessment of BLEVE and jet fire occurrence, and their respective effects. The tests were carried out using a horizontal position to increase heat flux incidence and engulfment because the fuel bed could not keep the cylinder fully engulfed for the entire test period (~20 min for tests T1CB and T2SP). A horizontal position was also used by Stawczyk (2003) and Tschirschwitz et al. (2017).

Four J-type thermocouples were used, three placed at the cylinder surface. The first was placed between the flames and the bottom of the cylinder, 10 cm from the cylinder surface (TI 1); the second (TI 2) was attached at the bottom surface of the cylinder; the third (TI 3) was attached to the cylinder surface at half its height; and the fourth thermocouple (TI 4) was placed at the top of the cylinder surface. A pressure transducer, model P2VA2 (PI) from HBM, and with a range between 0 and 500 bar (1 bar = 100 kPa) was used. To avoid damage to the pressure transducer by flame impingement, a steel tube of 1.5 m length was coupled to the valve, and the pressure transducer was coupled at the end of the tube (Fig. 1). The tube, valve and PI were protected by aluminium foil and fibreglass to allow a longer measurement time, given the fact that the valve commonly traded has polymeric pieces; when melted, the connection between the tube and PI fails. The thermocouples and PI were connected to a data logger from Eurotherm (model 6100A).

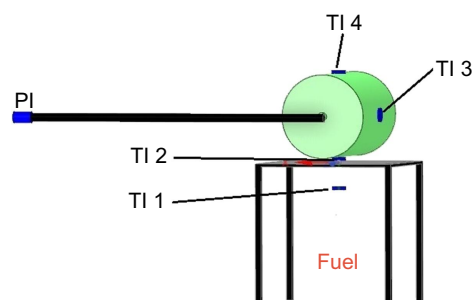


Fig. 1. Schematic drawing of the test performed. PI, pressure transducer; TI 1–4, J-type thermocouples.

The composite cylinder used in this work was equipped with a PRD set to open at 21 bar, plus a fuse that opens when the temperature is high. Both were evaluated to assess if the cylinder would remain safe when exposed to a fire. The PRD coupled onto the steel cylinder was set to open at 26 bar.

Three empty steel cylinders were weighed to determine the amount of gas that remained, as well as the weight percentage of the fragments collected after the burst.

Three tests were carried out, varying the type of cylinder (steel and composite), fluid (butane and propane) and presence or absence of a PRD (Table 3).

The experimental design of the tests was adapted from those carried out by other authors (Stawczyk 2003; Tschirschwitz *et al.* 2017, 2018; Barbosa *et al.* 2022a).

For image data acquisition, we used three visible cameras (UV CAM) and one infrared camera (IR CAM). The IR CAM used was an FLIR SC 660 with a specific lens for large distances, placed 200 m from the cylinder. The UV CAMs were SONY 4K, placed beside the IR CAM; the second UV CAM (action camera) was placed 20 m from the cylinder; and the last one used was fixed on a drone (Phantom 4 Pro V2.0) flying 100 m above the test. These images were used to estimate the velocity of the primary fragments (cylinder pieces) through the recorded time in the footage and the reference marks placed at the field test (at known distances).

The local experimental apparatus, where the cylinder was placed, was marked with a GPS (global positioning system; Garmin model ETREX 20) to be the reference point for further fragment distance measurements. Coloured traffic cones were placed at known distances from the cylinder to be used as reference to measure the fireball size, jet fire, fragment distance and velocity. A vertical indicator (black) 6 m high marked off at each metre (red) and each 20 cm (white) was also used as a reference.

After the BLEVE, the fragments were collected and weighed, and each landing point was marked using GPS. The field marks made with GPS were also used to calculate the distances and velocity of the primary fragments.

The forest fuel used was composed of small *Pinus Pinaster* logs, widely available in Portugal. For standardisation of the amount of wood used in all tests, each test used 60 logs, resulting in approximately 120 kg. In addition, each test also consumed 6 kg of shrub with 16% moisture content to start the wood combustion. These fuels have previously been used by other authors (Viegas *et al.* 2006; Pinto *et al.* 2017; Rodrigues *et al.* 2019; Barbosa *et al.* 2022a).

Table 3. Reference numbers for the field tests under different conditions.

Ref	Test	LPG	Type	PRD
9	T1CB	Butane	Composite	Yes
10	T2SP	Propane	Steel	Yes
11	T3SP	Propane	Steel	No

Ignition of the shrub was made directly with a torch. The time required for the heavy fuel to start burning and produce a measurable temperature or pressure increase was ~2–3 min, which was sufficient time for the operators to get to a shelter located at a safe distance (more than 100 m away).

Using a Vantage Vue Wireless Weather Station, from Davis Instruments, weather conditions were monitored during all tests, including environmental temperature, wind speed and direction, and relative humidity. These data were used to develop fireball and jet fire predictive models.

Results

Test T1CB

When the composite cylinder was exposed to fire, its polymer surface started burning and became engulfed in flames. The outermost layer manufactured from polyethylene was quickly burned. From the second layer, only the fibreglass remained, all the polypropylene having been consumed by fire as well.

Pressure measurement was lost 6 min after the beginning of the test, because polymeric pieces of the gauge melted, even though they were fully protected by fibreglass and aluminium foil. The temperature registered at the cylinder surface was higher than 1000°C at the bottom and ~700°C at the top (Fig. 2a).

The PRD system worked well, and the butane flowed out, preventing bursting. Despite the PRD opening at 21 bar (Fig. 2b), it was not enough to stop a fast pressure increase; it reached 46.4 bar. The PRD remained opened for 2 min (first opening), causing a jet fire with a height of 6.8 m, a width of 0.6 m and a geometry similar to that of a cylinder (Fig. 3). The jet fire happened again, lasting for 95 s. Gas flow was also registered through the fuse.

Test T2SP

In test T2SP (differently from T1CB), the steel cylinder was not consumed by the flames, allowing us to see the time when the PRD opened (Fig. 4). Pressure growth during the test is shown in Fig. 4. The pressure peak registered was 31.9 bar. After 11 min, pressure measurement was lost. The PRD was able to keep the cylinder safe.

Comparing the pressure and temperature increase in tests T1CB and T2SP, the burning of the polymer layer in test T1CB triggered a sharper increase in pressure and temperature rate than test T2SP (Figs 2b, e, 4b).

A jet fire with a similar length and width to the jet fire noted in test T1CB was observed during test T2SP. The infrared camera was set to record between 273 and 824 K in order to record the flame size, but the flame temperature in the centre of the jet fire was higher than 824 K. Other authors (Lowesmith *et al.* 2007; Palacios *et al.* 2012) found

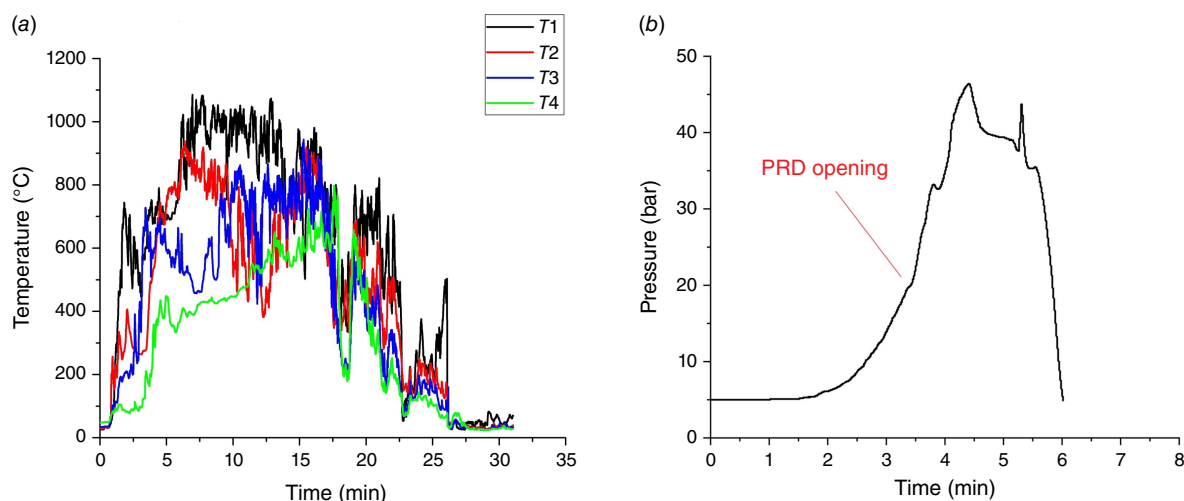


Fig. 2. Results of test TICB: (a) temperature, and (b) pressure.



Fig. 3. Image of test TICB showing the jet fire.

values between 700 and 1200 K. The jet fire happened three times, lasting 55, 20 and 25 s.

On average, the empty cylinder weight is 15.30 kg. After test T2SP, ~1 kg of propane remained in the cylinder.

Test T3SP

The steel cylinder used in test T3SP was not equipped with a coupled PRD, reaching 45.5 bar and temperatures of ~800°C (Fig. 5). After 14 min of exposure, when the external fire had extinguished and the internal temperature and pressure were decreasing, the cylinder burst. So the BLEVE did not happen at the maximum pressure and temperature. Immediately before the BLEVE, the internal pressure was 16.3 bar and the cylinder surface temperature was 62°C. It was noted that the cylinder diameter before burst was higher than at the beginning of the tests.

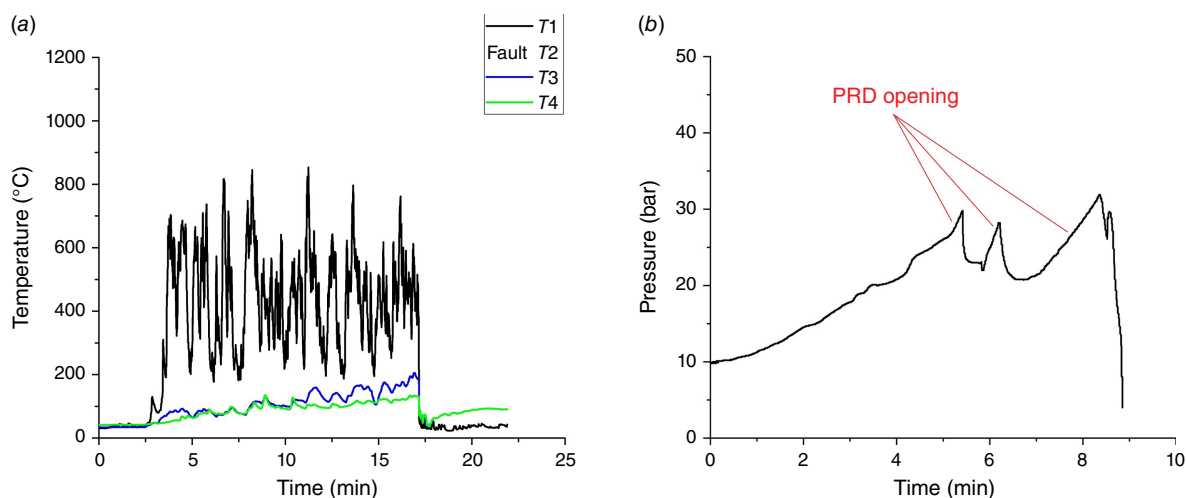


Fig. 4. Results of test T2SP: (a) temperature, and (b) pressure.

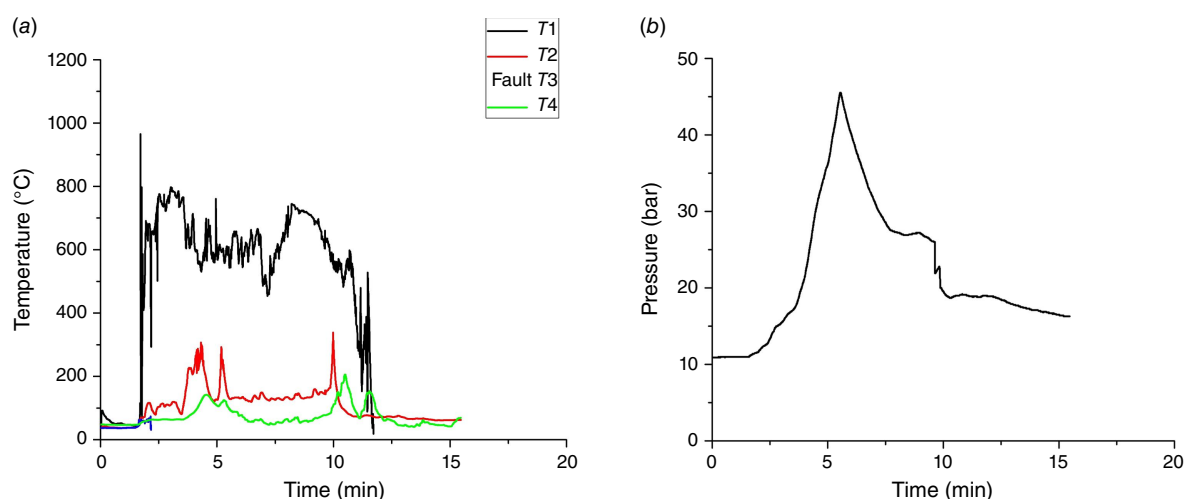


Fig. 5. Results of test T3SP: (a) temperature, and (b) pressure.

Comparing the burst pressure results found in test T3SP with the burst pressure in the hydrostatic tests, the cylinder explosion occurred at only 18% of the average burst pressure observed in the hydrostatic tests for steel cylinders. The hydrostatic tests results for steel cylinders showed an average of 91.49 ± 0.94 bar and 89.98 ± 1.22 bar for composite cylinders. During these tests, the mode of rupture was partial failure.

Four minutes before the BLEVE, there was no flame visible, only smouldering fire. Thus, the BLEVE happened in the fire aftermath owing to decreased resistance of the cylinder steel, which was caused by the exposure to high temperatures.

Fragmentation in test T3SP

As an effect of the BLEVE, cylinder fragments (primary fragments) were projected; other fragments (secondary fragments) – for instance pieces of the support, fixing rods and instruments – were also projected. The cylinder rupture generated two major pieces, the first of 10.63 kg weight and another 4.33 kg. Thus, 97.72% of the cylinder weight was recovered after the burst. There were several pieces of secondary fragments scattered randomly in the field.

The maximum distance reached by a fragment was 113 m, and the maximum velocity reached was 252 km m^{-1} . The fragments that reached the largest distances were the primary fragments (Fig. 6, Table 4). Table 4 also shows the fragment distribution, with the respective weight and distances from the initial point. The smaller primary fragment (fragment ref. 174) reached a higher distance when compared with the heavier primary fragment (fragment ref. 175).

Table 5 shows the average of the primary fragments' velocities at two instances, and their distances from the initial spot. At these velocities, the fragments may jeopardise the surrounding structure and cause injuries or even fatalities. It can be seen that the velocity of the fragments



Fig. 6. Fragments on the field after test T3SP: primary fragments (blue) and secondary (yellow).

Table 4. Fragmentation data for test T3SP.

Fragment	Origin	Type	Mass (kg)	Distance (m)
1	Support	Secondary	0.38	24
2	Support	Secondary	0.38	50
3	Support	Secondary	0.74	43
4	Support	Secondary	0.38	23
5	Rebar	Secondary	1.4	9
6	Support	Secondary	2.754	6
7	Support	Secondary	0.46	14
8	Support	Secondary	0.375	18
9	Support	Secondary	0.63	56
10	Cylinder	Primary	4.325	113
11	Cylinder	Primary	10.63	86
12	Valve	Secondary	0.167	22

decreases as distance increases, owing to air resistance and loss of energy due to impacts with the ground. The heavier fragment (11) reached lower velocities when compared with the smaller primary fragment (fragment 10).

Regarding the cylinder rupture profile, it did not occur on the weld (Fig. 7). The rupture profile was longitudinal and transversal, similarly to that described by other authors (Baum 1999; Casal 2008).

Fireball

The BLEVE was followed by a fireball of 14.5 m maximum height and 11.5 m diameter, lasting 1.3 s (Fig. 8). The fireball temperature reached more than 824 K. As the range selected for the IR camera was 273–824 K, the temperature at the centre of the fireball was higher than 824 K.

The results of the HT tests demonstrated that, on average, 91.9 bar for steel cylinders and 90 bar for composite cylinders are the pressures necessary to cause them to burst, showing a burst pressure higher than required by EN 1442 and EN 12245:2009 + A1:2012.

As mentioned previously, at the time of the BLEVE, the cylinder was at an internal pressure of 16.3 bar. The burst pressure under fire was much lower than the burst pressure for the HT. The centre of the fireball moved ~6 m away from where the cylinder was placed. The gas cloud moved in the same direction, following the wind direction. At the moment of bursting, the wind velocity was 6.3 km h^{-1} .

Discussion

The pressure in the cylinders during tests T1CB, T2SP and T3SP showed at least 2 min of inertia pressure. The fire takes some time to completely develop, which shows that LPG cylinders can absorb energy before the pressure increase starts. Considering the same heat flux and vessel volume, the greater the amount of LPG stored in the vessel, the greater the inertia pressure can be. For the three tests, after the inertia time, the pressure increase was rapid. Once the heat flux is very high, as seen during test T1CB, the pressure may still increase even after the PRD opens.

During test T1CB (butane), the highest temperature was observed. Even under these conditions, the inertia pressure time was similar to the other tests. This shows that butane is safer to store because, under the same conditions, a cylinder filled with propane can have a faster pressure increase.

The forest fuel gives an unsteady flame, which changes significantly owing to wind. Despite the same amount of fuel being used in all tests, during the tests we observed different wall temperatures at each instant. For instance, Fig. 4a shows a fluctuation up to 500°C in a few seconds and the peaks were observed at different moments. Thus, even using the same mass of fuel in tests with forest fuel, the same heat flux and wall temperature cannot be ensured during the tests.

Table 5. Estimate of primary fragment velocities.

Fragment	Average	Time (s)	Distance (m)	Velocity (m s^{-1})	Velocity (km h^{-1})
11	A11.1	0.3	15	50	180
	A11.2	1	40	40	144
10	A10.1	0.3	21	70	252
	A10.2	1	70	60	216

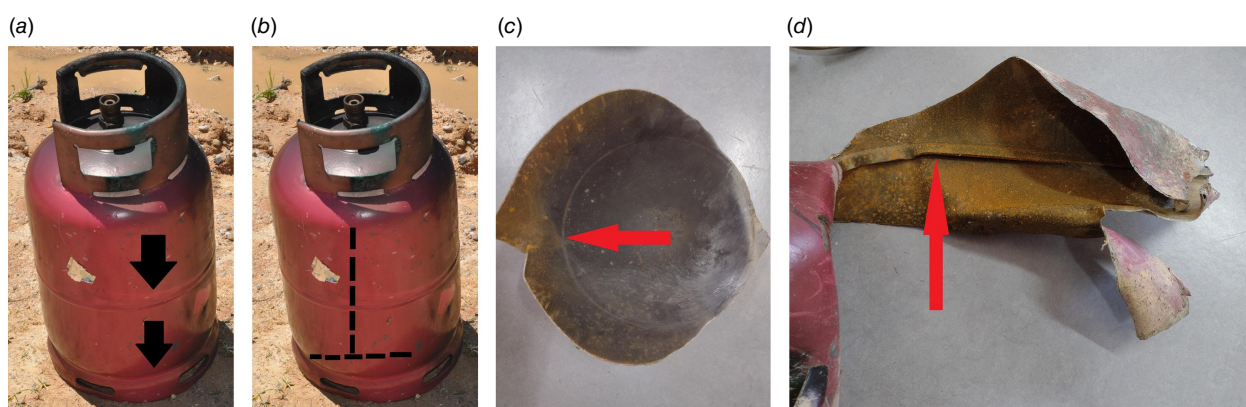


Fig. 7. (a) Welds before burst; (b) rupture profile; (c, d) rupture profile and weld after burst.



Fig. 8. Fireball: (a, b) images from drone; (c) IR CAM; (d) action camera.

Effects: radiation, overpressure and fragmentation

Radiation from a fireball

The radiation from a fireball and its effects on skin can be predicted through the data from test T3SP combined with equations available in the literature (Casal 2008; Gómez-Mares *et al.* 2010).

The emissive power E of a fireball varies with time; thus, an average value can be estimated using the following equation (Casal 2008):

$$E = \frac{M \times \Delta H_c \times \mu_{\text{rad}}}{\pi \times D^2 \times t} \quad (1)$$

where μ_{rad} is the radiant heat fraction 0.33, ΔH_c is the heat of combustion for propane (46 000 kJ kg⁻¹) (Casal 2008; Gómez-Mares *et al.* 2010), t is the duration time of the fireball (1.3 s for T3SP), D is the fireball diameter (11.5-m – T3SP) and M is the weight of fuel (11 kg).

The maximum view factor (F_{max}) corresponding to a sphere and a surface perpendicular to its radius is given by (Casal 2008):

$$F_{\text{max}} = \frac{D^2}{4\left(\frac{D}{2} + d\right)^2} \quad (2)$$

where d is the distance from the fireball surface to the target and theta (θ) is the angle between the ground and

the surface perpendicular to the radius of the fireball (Fig. 9).

For vertical targets like a person standing, the corresponding perpendicular surface is given by:

$$F_{\text{vertical}} = F_{\text{max}} \times \cos \theta \quad (3)$$

The thermal radiation intensity I is:

$$I = \tau \times F_{\text{vertical}} \times E \quad (4)$$

where τ is the transmissivity, given by:

$$\tau = 2.85 \times (P_w \times d)^{-0.09} \quad (5)$$

where P_w is the partial pressure of water:

$$P_w = P_{\text{wa}} \times \frac{H_R}{100} \quad (6)$$

H_R is the relative humidity (40% – T3SP), P_{wa} is the saturated water vapour pressure, which can be found through the Antoine equation (Poling *et al.* 2001; Casal 2008), expressed in Newtons per square metre (N m⁻²), and the environmental temperature (T) is 299.05 K (25.9°C) (T3SP)

$$\ln P_{\text{wa}} = 23.18986 - \frac{3816.42}{T - 46.13} \quad (7)$$

Therefore, the thermal radiative intensity for a target at different distances is presented in Fig. 10.

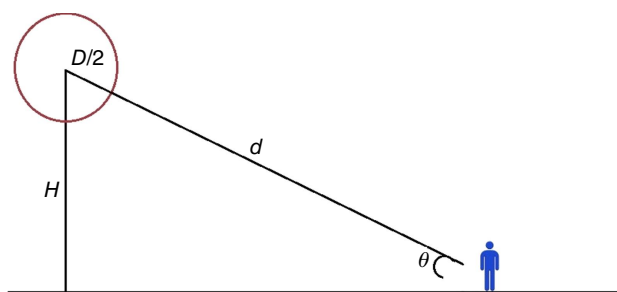


Fig. 9. Schematic drawing of the fireball and target.

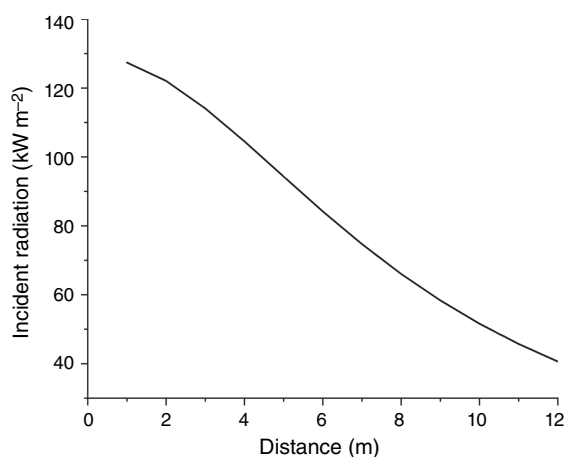


Fig. 10. Incident radiation from a fireball from a LPG mobile cylinder for each position (horizontal and vertical) considering the highest incident radiation on the target.

The fireball causes a significant visual impact and the incident radiation shows high values. However, considering the low time of duration of a fireball, the radiation from a fireball from an LPG domestic cylinder may not be lethal. Thus, for a time duration of a fireball less than 2 s and an incident radiation estimated at 120 kW m^{-2} (Fig. 10), the probability of second degree burns is 50% (Buettner 1951; Casal 2008).

Radiation from jet fire

The jet fire is an event that can trigger a domino effect because of its long duration and because it can happen twice or even more. This behaviour was observed during tests T1CB and T2SP. Caballero et al. (2019) identified three common layouts for stored LPG tanks found in recent WUI fires: LPG tank directly exposed to an incoming forest fire; LPG tank exposed to combustion of green hedges and ornamental plants; LPG tank exposed to combustion of other elements in the surroundings. For these three cases, if the vessel is placed close to a house, the jet fire may reach parts of the house, for instance, walls, windows, roof and furniture placed close the house. The jet fire may act by linking the outside fire (from the forest) and the house.

The jet fire thermal radiation intensity on a house and its surroundings can be predicted through the following equations, considering the length of the jet fire and its width – 6.8 and 0.6 m, respectively; during the majority of the time, the jet fire had a constant length and width such as in a steady state; a cylindrical shape; the average value of 1000 K for flame temperature (Lowesmith et al. 2007; Palacios et al. 2012):

$$E = \sigma \times \varepsilon \times T^4 \quad (8)$$

$$I = \tau \times F \times E \quad (9)$$

where ε (0.5) is the emissivity (Lowesmith et al. 2007; Palacios et al. 2012), and the view factor was found using the table for a horizontal cylindrical fire (Casal 2008).

In Fig. 11, the thermal radiation intensity for the jet fire is shown.

At a distance of less than 1 m from the jet fire, construction materials can ignite in a short time. A thermal radiation intensity of 10 kW m^{-2} , during ~215 and 100 s (T1CB and T2SP, respectively) is enough to ignite several materials used in furniture and room materials, starting a secondary fire. The ignition time for these materials may be shorter than 90 s (DiNenno et al. 2002; Quintiere 2006). Furthermore, considering the jet fire length, if the target is impinged or engulfed by a jet fire, the ignition time can decrease significantly.

Therefore, a cylinder under fire at a house may spread the fire, as was seen by Caballero et al. (2019).

Overpressure

The overpressure (ΔP) caused by the blast wave can be easily predicted through the polynomial method (Hemmatian et al. 2017a). This method uses the filling degree (% FD) and the temperature (K) of the vapour in the vessel just before explosion to find the energy (ϵ).

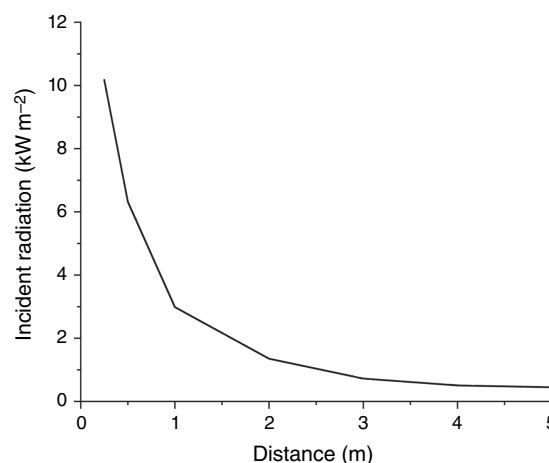


Fig. 11. Thermal radiation intensity for a jet fire.

For test T3SP (FD = 95% and $T = 343.15$ K):

$$\begin{aligned} \epsilon = & 43.97 - 213.9 \times \text{FD} - 0.152 \times T + 1.349 \\ & \times \text{FD} \times T - 0.0004361 \times T^2 - 0.002045 \\ & \times \text{FD} \times T^2 + 1.55 \times 10^{-6} \times T^3 \end{aligned} \quad (10)$$

Once the energy (MJ m^{-3}) is estimated, the TNT equivalent mass (M_{TNT}) and the scaled distance (R) can be found, where r is the distance from the explosion and β is the fraction of the explosion converted into a blast wave. Values for β , usually ranging between 0.4 and 0.5 for ductile breaking, were used by other authors (Casal and Salla 2006; Casal 2008; Hemmatian *et al.* 2017a, 2017b). For our estimate, a value of 0.45 for β was used.

$$M_{\text{TNT}} = \frac{\beta \times \epsilon (\text{MJ}) \times 10^3 (\text{kg})}{4680} \quad (11)$$

$$R = \frac{r}{M_{\text{TNT}}^{1/3}} \quad (12)$$

By using the TNT curve (Casal 2008), the value of ΔP is found.

Fig. 12 presents ΔP up to 7 m from the explosion. Through the graph, it is possible to estimate the damage to structures and people at each distance.

Using a probit analysis for damage in humans at distances shorter than 1 m, the probability of lethality can reach 100% owing to pulmonary haemorrhage (Eisenberg *et al.* 1975; Casal 2008). According to the overpressure and consequences tables, at a distance of up to 3 m, the pressure is likely to project a human to the ground and cause eardrums to rupture (Casal 2008).

Regarding structures, up to 2 m, the explosion may cause damage to houses. For distances greater than 2 m, damage to windows and ceilings and minor structural damage may occur (Crowl and Louvar 2002; Casal 2008).

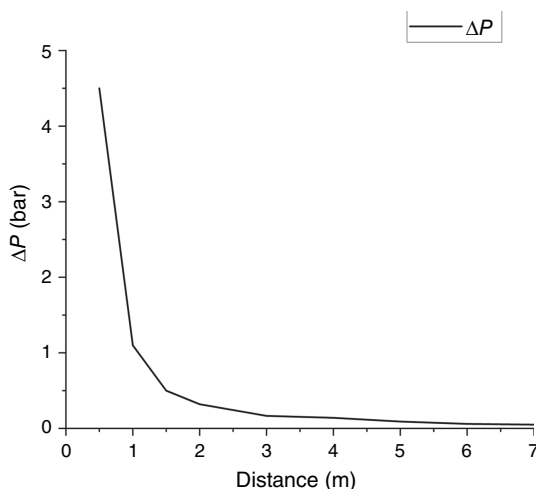


Fig. 12. ΔP at different distances from the explosion.

Fragmentation

Whereas thermal radiation and overpressure may cause damage to people and structures at short distances, fragmentation may be the worst effect because fragments may reach people and structures at large distances from the explosion. People, firefighters and structures may become a target of the pieces or fragments released. From each LPG cylinder, a zone of 300-m radius may be affected by primary fragments with a weight of up to 10 kg and velocities higher than 200 km m^{-1} , which can be lethal considering their kinetic energy. The secondary fragments from structures in the proximity of the cylinder can be projected several metres away by the explosion. In test T3SP, for instance, secondary fragments landed within a radius of 56 m from the point of the LPG cylinder explosion.

Other authors also carried out tests with LPG cylinders. A summary of fragmentation features gathered from 18 tests is shown in the Table 6.

Lessons learnt from the tests

A very important factor to be mentioned is the shape of the LPG cylinder. If it is deformed, this is a visible sign that the vessel is becoming unsafe. Furthermore, our findings (test T3SP) showed that owing to fire incidence – induced thermal stress and the internal pressure increase – the material resistance can significantly decrease. In fact, cylinder explosion occurred at only 18% of the average burst pressure found in the hydrostatic tests. The material rupture can happen in the fire aftermath; therefore, people should keep a safe distance from cylinders previously exposed to fire.

Regarding the composite cylinder filled with butane, its surface reached temperatures 200°C higher than the steel cylinders filled with propane. The peak pressure was 46.4 bar 5 min after the start of test T1CB. Comparing the tests with PRD-equipped cylinders (T2SP with T1CB), the pressure peak for the steel cylinder was lower (31.9 bar) and it occurred after 7 min. Moreover, in T1CB, the PRD opening time was longer than in T2SP. Therefore, the composite cylinder is more sensitive than the steel one, leading to faster increases of temperature and pressure.

Recommendations for LPG stored by users at the WUI

Before the front fire arrives, it is common that spot fires, caused by flying embers landing on roofs, windows, gardens, ornamental vegetation and external furniture, take place near or at houses. These fires can heat stored LPG vessels and trigger a jet fire or a BLEVE. The effects caused by heating the LPG cylinder may lead to a worse fire scenario. Thus, where the LPG cylinder is placed should be carefully chosen and should be far from any fuel.

Through the information gathered in the cases of accidents related to gas stored at the WUI, we found some unsafe practices that occurred in more than one case,

Table 6. Burst features related to tests performed with LPG cylinders.

Overpressure (bar)	Time to failure (min)	Burst pressure (bar)	Fireball diameter/height (m)	Fragment velocity (km h^{-1})	Maximum distance reached (m)	Number of burst tests	Reference
–	15	16.3	11.5/14.5	Up to 252	113	1	Present work
0.05–0.27 bar at 5 m and 0.04–0.1 bar at 9 m	1.5–2.5	70.7–98.2	–	–	262	15	Tschirschwitz et al. (2017)
0.5 bar at 2 m and 0.15 bar at 10 m	–	120	–	–	300	2	Stawczyk (2003)

which should not be done. These accidents could be avoided through good practice carried out by the users, for instance placing cylinders at a safe distance from forests and artificial fuels, only one cylinder should be stored, and forest fuels (and other types of fuels) in the house surroundings should be eliminated.

Steel cylinders that are still being traded without PRDs are not recommended to be used in houses that may be exposed to wildfires. For domestic applications, we encourage the use of steel cylinders filled with butane and always with a PRD coupled to the valve.

Protection made with a non-combustible fabric, low-cost and easy to build was suggested by Barbosa et al. (2022a, 2022b).

The users should consider any eventual jet fire direction through the PRD opening and its length before positioning a cylinder.

These safe practices may help avoid future LPG accidents at the WUI.

Recommendations for firefighters and civil protection agents

Ricci et al. (2021) proposed a methodology to assess safe distances to prevent accidents resulting from the failure of a tank exposed to radiation caused by a wildfire front. This can be used by civil protection agents mainly in WUI zones where LPG reservoirs are located and with greater volumes than the smaller cylinders normally used by civilians.

If the steel cylinder is deformed, this is a visible sign that it has become unsafe. Steel cylinders are designed to expand at least 20% of their volume; thus, once a cylinder is deformed, this safety feature is already used. A decision to approach and move a cylinder should also take into account its shape: deformed (or not) for steel cylinders; composite cylinders may have lost their handles.

In test T2SP, 1 kg of propane remained in the cylinder, even after three jet fires. This means that the cylinder was 10 kg lighter than a new one because 10 kg of propane was burned during jet fires. Thus, even burned and lighter after a fire, a cylinder in a fire aftermath may have an unknown amount of propane and a weak structure prone to burst.

Some composite cylinders have a fuse, which melts at high temperatures. Thus, the gas may still flow in the fire aftermath. As there is no flame to ignite the gas

immediately, if the place is enclosed or partially closed, a flash fire may happen. This might have been the cause of an accident that occurred in a warehouse in Freamunde, Portugal, in 2020, in which two firefighters were burnt.

Considering the fragmentation effect, for cylinders with up to 13 kg of LPG, the safe distance is 300 m. Otherwise, primary fragments crashing into the body may be lethal. For overpressure, a safe distance of 10 m should be considered. Furthermore, at distances shorter than 1 m, the blast wave may be lethal.

Regarding a fireball, for non-protected people, a distance greater than 15 m may avoid burns. For protected people, the distance may be significantly shorter. Despite the visual shock that a fireball can cause, for firefighters with protection, its effect is the least dangerous.

Conclusion

In this work, we evaluated LPG cylinders manufactured in composite or steel, butane or propane filled, with or without PRD. Predictive models and experimental results were used to estimate BLEVE effects at the WUI. Considering experimental results carried out by different authors and the distances reached by fragments, safe zones may be considered to be 300 m from the cylinder. The total time of a jet fire can be up to 178 s, which can trigger secondary fires in house surroundings.

The PRD worked well and avoided the BLEVE in the tests using cylinders with a coupled PRD. Propane should be only put in steel cylinders and always with a PRD. For domestic use and in WUI areas, only butane-filled cylinders equipped with a PRD should be used. The polymers on surface composites cylinders become fuel, burning and increasing the temperature of the cylinder, as well as causing a faster pressure increase rate when compared with the steel cylinders.

It was found that after thermal stress, cylinder resistance is significantly reduced. BLEVE happened in the absence of external flames, at that moment with only 18% of the average burst pressure found in the hydrostatic test.

The place where a LPG cylinder is located should be carefully chosen. It should be far from any fuel, including vegetation, ornamental vegetation and furniture to avoid heating the stored LPG and, ultimately, leading to BLEVE and jet fires.

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