fire

Article

A Protection for LPG Domestic Cylinders at Wildland-Urban Interface Fire

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Abstract: Wildland fires are frequent events worldwide, particularly in the European-Mediterranean region, USA, and Australia. These fires have been more frequent and intense in recent years due to climate changes and may cause significant damage, especially when reaching the Wildland-Urban Interface (WUI) areas. The presence of liquefied petroleum gas (LPG) cylinders may cause severe events in WUI areas, as occurred in Portugal during the large wildfires of 2017, which could have been avoided if the cylinders were protected. Devices for protecting the parts of houses under WUI fire were previously presented, but a protective device for cylinders was not. In this work, a protective device for LPG cylinders made with a thin fabric with an aluminum coating on the external face was tested in laboratory and field conditions. The cylinder and the fabric were equipped with thermocouples and heat flux sensors attached to their surfaces. The tests showed that the device gave effective protection to the cylinder, decreasing the radiative heat flux that reaches it and keeping it in a safe condition when exposed to a fire; consequently preventing extreme behavior such as an explosion.

Keywords: LPG cylinders; protection; wildland-urban interface fires; safety; forest fire

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1. Introduction

Wildland fires are frequent events in several parts of the world, including in the USA, Canada, Australia, and the European-Mediterranean region. Portugal and Greece suffered large fires in 2017 and in 2018, respectively, which caused more than two hundred fatalities [1–5].

Wildfires cause huge socio-economic damages, particularly when they occur in Wildland-Urban Interface (WUI) areas. These fires are becoming more frequent and severe in recent years due to climate change [3–5]. The burned area is also increasing in regions that were not previously affected by wildfires. Thus, academics and other stakeholders are developing greater efforts and studies to prevent fires in the WUI and reduce their impacts, by using protective devices, increasing awareness and education, and improving policies.

Liquefied petroleum gas (LPG) cylinders are widely used in many countries for different domestic purposes, such as cooking, heating water, and keeping homes warm [6,7]. Given the fact that the majority of rural WUI areas do not have a gas distribution network, the presence of mobile gas cylinders near each house is common. When a wildfire occurs nearby, the cylinders become a relevant hazard for the people and structures because of the enormous amount of energy stored. Regarding the microscale of WUI areas, where citizens can adopt basic and effective safety measures, quite often, the domestic LPG cylinders are improperly stored near the buildings also being placed close to forests and synthetic fuels. In fact, they are a potential risk for the habitants, being the gas cylinder's behavior as well as its effects, when exposed to fire, uncertain. Moreover, civil protection agents during an emergency may become exposed to an increased risk of explosion. They may not know in advance whether there is LPG stored or not, its size, and where it is placed. This situation may jeopardize the firefighters' strategy and the decision-making process.

Accidents related to LPG cylinders have been registered in Portugal during at least five large fires. Two accidents occurred in two different houses during a large wildfire in Funchal [8], in which a boiling liquid expanding vapor explosion (BLEVE) occurred in one of them. During the Pedrógão Grande Fire Complex in June 2017, two cylinders burst in the same event. Another three accidents related to LPG cylinders were registered during the October Large Fire Complex [9–11].

Domestic LPG cylinders, when heated, can become dangerous and extreme events may happen, for instance, a jet fire or a BLEVE. The BLEVE is the most dangerous phenomenon that may happen in any type of pressurized vessel, even if the fluid is non-combustible. There are three main hazards associated with BLEVE: overpressure, fireball (for combustible fluids), and fragment projection that can reach large distances [12–14]. Hence, these effects can impact people nearby, as well as firefighters, buildings [15,16], and other infrastructures.

Regarding the effects caused by an LPG cylinder's explosion, experimental tests with an LPG cylinder were carried out by other authors [16,17]. The flying projectiles could reach up to 300 m from the initial position. The overpressure presented high values at distances shorter than 10 m from the explosion. These effects may jeopardize the safety of persons and structures in the surroundings.

To avoid LPG accidents, two vulnerability assessment methodologies were proposed [6,18]. They consider: (1) the forest fuel characterization and heat flux released; (2) how much flux reaches the target; (3) estimation of the time to burst; (4) estimation of the safety distance; (5) Computational Fluid Dynamics (CFD) to estimate the internal pressure increment.

Although the possibility of LPG cylinder protection was not previously mentioned, protecting the gas cylinder is an alternative to blocking the heat flux and preventing the explosion. It could have avoided the accidents that occurred in Portugal. If the cylinder is not heated, it will not increase the temperature and pressure, which results in a safer condition.

Protective devices were presented to protect house walls and roofs in a WUI fire case [19,20]. However, the LPG cylinders are commonly placed outside of the houses as a safety recommendation. Thus, cylinders should also be protected to avoid accidents.

The cylinders used in WUI areas are mobile, with a capacity of 26 L with up to 11 to 13 kg of gas, depending on the fluid, propane or butane, respectively. Hence, the protective device should be mobile and light, able to be easily moved and placed by the users.

To fill the gap related to the LPG cylinder's protection, this study presents a light and cheap protection for LPG cylinders capable of keeping them in a safe condition when exposed to WUI fires. This work was motivated by the increasing number of accidents due to WUI fires, which occurred in the last years related to LPG stored in houses. The goal of this work was to develop a protective device that is easy to move and can be suited for many reservoir sizes to avoid the occurrence of severe events, such as a BLEVE. The protective device studied could block a great percentage of heat flux and keep the cylinder surface at safe temperatures, even close to room temperature.

2. Materials and Methods

2.1. Protective Device

In this work, a protective device was developed to block the heat flux and keep the gas cylinder under safe temperatures when a fire occurs in its vicinity. It was manufactured with two main parts. The first and most external one is made with a fabric with an aluminum coating on the external face to decrease the radiative heat flux. The second one is a structure made with a square metal tube, with geometry the same as a cube, with opened faces and a handle on top used for moving. On one face, near the bottom, there is a small vent square of 15×15 cm^2 to pass the gas tube. This tube was wrapped in the fabric. The goal of the protection device is to reduce the heat flux that reaches the cylinder and prevent the LPG stored in the cylinder from getting warm. It is an alternative system for people living in rural areas without access to an industrialized or commercial protection system;it is easy to be built, cheap, light, mobile, and ergonomic.

The protective device was built for cylinders of 11 kg of propane or 13 kg of butane and manufactured in accordance with European codes [21,22]. It has the following dimensions: 65 cm in height and 45 cm in length and width. The fabric is manufactured with fiberglass and a very thin aluminum coating on the external face. The emissivity can be considered as 0.85 (typical value for plain fiberglass fabrics) [19,23]. The fabric is 0.5 mm in thickness, 220 kg·m^{-3} in density, has a specific heat capacity of 795 J·kg^{-1}·K^{-1}, and thermal conductivity of 0.04 W·m^{-1}·K^{-1}. The chemical composition of the fabric is: 14–15.5% Al_2O_3; 53–55% SiO_2, 16.5–17% CaO_2; 6.5–8.5% B_2O_3; 4–5.5% MgO; and others. The fabric is classified according to the European fire classification for construction products (EN 13501) M0 (old classification) and A (current classification). It is a non-combustible material. This fabric was chosen due to research developed at the Forest Fire Research Center (CEIF) of the Association for the Development of Industrial Aerodynamics (ADAI) of the University of Coimbra, in the scope of a research project named FIRE PROTECT (CENTRO-01-0246-FEDER-000015), which discovered that this fabric was better than the other four fabrics tested [19,20,24,25]. The cost of the protection was 56 Euros, and the total system weight was 6.4 kg.

2.2. Laboratory Tests

Nine tests were carried out (Table 1), eight at the laboratory and one in the field. The laboratory tests were performed in the Forest Fire Research Laboratory (LEIF) in Lousã, Portugal, using the same fuel load of 10 kg of shrub vegetation and four different flame distances, to evaluate the protection efficiency related to the heat flux at flame distances similar to those found in fires near rural houses. The field test was aimed at evaluating the cylinder protection in a real fire scenario and validating the laboratory tests.

Table 1. Summary of the performed tests.

Ref.	Test	Distance (m)	Fuel Load (kg)	Time of Exposure (min)	Place
[1]	PS025	0.25	10	6	Lab
[2]	PS050	0.50	10	6	Lab
[3]	PS075	0.75	10	6	Lab
[4]	PS100	1.00	10	6	Lab
[5]	REF025	0.25	10	6	Lab
[6]	REF050	0.50	10	6	Lab
[7]	REF075	0.75	10	6	Lab
[8]	REF100	1.00	10	6	Lab
[9]	PSS	Surrounded	-	14	Field

To resemble a real case and different scenarios, in the laboratory tests, cylinders were placed at four different distances "D" between the faces of the fuel basket and the protective device (Figure 1), given the fact that it is important to clarify how the protective device works in different fire conditions. These four distances were used to assess the blockage efficiency of the protective device at different distances from the fire. By reason that once the distance increases, the heat flux that reaches the surfaces of the cylinder and the fabric decreases, which also changes the blockage efficiency. The distances from the flames used were 0.25, 0.5, 0.75, and 1 m. For each test, we used 10 kg of shrubs with a moisture content of 16%. Shrubs were used according to previous studies [3,26–28], and it is the same fuel present in the field test. This fuel was placed in a basket with a volume of 1 m^3. Reference tests with the cylinder and without protection were performed to obtain the heat flux and temperature on the cylinder's surface.

The resistance of the protective device was tested, and the differences in temperature and heat flux that reached the cylinder and the fabric surface were measured. The environmental laboratory temperature was measured in a place far from the flames' influence.

The cylinders were equipped with the temperature and heat flux sensor IHF01 Hukseflux attached to the external surface (FI 1, TI 1) halfway up the cylinder's height; the same was attached to the external surface of the fabric (FI 2, TI 2) (Figure 1). Two thermocouple type K were used; the first thermocouple was attached to the floor at 10 cm from the fuel basket (TI 3); and the second was attached to a wall surface, far from the influence of the flame (TI 4). The flux sensors were connected to the model 9211 (±80 mV) from National Instruments (NI), and it was plugged into the chassis 9174, also from NI. These instruments allow for the continuous measurement of the signal from the sensor with a frequency of 1 Hz, being able to load and process the data directly to a computer. The thermocouples were connected to a model 9213 from NI. The tests were recorded using an InfraRed (IR) camera FLIR SC 660 and a Sony 4K video camera. The settings of the heat flux sensor, chassis, and IR camera were adapted from previous studies [29]. The IR and video cameras were placed 8 m from the lateral face of the basket fuel.

The cylinders used were manufactured under the European Code [21] and placed at the previously mentioned four distances in front of the fuel basket (Figure 1).

The combustion of the fuel baskets lasted around six minutes. At 150 s, the flames' temperature started to decrease. At five minutes, only small flames lasted. The time of exposure in all laboratory tests was considered 6 min, and it is more time than the residence time of the flames for fire fronts in vegetation fuels without stem wood [30,31].

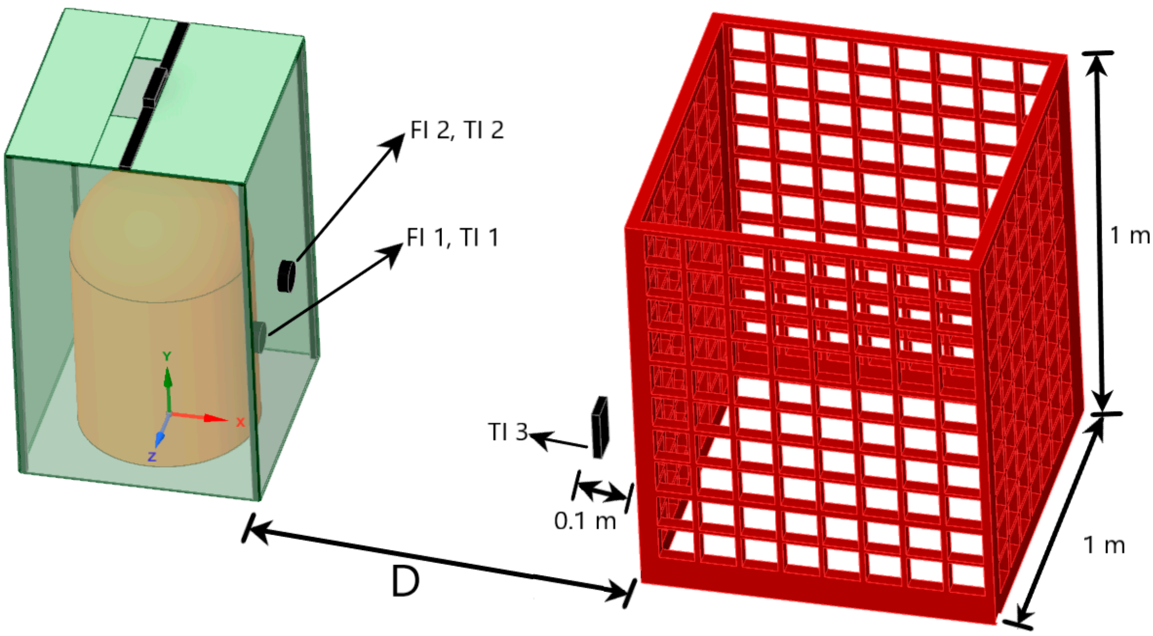


Figure 1. Schematic drawing of laboratory test: protective device at the four distances "D" from the fuel basket, and the instrument's position on the cylinder's surface (FI 1, TI 1), fabric's surface (FI 2, TI 2), and thermocouple 3.

2.3. Field Test

In the field test, the instrumental apparatus used was the same as in the laboratory tests.

The field test was performed on a slope of 30% covered by shrubs with less than 50 cm in height and an average moisture content of 40%.

The LPG cylinder was covered by the protective device and surrounded by shrubs. The ignition was made on the bottom of the hill (Figure 2).

The field test was carried out under adverse conditions, wind and slope influence, which are different from the laboratory conditions. For this reason, weather measurements were used to know the wind velocity, temperature, and air humidity using a weather station Vantage Vue from Davis Instruments. The wind direction was crossing the sides of the slope. The air humidity was 57%, the air temperature was 21 °C, and the wind speed was 5–9.7 km·h^{-1}.

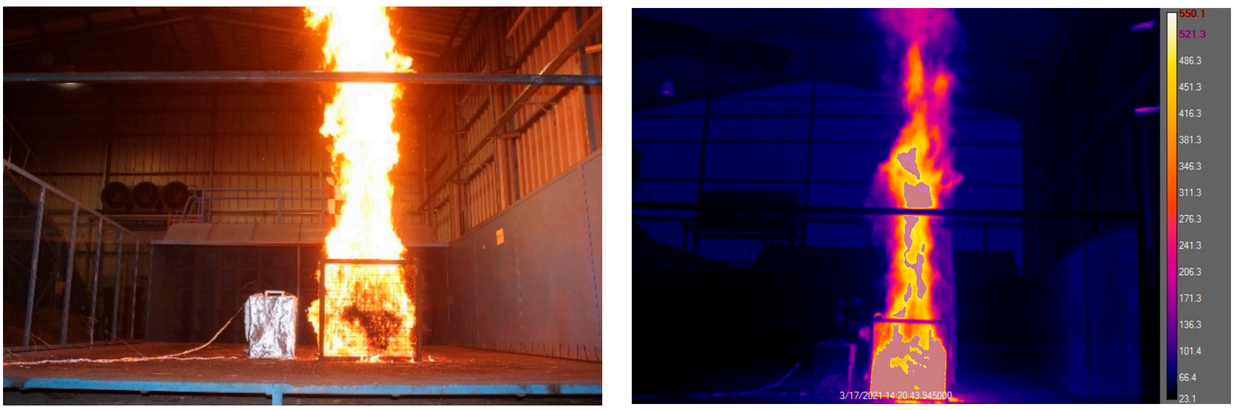
Figure 2. Field test (PSS) views during the arrival of the fire front at the protective device of the gas cylinder.

3. Results

3.1. Laboratory Tests

In Figure 3, the typical laboratory experiment (PS025) with a nominal distance of 25 cm between the edge of the fuel box and the face of the protective device is shown using both a video camera image and an IR camera frame.

In all tests with the protective device and during the time of fire exposure, the cylinder surface temperature remained close to the laboratory environmental temperature (Figure 3). Thus, the LPG cylinder was not heated and stayed under safe conditions, even when the fabric was reached by the intense heat flux of up to 8 kW·m^{-2} (Figure 4).



(**a**) (**b**)

Figure 3. Laboratory test (PS025) at 0.25 m from the basket fuel: (**a**) video and (**b**) InfraRed camera image.

Regarding the heat flux measurements, a substantial difference was found related to the heat flux that reached the cylinder's surface and the fabric's surface, showing that the high level of heat flux decreased, and this factor is decisive in keeping the conditions safe in a fire scenario; since if there is no high heat flux reaching the vessel, the fluid pressure and temperature will not be high enough to produce an explosion.

The flux sensor attached to the surface cylinder showed almost constant values with no significant changes (Figure 4). For the test at 0.25 m from the flames, the difference related to the heat flux that reaches the surface was up to 5.5 kW·m^{-2}, which shows that the protection device works even at a short distance from the flames. The initial flux reduction at the beginning of the cylinder heat flux curve was caused by the convective flux from the fire. As the distance from the fire rises, this behavior decreases. The heat flux registered in the reference tests (Ref) without protection, and the flux on the cylinder's surface under protection (Cylinder), show a significant difference in the flux that reaches the cylinder.

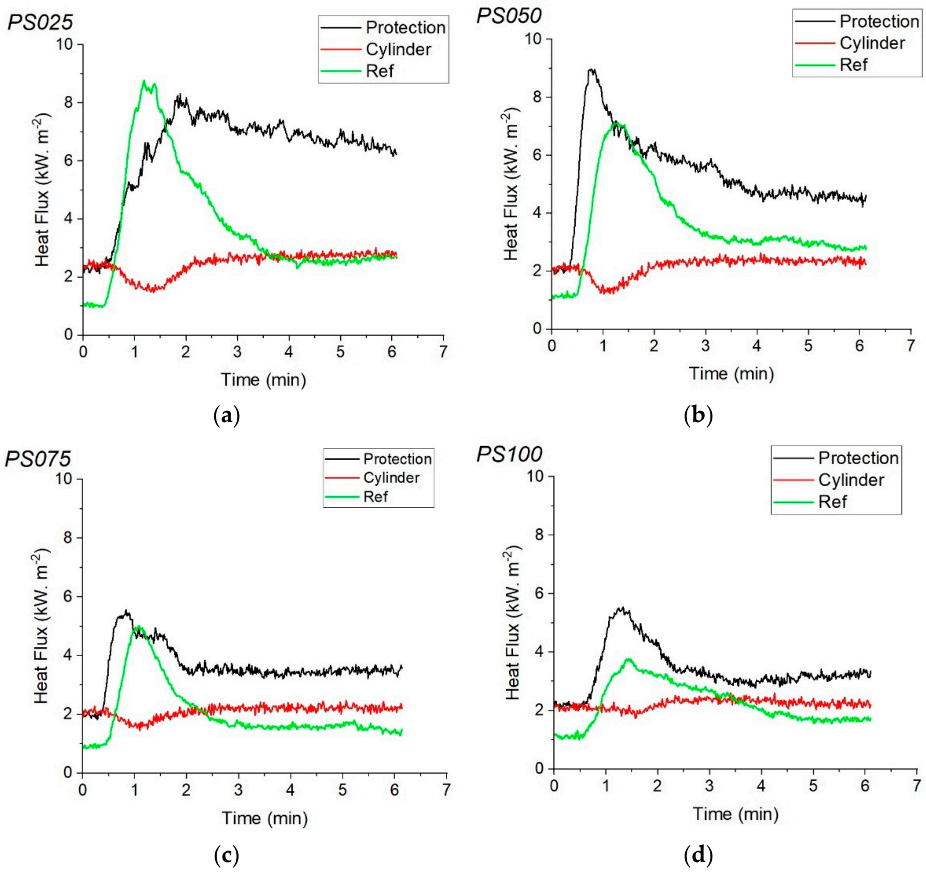


Figure 4. Heat flux on the protection, cylinder, and reference tests at (**a**) 0.25, (**b**) 0.50, (**c**) 0.75, and (**d**) 1 m from the basket fuel.

In all laboratory experiments despite the nominally similar conditions, the burning conditions of the natural vegetation changed slightly from one test to the other. This is illustrated in Figure 5, in which the temperature at a point on the ground at 10 cm from the fuel basket is shown, (a) for tests with the protective device and (b) for the reference tests. The average temperature for the tests with the protective device was 116 °C (Stdev 16 °C), while for the reference tests (without the protective device), which were performed with a 10 °C lower ambient temperature, the average and Stdev were respectively 80 °C and 26 °C, indicating a variability between the individual experiments.

Despite the variability that was found between individual tests, the analysis of the integral of the heat fluxes that is shown below shows consistent behavior of the relevant parameters.

Figure 6 shows the temperature on the cylinder's surface (Cylinder), the temperature on the fabric's surface (Protection) and the room temperature (Lab). There is a great difference between the cylinder and fabric surfaces, reaching 80 °C, as can be seen in Figure 6. The cylinder's surface temperature was kept at safe values, being close to the laboratory environmental temperature during; the whole time the flames lasted and much below the temperature needed to cause high pressure and open a pressure relief valve (26 bar). The temperature registered in the reference tests (Ref) without protection and the temperature on the cylinder's surface under protection (Cylinder) show a significant difference in the cylinder's temperature, up to 110 °C (Figure 6).

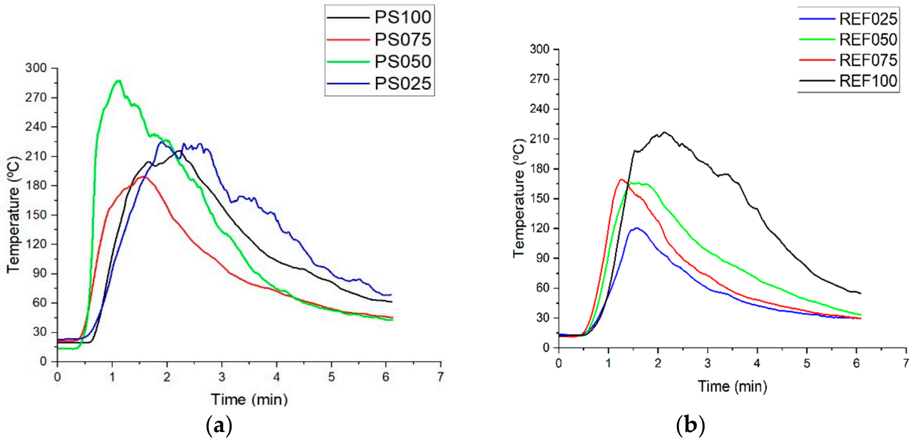


Figure 5. The temperature 10 cm from the basket fuel for (**a**) tests with the protective device and (**b**) reference tests.

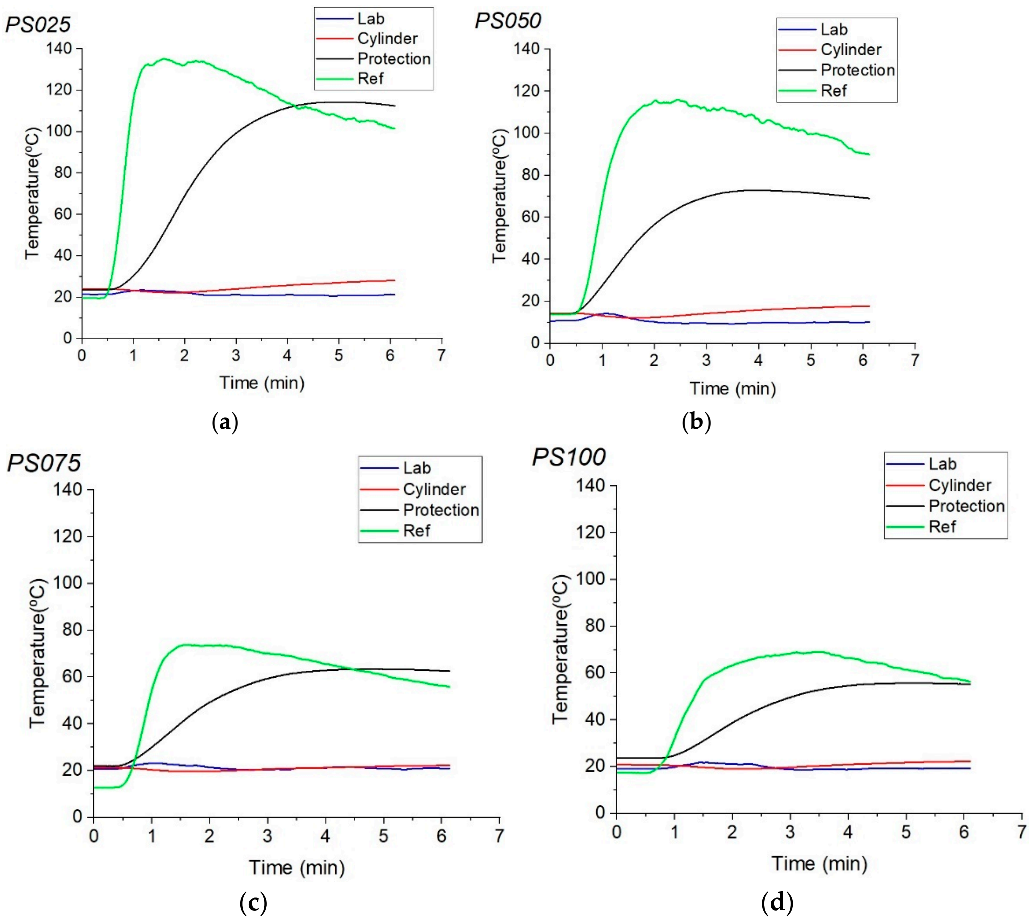


Figure 6. Temperature profile in the laboratory, on the protection, cylinder, and reference tests at (**a**) 0.25, (**b**) 0.50, (**c**) 0.75, and (**d**) 1 m from the basket fuel.

3.2. Field Test

In the field test, the behavior of the bottle and protection was similar to the laboratory tests. There was a large difference between the temperatures of the cylinder's surface and the fabric's surface (Figure 7), and the same occurred for the heat flux applied to the internal and external surface of the protection (Figure 7). On the outer face of the protection, the thermal radiation peak was 7 kW·m^{-2} and the peak temperature was 174 °C; on the face of the bottle, the radiation peaked at 2.5 kW·m^{-2}, and the surface temperature had a maximum of 51 °C.

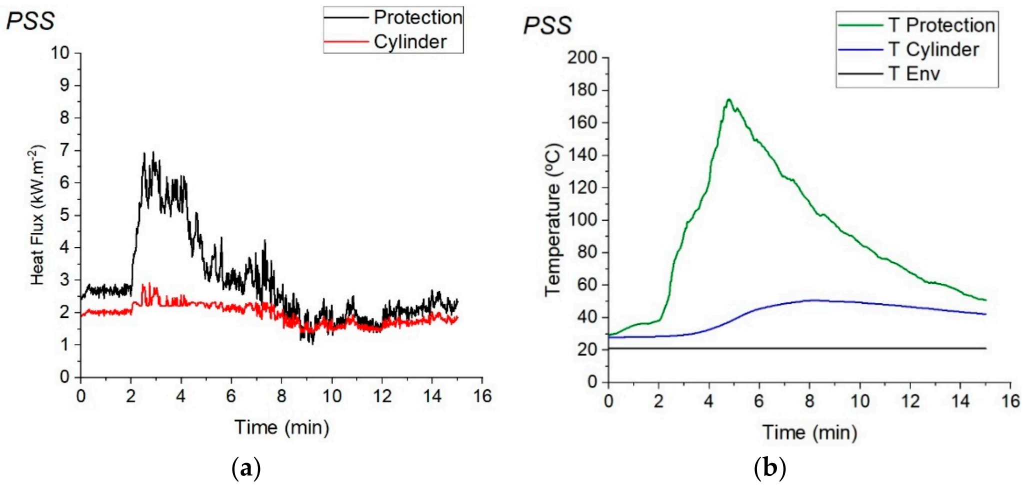


Figure 7. Field test (PSS)—(**a**) Heat flux and (**b**) temperature on the surfaces of the protection and cylinder.

4. Discussion

In WUI fires, spot fires caused by embers taken by wind flow are common. They cause fires away from the original fire front, inside cities and villages, where residential LPG vessels can be placed, as happened in the cases cited by [6]. These embers may ignite fuels in the vicinity of LPG vessels, but they cannot affect the protection device as the fabric material is non-combustible.

In Table 2, values of the integral of the heat flux on each measuring point after six minutes of the test are given for tests with and without the protective device at various distances, and also for the field test. In Figure 8, the flux of energy received after six minutes of the test at each measuring surface is shown as a function of the distance between the face of the fuel basket and the face of the protective device. As can be seen, the flux of energy that reaches the face of the protective device decreases with distance.

Table 2. Integral of heat flux on surfaces of the cylinder and protection.

Test	Distance (m)	Protective Device (kJ·m^{-2})	Cylinder (kJ·m^{-2})	Difference (kJ·m^{-2})	Ratio
PS025	0.25	37.12	14.81	22.31	0.399
PS050	0.50	31.92	12.95	18.97	0.406
PS075	0.75	21.76	12.62	9.14	0.580
PS100	1	20.4	13.18	7.22	0.646
PSS	Field	29.352	12.9	16.45	0.439

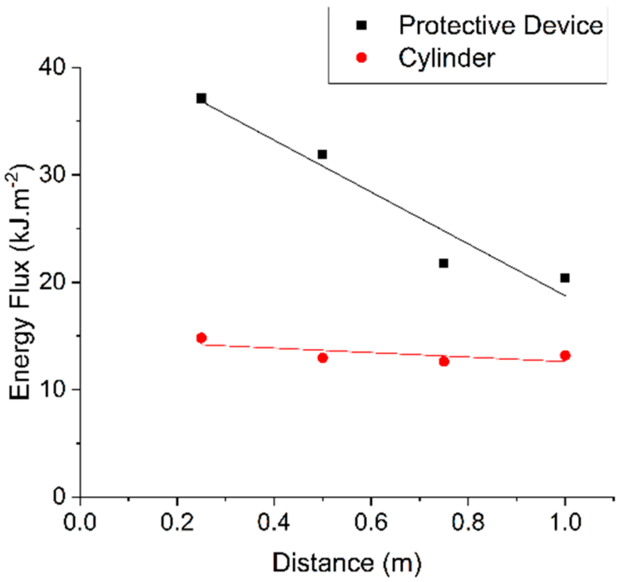


Figure 8. Energy flux on surfaces of the cylinder and protection for laboratory tests with the protective device.

Our findings have shown that an LPG vessel can be protected and safe from a heat flux emitted by fires from the scenarios cited, even at short distances. The protection was considered efficient because during the tests, under intense heat flux up to 7 kW·m^{-2}, the cylinder's surface temperature was kept without significant changes.

At the shortest distance from the flame, the protection device has the highest level of flux blockage effect. For the distances tested, the flux blockage was 61%, 58%, 42%, and 33% for distances of 0.25, 0.5, 0.75, and 1 m, respectively (Table 3).

Table 3. Average of heat flux blocked.

Test	% Average of Flux Blockage	Average of Flux Blockage (kW·m^{-2})
PS025	61	2.48
PS050	58	3.1
PS075	42	1.5
PS100	33	1.1
PSS	46	1.0

Corrosion, impacts, high temperature and pressure can lead to a vessel burst. The presence of high values of pressure and temperature are the main reasons that lead to a cylinder burst. The high vessel surface temperatures under contact with the gas phase, combined with lower temperatures of the surfaces wetted by the liquid phase, lead to temperature gradients that decrease the metal resistance [15,32]. Once the material is weakened, the increase of internal pressure will cause a sudden release of energy. If the gas cylinders are equipped with the protection device, the rupture and the severe effects of a BLEVE may be avoided; as the surface temperature, gradient temperatures, and internal pressure values are kept low.

The internal pressure can be estimated considering that the fluid is at the same temperature as the cylinder's surface. The Wagner equation for pure fluids [33] may be used to predict the internal pressure, considering the cylinder surface temperature and propane pureness, because the Portuguese law sets a minimum of 90% of propane pureness, and the supplier ensures a minimum of 95% pureness. Table 4 shows the pressures for propane related to the maximum temperatures measured in the tests on the surface of the cylinder. The values found through the Wagner equation were compared to the NIST table for propane. There was not a significant difference. The approximate uncertainty is 0.02% for pressure vapor above 180 K [34,35].

The Wagner equation [33] allows the estimation of the internal pressure as a function of the following parameters:

$$lnP_{vPR} = \frac{\left(\alpha\tau + b\tau^{1.5} + c\tau^{2.5} + d\tau^{5}\right)}{T_R} \quad (1)$$

where $\alpha = -6.76368$; $b = 1.55481$; $c = -1.5872$; $d = -2.024$; $Tc = 369.85\ K$; Pc = 42.47 bar; $\tau = 1 - T_R$.

In the laboratory, we carried out seven hydrostatic tests (HT) at room temperature. The average burst pressure was 91 ± 0.94 bar. Tschirschwitz [15] carried out tests with an LPG vehicle tank, and the burst pressure was from 70.7 up to 98.2 bar. The EN 1442 requires a minimum burst pressure of 50 bar. The maximum pressure predicted (17.5 bar) is only 67% of the pressure needed to open the pressure relief device (26 bar), 35% of the minimum burst pressure (50 bar) required by EN 1442, and 20% of HT burst pressure. Thus, our findings show that the pressures estimated using the cylinder surface temperature with the protection device are far from burst pressure. Hence, they are safe conditions.

Table 4. Maximum surface temperatures of the tests and the estimative of the pressure in the cylinder.

Test	Environmental Temperature (°C)	Max Surf. Protection Temperature (°C)	Max Surf. Cylinder Temperature (°C)	Difference of Surf. Temperatures (°C)	Estimative of Maximum Pressure (bar)
PS025	21	110	30	80	10.8
PS050	10	73	18	55	7.93
PS075	20	63	22	41	8.81
PS100	19	56	23	33	9.04
PSS	21	174	51	123	17.5

Therefore, cylinder bursts may be prevented by our protection device, even when exposed to a high-intensity fire. In fact, the fluid inside the vessel does not warm up enough to achieve burst pressure, as the surface temperature is low, contributing to keeping the structure resistant.

5. Conclusions

WUI fires are frequent events, and they may cause accidents related to LPG cylinders. Some protective devices were proposed to improve house walls and roofs resilience. However, protection for cylinders used in WUI areas was not previously proposed.

In this work, the efficiency of a cheap and light, protective device manufactured in an insulating fabric with a reflective external surface to cover an LPG cylinder and block the heat flux when a WUI fire occurs was assessed. Laboratory and field tests were carried out with the protective device at different distances from the fire to find the block rate of the heat flux and determine if the protective device works in a real fire event. The protective device could block up to 61% of the heat flux and keep the cylinder's temperature close to room temperature even under high heat flux and at a short distance from the flame. The highest estimated pressure was 67% of the pressure needed to open the pressure relief device.

Regarding the accidents mentioned, the protective device tested in this work could have avoided these burst vessel cases. It shows the importance of a protection system and how positive its use can be in avoiding the heating of the fluid, and hence the material rupture, decreasing the probability of extreme events, such as a BLEVE.

The proposed protective device is a safe alternative to prevent accidents related to LPG cylinders in WUI fires.

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References

1. Tedim, F.; Leone, V.; Amraoui, M.; Bouillon, C.; Coughlan, M.; Delogu, G.; Fernandes, P.; Ferreira, C.; McCaffrey, S.; McGee, T.; et al. Defining Extreme Wildfire Events: Difficulties, Challenges, and Impacts. *Fire* **2018**, *1*, 9. [CrossRef]
2. Ribeiro, L.M.; Rodrigues, A.; Lucas, D.; Viegas, D.X. The impact on structures of the pedrógão grande fire complex in June 2017 (Portugal). *Fire* **2020**, *3*, 57. [CrossRef]
3. Viegas, D.X.; Rodrigues, A.; Abouali, A.; Almeida, M.; Raposo, J. Fire downwind a flat surface entering a canyon by lateral spread. *Fire Saf. J.* **2021**, *122*, 103349. [CrossRef]
4. Oliveira, R.; Oliveira, S.; Zêzere, J.L.; Viegas, D.X. Uncovering the perception regarding wildfires of residents with different characteristics. *Int. J. Disaster Risk Reduct.* **2020**, *43*, 101370. [CrossRef]
5. Pastor, E.; Muñoz, J.A.; Caballero, D.; Àgueda, A.; Dalmau, F.; Planas, E. Wildland–Urban Interface Fires in Spain: Summary of the Policy Framework and Recommendations for Improvement. *Fire Technol.* **2020**, *56*, 1831–1851. [CrossRef]
6. Scarponi, G.E.; Pastor, E.; Planas, E.; Cozzani, V. Analysis of the impact of wildland-urban-interface fires on LPG domestic tanks. *Saf. Sci.* **2020**, *124*, 104588. [CrossRef]
7. Heymes, F.; Aprin, L.; Forestier, S.; Slangen, P.; Baptiste Jarry, J.; François, H.; Dusserre, G. Impact of a distant wildland fire on an LPG tank. *Fire Saf. J.* **2013**, *61*, 100–107. [CrossRef]
8. O Instituto Português do Mar e da Atmosfera, Análise Preliminar do Período 5 a 10 Agosto 2016 na Madeira. 2016. Available online: https://www.ipma.pt/pt/media/noticias/news.detail.jsp?f=/pt/media/noticias/arquivo/2016/madeira-5-10-ago-2016.html (accessed on 2 March 2022).
9. Viegas, D.X.; Figueiredo Almeida, M.; Ribeiro, L.M.; Raposo, J.; Viegas, M.T.; Oliveira, R.; Pinto, C.; Jorge, H.; Rodrigues, A.; Lucas, D. *O Complexo de Incêndios de Pedrógão Grande e Concelhos Limítrofes, Iniciado a 17 de Junho de 2017*; Centro de Estudos Sobre Incêndios Florestais (CEIF/ADAI/LAETA): Coimbra, Portugal, 2017.
10. Viegas, D.X.; Almeida, M.A.; Ribeiro, L.M.; Raposo, J.; Viegas, M.T.; Oliveira, R.; Alves, D.; Pinto, C.; Rodrigues, A.; Ribeiro, C.; et al. *Análise dos Incêndios Florestais Ocorridos a 15 de Outubro de 2017*; Centro de Estudos Sobre Incêndios Florestais (CEIF/ADAI/LAETA): Coimbra, Portugal, 2017.
11. Pinto, P.; Silva, Á.; Viegas, D.; Almeida, M.; Raposo, J.; Ribeiro, L. Influence of Convectively Driven Flows in the Course of a Large Fire in Portugal: The case of Prdrógão Grande. *Atmosphere* **2022**, *13*, 414. [CrossRef]
12. Hemmatian, B.; Planas, E.; Casal, J. Comparative analysis of BLEVE mechanical energy and overpressure modeling. *Process Saf. Environ. Prot.* **2017**, *106*, 138–149. [CrossRef]
13. Planas-Cuchi, E.; Salla, J.M.; Casal, J. Calculating overpressure from BLEVE explosions. *J. Loss Prev. Process Ind.* **2004**, *17*, 431–436. [CrossRef]
14. Casal, J.; Salla, J.M. Using liquid superheating energy for a quick estimation of overpressure in BLEVEs and similar explosions. *J. Hazard. Mater.* **2006**, *137*, 1321–1327. [CrossRef] [PubMed]
15. Tschirschwitz, R.; Krentel, D.; Kluge, M.; Askar, E.; Habib, K.; Kohlhoff, H.; Krüger, S.; Neumann, P.P.; Storm, S.U.; Rudolph, M.; et al. Experimental investigation of consequences of LPG vehicle tank failure under fire conditions. *J. Loss Prev. Process Ind.* **2018**, *56*, 278–288. [CrossRef]
16. Tschirschwitz, R.; Krentel, D.; Kluge, M.; Askar, E.; Habib, K.; Kohlhoff, H.; Neumann, P.P.; Storm, S.U.; Rudolph, M.; Schoppa, A.; et al. Mobile gas cylinders in fire: Consequences in case of failure. *Fire Saf. J.* **2017**, *91*, 989–996. [CrossRef]
17. Stawczyk, J. Experimental evaluation of LPG tank explosion hazards. *J. Hazard. Mater.* **2003**, *96*, 189–200. [CrossRef]
18. Ricci, F.; Scarponi, G.E.; Pastor, E.; Planas, E.; Cozzani, V. Safety distances for storage tanks to prevent fire damage in Wildland-Industrial Interface. *Process Saf. Environ. Prot.* **2021**, *147*, 693–702. [CrossRef]
19. Viegas, C.; Batista, R.; Albino, A.; Coelho, M.; Andrade, J.; Alves, D.; Viegas, D.X. Active Barrier Combining Fire-Resistant Fiberglass Fabric and Water Sprinkler System for Protection against Forest Fires. *Fire Technol.* **2021**, *57*, 189–206. [CrossRef]

20. Takahashi, F. Whole-House Fire Blanket Protection from Wildland-Urban Interface Fires. *Front. Mech. Eng.* **2019**, *5*, 60. [CrossRef]
21. *EN 1442*; LPG Equipment and Accessories-Transportable Refillable Welded Steel Cylinders for LPG-Design and Construction. European Committee for Standardization: Brussels, Belgium, 2017.
22. *EN 12245:2009 + A1: 2011*; Transportable Gas Cylinders-Fully Wrapped Composite Cylinders. European Committee for Standardization: Brussels, Belgium, 2011.
23. Redmond, M.; Mastropietro, A.J. Thermophysical and Optical Properties of Materials Considered for use on the LDSD Test Vehicle. In Proceedings of the 45th International Conference on Environmental Systems, Bellevue, WA, USA, 12–16 July 2015.
24. Batista, R.M. Mechanisms for Active Protection of People and Infrastructures against Forest Fires. Ph.D. Dissertation, Universidade de Coimbra, Coimbra, Portugal, 2019. Available online: http://hdl.handle.net/10316/86026 (accessed on 10 January 2022).
25. Pereira, D.J.S.; Viegas, C.; Panão, M.R.O. Heat transfer model of fire protection fiberglass thermal barrier coated with thin aluminium layer. *Int. J. Heat Mass Transf.* **2022**, *184*, 122301. [CrossRef]
26. Pinto, C.; Viegas, D.; Almeida, M.; Raposo, J. Fire whirls in forest fires: An experimental analysis. *Fire Saf. J.* **2017**, *87*, 37–48. [CrossRef]
27. Viegas, D.X.; Palheiro, P.M.; Pita, L.P.; Ribeiro, L.M.; Cruz, M.G.; Ollero, A.; Arrue, B.; Ramiro, M.D. Analysis of fire behaviour in Mediterranean shrubs: The Gestosa fire experiments (Portugal). *For. Ecol. Manag.* **2006**, *234*, S101. [CrossRef]
28. Rodrigues, A.; Ribeiro, C.; Raposo, J.; Viegas, D.X.; André, J. Effect of Canyons on a Fire Propagating Laterally over Slopes. *Front. Mech. Eng.* **2019**, *5*, 41. [CrossRef]
29. Raposo, J.R.N. Extreme Fire Behaviour Associated with the Merging of Two Linear Fire Fronts. Ph.D. Dissertation, Coimbra University, Coimbra, Portugal, 2016.
30. Cohen, J.D.; Butler, B.W. Modeling potential structure ignitions from flame radiation exposure with implications for wildland/urban interface fire management. In Proceedings of the 13th Fire and Forest Meteorology Conference, International Association of Wildland Fire, Victoria, Australia, 27–31 October 1996; pp. 81–87. Available online: https://www.fs.fed.us/rm/pubs_other/rmrs_1998_cohen_j001.pdf (accessed on 20 March 2022).
31. Cohen, J.D. The Structure Ignition Assessment Model (SIAM). In *The Biswell Symposium: Fire Issues and Solutions in Urban Interface and Wildland Ecosystems*; 1995; pp. 85–92. Available online: https://www.fs.usda.gov/treesearch/pubs/27418 (accessed on 20 March 2022).
32. Scarponi, G.E.; Landucci, G.; Birk, A.M.; Cozzani, V. LPG vessels exposed to fire: Scale effects on pressure build-up. *J. Loss Prev. Process Ind.* **2018**, *56*, 342–358. [CrossRef]
33. Poling, B.E.; Prausnitz, J.M.; O'Connell, J.P. *The Properties of Gases and Liquids*; McGraw-Hill: New York, NY, USA, 2001; p. 7.5. ISBN 0071499997.
34. National Institute of Standards and Technology, Saturation Properties for Propane—Temperature Increments, (n.d.). Available online: https://webbook.nist.gov/cgi/fluid.cgi?Action=Load&ID=C74986&Type=SatP&Digits=5&THigh=60&TLow=0&TInc=1&RefState=DEF&TUnit=C&PUnit=bar&DUnit=kg%2Fm3&HUnit=kJ%2Fkg&WUnit=m%2Fs&VisUnit=uPa*s&STUnit=N%2Fm (accessed on 7 April 2022).
35. Lemmon, E.W.; McLinden, M.O.; Wagner, W. Thermodynamic properties of propane. III. A reference equation of state for temperatures from the melting line to 650 K and pressures up to 1000 MPa. *J. Chem. Eng. Data* **2009**, *54*, 3141–3180. [CrossRef]