CHEMICAL ENGINEERING TRANSACTIONS

VOL. 86, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

**ISBN** 978-88-95608-84-6; **ISSN** 2283-9216

# Vulnerability of Industrial Storage Tanks to Wildfire: a Case Study

Federica RICCI[a,*], Giordano Emrys SCARPONI[a], Elsa PASTOR[b], Juan Antonio MUÑOZ[b], Eulàlia PLANAS[b], Valerio COZZANI[a],

[a] LISES – Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali - Alma Mater Studiorum – Università di Bologna, via Terracini 28, 40131 Bologna (Italy)
[b] Department of Chemical Engineering, Centre for Technological Risk Studies - Universitat Politècnica de Catalunya BarcelonaTech, Eduard Maristany 16, E-08019 Barcelona, Catalonia, Spain
*federica.ricci18@unibo.it

Wildfires approaching the Wildland-Industrial Interfaces can be a serious threat for industrial items located at the plant boundary. These items are typically storage tanks involving large amounts of hazardous substances. Ensuring their integrity is of paramount importance to prevent the wildfire spread inside the industrial plant, avoiding the occurrence of major accidents such as fires, explosions and toxic releases. A methodology for the evaluation of safety distances between tanks and vegetation for the protection from wildfire hazard was developed and applied to a case study. The outcomes provide useful information for an effective emergency response planning in the case of wildfire. Moreover, the results obtained rise concern about the appropriateness of clearance areas between the vegetation and industrial areas currently adopted.

## 1. Introduction

Climate change and global warming are lengthening hot and dry seasons, making weather conditions around the world increasingly favourable to the development and spread of wildfires (Flannigan et al., 2016). In recent years, a large number of extreme wildfires occurred, such as those observed in Mediterranean Europe (Viegas et al., 2017), Australia (Kwai, 2019) and California (Healy et al., 2020). This kind of events represents a serious threat for the population living at the Wildland-Urban Interface (WUI) as well as for industrial facilities and infrastructures built in the proximity of wildland areas, in this case usually referred to as Wildland-Industrial Interface (WII) areas. Moreover, the rapid urbanization and industrialization of rural areas is increasing the extension of the WUI and WII (Wigtil et al., 2016), rising concern about the wildfire issue.

Ensuring safety of people and assets in these scenarios is a challenging task, due to the large scale and complexity of the phenomena involved, and requires understanding wildfire behaviour in the proximity of WUI and WII as well as knowledge of how structures respond to fire exposure.

In the last decade, the attention of researchers focused mainly on the WUI (Pastor et al., 2019) and only recently it is moving also towards the WII (Khakzad, 2019). The WII is often characterized by the presence of bulk storages of hazardous substances. Atmospheric and pressurized tanks are typically located at plant boundary, thus resulting the most exposed targets in case of wildfires in the plant surroundings. An experimental and numerical study of the response of pressure tanks exposed to a wildfire front was carried by Scarponi and co-workers (2018), who showed that, under severe wildfire conditions, the integrity of such pieces of equipment can be threatened. This may lead to major accidents such as fires, explosions and toxic releases. Similar conclusions were presented by Scarponi and co-workers (2020), who proposed a methodology for the assessment of WUI fire scenarios on domestic LPG tanks, based on 3D CFD simulations (Scarponi et. al 2019). It is clear that preventing failure of storage tanks in case of wildfires is of paramount importance.

In the current industrial practice, this objective is often pursued by the provision of a clearance area in the surrounding of the tank. However, the dimension of this area, and more specifically the separation distance between the tank and the vegetation, is often defined applying empirical rules of thumbs (e.g. FireSmart Guideb. oil gas Ind., 2008) rather than as the result quantitative assessments considering the fire radiation and the resistance of the structure. Recently, Ricci and co-workers (2021) have developed a methodology aimed at filling this gap providing a physically sound approach for the evaluation of safety distances for industrial tanks at the WII is presented. The methodology is based on the characterization of the wildfire in terms of flame geometry, flame emissive power and fire residence time, and makes use of specific vulnerability models for the assessment of the response of storage tanks to fire exposure. In the present work, the use of the methodology is demonstrated through the analysis of a case study, representative of a real tank farm surrounded by a forest. Values of safety distances obtained from the application of the methodology are compared with the dimension of existing clearance areas to assess the appropriateness of the latter. Furthermore, a vulnerability ranking is obtained, that allows identifying which items in the tank farm may require the application of further safety measures, such as the installation of thermal protection systems and other typologies of fire safety barriers, and to prioritize the intervention of emergency response teams. More in general, the outcomes of the present study may provide useful information for an effective emergency response planning in the case of wildfire.

## 2. Methodology

The methodology for the definition of safety distances between storage tanks and vegetation provided by Ricci and co-worker (2021) consists of 4 steps: (a) wildfire characterization, (b) calculation of the incident radiation, (c) evaluation of the time to failure of tanks and (d) definition of safety distance. Main features of each step are described in the following.

### 2.1 Wildfire characterization

Anthropic structures can be affected by the heat load generated by a wildfire front due to convection and thermal radiation (Zárate et al., 2008). Nevertheless, convection can be disregarded when direct contact between flames and target is unlikely. This is the case of tanks inside industrial plants since they are usually surrounded by a clearance area. Therefore, the heat transfer between the fire and tanks can be calculated using the solid flame model approach (Eisenberg et al., 1975), in which the flame is modelled as a solid body with defined shape, dimensions and emissive power *E*. Figure 1 shows a wildfire front approaching an industrial site (panel a) and its representation under the solid flame model assumption (panel b): a flat plane of dimension $L_f$ x $W_f$ (flame length and fire front width respectively), inclined by a tilt angle $\theta$ with respect to the ground.
According to specialized literature (Zárate et al., 2008), the flame length $L_f$ for crown fires can vary between 2.5 and 3.5 times the height of the trees. Thus, as a conservative choice, the upper value is considered. The fire front width $W_f$ depends, among other variables, on the terrain morphology, the distribution of the vegetation and the way the fire spreads. This makes it difficult to perform a general estimate of such parameter. For this reason, the conservative assumption of an infinite fire front is made. The flame tilt angle $\theta$ is strongly affected by wind speed, which is very case specific and may vary considerably during a wildfire event. Therefore, staying again on the conservative side, the tilt angle maximizing the view factor (and therefore the incident radiation) is considered. This value changes as a function of the fire-target distance and height of the trees.

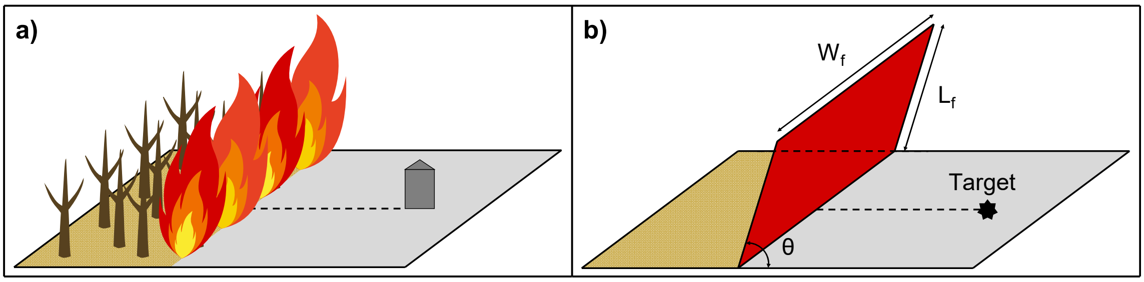


*Figure 1: Panel a) Representation of the wildfire approaching an industrial site. Panel b) Scheme of the flame shape and geometrical parameter used to model the fire scenario.*

The fire front emissive power is calculated using the Stefan-Boltzmann law reported in Eq. 1, where *E* is the emissive power (W/m$^2$), $\varepsilon_f$ is the emissivity of the flames, $T_f$ is the flame temperature (K) and $\sigma$ is the Stefan-Boltzmann constant (5.67 10$^{-8}$ W·m$^{-2}$·K$^{-4}$). Thus, following the approach by Billaud et al. (2011), the fire is conservatively modelled as a black body ($\varepsilon_f$ = 1) with a flame temperature of 1200 K.

$$E = \varepsilon_f \cdot \sigma \cdot {T_f}^4 \quad (1)$$

### 2.2 Calculation of the incident radiation

Under the solid flame assumption, the incident radiation to the tank surface can be calculated using Eq. 2:

$$I = E \cdot F_{view} \cdot \tau_a \quad (2)$$

where $I$ is the incident radiation (W/m$^2$), $\tau_a$ is the atmospheric transmissivity (set to 1 as conservative assumption) and $F_{view}$ is the view factor between the tank and the flame. This is calculated using the method proposed by Mudan (1987), in accordance with the flame shape defined in the previous section (see Figure 1b).

### 2.3 Evaluation of the time to failure of tanks

The time to failure *TTF* of tanks exposed to distant source of radiation can be calculated according to the correlations developed by Landucci and co-workers (2009). They differ according to whether the tank is an atmospheric (Eq. 3) or a pressurized one (Eq. 4) and allow to calculate the time to failure *TTF* (s) given the incident radiation onto the tank surface $I$ (kw/m$^2$) and the volume of the tank $V$ (m$^3$).

$$\ln TTF_{atm} = -1.13 \cdot \ln I - 2.67 \cdot 10^{-5} \cdot V + 9.9 \quad (3)$$

$$\ln TTF_{press} = -0.95 \cdot \ln I - 8.845 \cdot V^{0.032} \quad (4)$$

It is important to remark that these correlations do not consider protections or shielding effects and therefore provide a conservative value of the time to failure.

### 2.4 Definition of safety distances

The evaluation of the safety distances passes through the definition of a reference time *RT*, which is compared with the time to failure *TTF* of the tanks. This value is defined as the minimum between the exposure time to the wildfire front $t_e$ and the maximum response time of emergency teams in the plant considered $t_r$, as shown in Eq. 5.

$$RT = \min(t_e, t_r) \quad (5)$$

The exposure time is strongly related to the fire residence time and spread rate, both depending on site-specific variables and weather conditions. Based on the indication of experienced firefighters, 15 minutes is a credible and conservative estimate of the exposure time to wildfires for a target placed at the forest edge.
The response time of emergency teams $t_r$ depends on the industrial site being considered and should be readily available. Alternatively, a plausible estimate of its value can be done based on experience, guidelines and technical standards. Once *RT* has been estimated comparing the exposure time and the residence time, the safety distance is identified as the minimum value of distance that satisfies the following condition:

$$TTF < RT \quad (6)$$

## 3. Case study

With the aim of demonstrating the use of the methodology and discuss the appropriateness of currently adopted separation distances between storage tanks and vegetation, a case study was defined. This was inspired to a real refinery tank farm placed at the edge of the Amazon rainforest, a few kilometers from the Pacific coast (the specific geographic coordinates are omitted for the sake of confidentiality).
The layout of the tank farm is reported in Figure 2. The facility is mostly surrounded by the forest (green area). According to the NASA Jet Propulsion Laboratory (2015), the height of the trees in the region where the refinery is placed is around 15 meters. This value was assumed for the vegetation height in the case study.
The tank farm contains 22 among atmospheric and pressurized storage tanks, the main features of which are reported in Table 1.

*Table 1: Main features of tanks considered in the case study.*

| Tank ID | Type of tank | Diameter (m) | Height/Length (m) | Volume (m$^3$) |
|---|---|---|---|---|
| 1, 5, 11, 12 | Atmospheric | 40 | 10 | 12566 |
| 2, 3, 21 | Atmospheric | 40 | 8 | 10053 |
| 4, 6 | Atmospheric | 60 | 6 | 16965 |
| 7, 8, 9 | Pressurized | 5 | 8 | 223 |
| 10, 18, 19, 20 | Atmospheric | 30 | 8 | 5655 |
| 13, 14 | Atmospheric | 50 | 4 | 7854 |
| 15, 16, 17 | Pressurized | 3 | 12 | 99 |
| 22 | Atmospheric | 14 | 12 | 1847 |

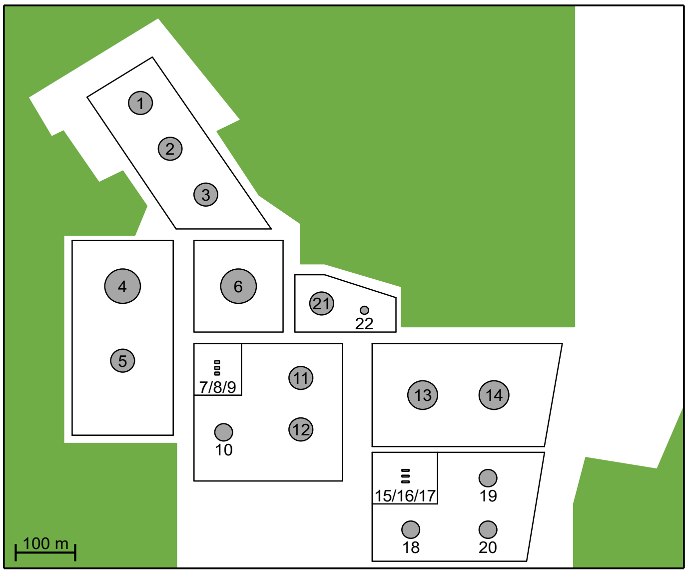


*Figure 2: Layout of the tank farm considered as case study. Green areas represent the forest.*

## 4. Results and Discussion

Figure 3 shows the time to failure calculated as function of the distance for all the tanks considered in the case-study, listed in Table 1. The time to failure was calculated according to Eq. 3 and Eq. 4 for atmospheric (black lines) and pressurized (red lines) tanks respectively. The figure points out that atmospheric tanks are more vulnerable to wildfire with respect to pressurized ones. In fact, the higher values of time to failure were obtained for tanks in this latter category. Focusing on atmospheric tanks, those featuring higher volumes present shorter time to failure. The opposite is true for pressurized tanks, with higher time to failure for smaller volumes.

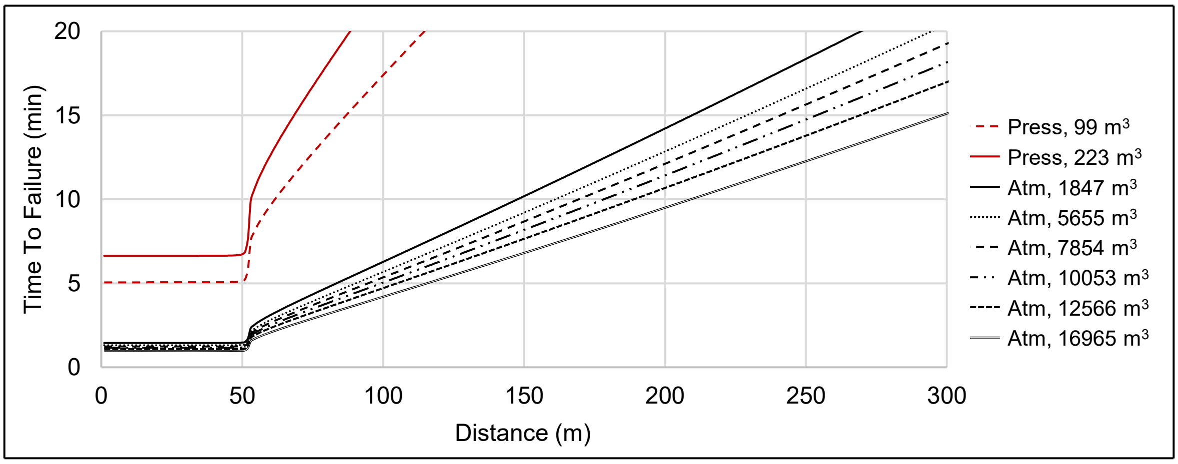


*Figure 3: Time to failure as function of the type and volume of the tank.*

As described in Section 2.4, time to failure must be compared with a reference time in order to evaluate the safety distance. Here, two different values of reference time were considered: 5 and 15 minutes. The first one is representative of the response time of emergency teams in the industrial sites, while the second one is the maximum exposure time to the wildfire front (see Section 2.4). Table 2 reports the values of safety distances calculated from the time to failure curves shown in Figure 3. Clearly enough, atmospheric storage tanks require higher safety distances than pressurized ones, as they result in lower time to failure. Analyzing the data in Table 2, it is possible to note the strong influence of the reference time chosen on the resulting safety distances. In fact, the higher the reference time, the higher the safety distance required to ensure tank integrity in case of wildfire.

*Table 2: Safety distances of the tanks considered in the case study.*

| Tank ID | Type of tank | Safety Distance (m) with RT=5 min | Safety Distance (m) with RT=15 min |
|---|---|---|---|
| 1, 5, 11, 12 | Atmospheric | 105 | 270 |
| 2, 3, 21 | Atmospheric | 100 | 254 |
| 4, 6 | Atmospheric | 116 | 299 |
| 7, 8, 9 | Pressurized | No failure | 69 |
| 10, 18, 19, 20 | Atmospheric | 91 | 230 |
| 13, 14 | Atmospheric | 95 | 242 |
| 15, 16, 17 | Pressurized | No failure | 87 |
| 22 | Atmospheric | 84 | 210 |

Safety distances obtained through the application of the procedure presented in Section 2 can be compared with the existing clearance areas between vegetation and tanks present in the facility taken as reference in the case study. This is done in Figure 4, in which safety distances reported in Table 2 are overlapped with the plant layout, considering both the reference time of 5 min (red line) and 15 min (yellow line).

When a reference time of 5 minutes is considered, existing clearance areas appear adequate to ensure tank integrity only for part of the tanks. The situation appears even worse is the case of safety distance obtained assuming a reference time of 15 minutes. This means that, in this latter case, the integrity of most of the tanks might be affected by the wildfire, with the only exception of tank number 18 and of pressurized tanks. It is therefore demonstrated that actual clearance areas are not sufficient to ensure tanks integrity and avoid the escalation of the wildfire to major accidents inside the plant considered for the analysis. Therefore, measures should be taken in order to protect the tanks that are more prone to failure in the case of a wildfire approaching the plant, such as the installation of fireproofing systems and other typologies of fire safety barrier.

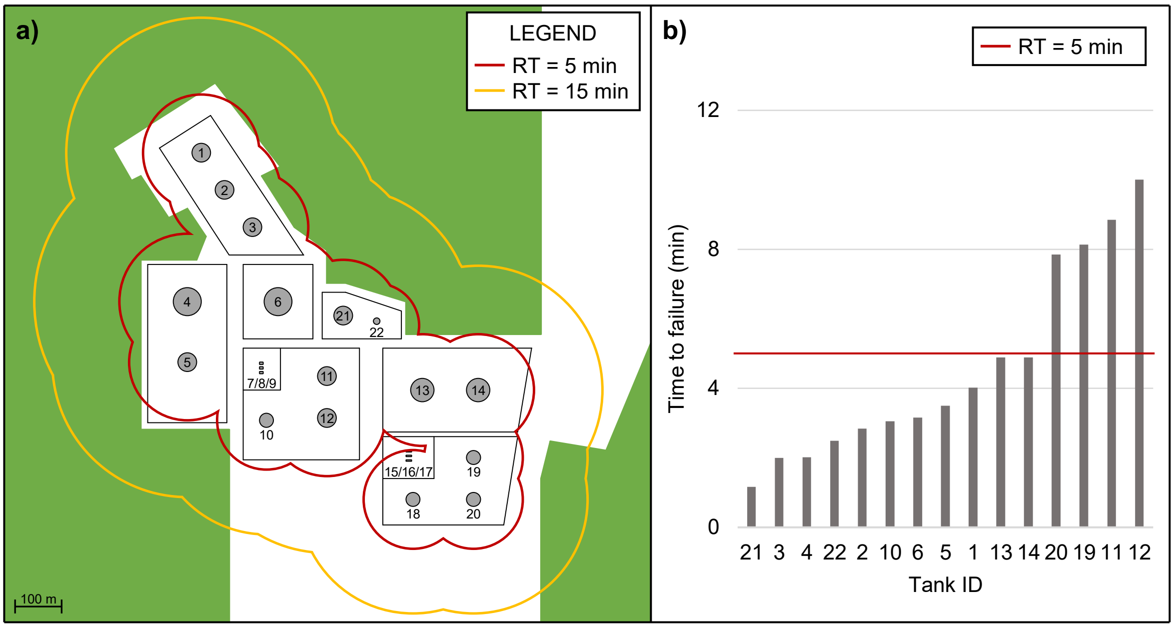


*Figure 4: Panel a) Representation of the safety distances in the layout. Panel b) Ranking of tanks based on the vulnerability to the wildfire scenario (safe tanks with both reference times are not shown in the figure).*

Using an approach similar to the one at the base of the methodology presented above it is also possible to identify the most vulnerable items. This is done by calculating the time to failure of each tank considering the actual minimum distance from the vegetation according to the plant layout. Thus, a vulnerability ranking is obtained by sorting the tanks according to the values of *TTF* (from lowest to highest), as shown in Figure 4b. In the case study under analysis, tanks 21, 3, and 4 resulted to be the most vulnerable ones. This information may be used to support decision makers in identifying the items requiring more protection and prioritize intervention such as fire safety barriers installation. These measures aim at increasing the time to failure in case of fire exposure, making them less vulnerable. At the same time, the vulnerability ranking can support the definition of a more effective emergency response plan in the case of wildfire: the intervention of the emergency teams can be prioritized towards the most vulnerable tanks, reducing the response time and decreasing escalation risk.

## 5. Conclusions

Wildfires approaching the Wildland-Industrial Interfaces may represent a serious threat for industrial items located at the plant boundary. Ensuring the integrity of such items in case of wildfire is of paramount importance. In the present work, a methodology for the evaluation of safety distances for atmospheric tanks and pressurized vessels was presented and applied to a case study inspired to a real tank farm. Results obtained in the case under analysis highlight that actual clearance areas are not sufficient to avoid the spreading of wildfire inside the industrial plant. This rises concern about the appropriateness of distances used in the current practice. Finally, it was shown how the approach at the base of the methodology can be used to obtain a vulnerability ranking, allowing to identify which tanks require the application of further safety measures and to prioritize the intervention of emergency response teams.

### Acknowledgments

This research was partially funded by the European Union Civil Protection (Project GA 826522 WUIVIEW UCPM-2018-PP-AG), by the Spanish Ministry of Economy and Competitiveness (project CTQ2017-85990-R, co-financed with FEDER funds) and by the Italian Ministry of Scientific Research (PRIN2017 program - Project 2017CEYPS8).

### References

Billaud, Y., Kaiss, A., Consalvi, J.-L., Porterie, B., 2011. Monte Carlo estimation of thermal radiation from wildland fires. International Journal of Thermal Sciences, 50, 2–11.

Eisenberg, N., Lynch, C., Breeding, R., 1975. Vulnerability model. A simulation system for assessing damage resulting from marine spills, Report No. CG-D-137-75.

FireSmart guidebook for the oil and gas industry, 2008. FireSmart guidebook for the oil and gas industry. Alberta Sustainable Resource Development, Edmonton.

Flannigan, M.D., Wotton, B.M., Marshall, G.A., de Groot, W.J., Johnston, J., Jurko, N., Cantin, A.S., 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climate Change, 134, 59–71.

Healy, J., Taylor, K., Penn, I., 2020. California Wildfires: Extreme Heat Turns State Into a Furnace. New York Times.

Khakzad, N., 2019. Modeling wildfire spread in wildland-industrial interfaces using dynamic Bayesian network. Reliability Engineering and System Safety, 189, 165–176.

Kwai, I., 2019. Apocalyptic Scenes in Australia as Fires Turn Skies Blood Red. New York Times.

Landucci, G., Gubinelli, G., Antonioni, G., Cozzani, V., 2009. The assessment of the damage probability of storage tanks in domino events triggered by fire. Accident Analysis and Prevention, 41, 1206–1215.

Mudan, K.S., 1987. Geometric view factors for thermal radiation hazard assessment. Fire Safety Journal, 12, 89-96.

NASA Jet Propulsion Laboratory, 2015. Landscape - Remote Sensing of Land Surfaces. https://landscape.jpl.nasa.gov/ (accessed 10.22.20).

Pastor, E., Muñoz, J.A., Caballero, D., Àgueda, A., Dalmau, F., Planas, E., 2019. Wildland–Urban Interface Fires in Spain: Summary of the Policy Framework and Recommendations for Improvement. Fire Technology, 56, 1831–1851

Ricci, F., Scarponi, G.E., Pastor, E, Planas, E., Cozzani, V., 2021. Safety distances for storage tanks to prevent fire damage in Wildland-Industrial Interface. Process Saf. Environ. Prot. 147, 693–702.

Scarponi, G.E., Landucci, G., Heymes, F., Cozzani, V., 2018. Experimental and numerical study of the behavior of LPG tanks exposed to wildland fires. Process Saf. Environ. Prot. 114, 251–270.

Scarponi, G. E., Landucci, G., Birk, A. M., & Cozzani, V. (2019). An innovative three-dimensional approach for the simulation of pressure vessels exposed to fire. *Journal of Loss Prevention in the Process Industries*, *61*, 160–173.

Scarponi, G.E., Pastor, E., Planas, E., Cozzani, V., 2020. Analysis of the impact of wildland-urban-interface fires on LPG domestic tanks. Safety Science, 124, 104588.

Viegas, D.X., Figueiredo, M., Ribeiro, L.M., 2017. O complexo de incendios de pedrógao grande e conchelos limítrofes, iniciado a 17 de Junho de 2017.

Wigtil, G., Hammer, R.B., Kline, J.D., Mockrin, M.H., Stewart, S.I., Roper, D., Radeloff, V.C., 2016. Places where wildfire potential and social vulnerability coincide in the coterminous United States. International Journal of Wildland Fire 25, 896–908.

Zárate, L., Arnaldos, J., Casal, J., 2008. Establishing safety distances for wildland fires. Fire Safety Journal, 43, 565–575.