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Report on LPG infrastructure impact at the WUI microscale

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Abstract	Preventing and mitigating the consequences of forest fires at the WUI is a challenging task due to the inherent complexity of the WUI environment. Safety measures have to be implemented at different scales (macro, meso and micro scale) to ensure the success of population and structures protection strategies. The present document focuses on the home owner scale identifying in the possible presence of LPG tanks a potential additional threat in case of fire. Recent accidents have demonstrated that the risk associated with this type of installation is real, but often disregarded by residents. Furthermore, legislations regulating the use of LPG tanks is far from being harmonized among countries. There is no general agreement in the definition of safety distances. The methodology presented in this document provides an advanced tool to assess whether the response of an LPG tank exposed to WUI fire scenarios falls within acceptable safety limits. This can be applied to a vast range of situations and at a different level of detail according to available data. The outcome of the methodology is in the in form of indicators that may easily be compared with acceptance criteria to assess whether the scenario under analysis falls within safety limits.

	The first part of the documents describes problematics related to the possible exposure of domestic LPG tanks to WUI fires, providing also an overview of the legislation framework regulating the use of this kind of infrastructure at EU level. Then, a brief review of the research in the field of LPG tanks exposed to fire is presented. The central part of the document is dedicated to the description of the methodology for the assessment of the response of LPG tanks exposed to WUI fires. Finally, the methodology is applied to a series of five case studies, representative of situations that are commonly found at the WUI, as described in previous D5.1.

(1) Draft / Final

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1. Introduction

Forest fires affecting urban and rural communities represent an increasing problem throughout the world. They pose tremendous management challenges in terms of civil protection and fire mitigation (Manzello et al., 2018). These emergencies often exceed fire-fighters capacities due to their multi-risk nature: they usually involve wildfire suppression, structures protection and communities' evacuation, and they can even trigger Natech events when interfacing industrial infrastructure (Krausmann et al., 2016; Cozzani et al., 2014; Naderpour et al., 2019).

The WUI (wildland-urban interface) fire problem is inherently complex, as it is characterized by the interaction of multiple phenomena of diverse nature occurring at different observation scales: the macroscale or landscape scale, the mesoscale or settlement scale and the microscale or home/plot scale (Pastor et al., 2019a). It is at the microscale where the specific events that jeopardize residents and assets can be observed and where prevention actions at home-owner level must be undertaken. The WUI microscale is quite often characterized by the presence of all sorts of combustible elements around structures (ground fuels, ornamental vegetation, stored material, etc.) whose hazard is poorly characterized and thus remarkably disregarded by residents (Pastor et al., 2019a).

The hazard associated with domestic LPG (liquefied petroleum gas) storage tanks, used as energy source for heating, hot water production or cooking in WUI developments has to be highlighted in this framework. This type of infrastructure may be seriously threatened by a fire, particularly in those cases where negligence or regulatory gaps allow a very close exposure of these tanks to flames coming from nearby fuels. In these situations, the tank will heat up and pressurize. If the tank pressure reaches the Pressure Relief Valve (PRV) set point, this will open, releasing LPG that will immediately ignite forming a jet fire. The jet fire will hence worsen the heat load to the tank and the surroundings. If no measure is taken in order to cool down the tank and/or extinguish the fire, the tank may fail, leading to a loss of containment. Depending on the type of failure, intense jet fires from shell cracks, BLEVEs (Boiling liquid Expanding Vapor Explosions) and fireballs may follow (Abbasi and Abbasi, 2007; Birk and Cunningham, 1994; Leslie and Birk, 1991; Mcdevitt, 1990; Moodie et al., 1985). Furthermore, fragments resulting from the destruction of the tank shell can be projected to the surrounding, potentially worsening the consequences of the explosion (Tugnoli et al., 2013).

In recent WUI fire events (e.g. Benitatxell, Spain, 2016; Madeira, Portugal, 2016; Calabassas, California, 2016; Mati, Greece, 2018) these type of infrastructures were dangerously affected (Figure 1). The lack of an effective safety distance between the LPG tank and the surrounding fuels caused the opening of the safety relief valves and intense jet fires. Although explosions did not occur, the magnitude of the consequences in case of a BLEVE-Fireball event could have been severe, given the high population and assets density that usually characterize WUI areas. Being able to assess whether a given fire scenario represents or not a threat for LPG tanks' integrity is therefore critical to ensure safety of this type of installations.

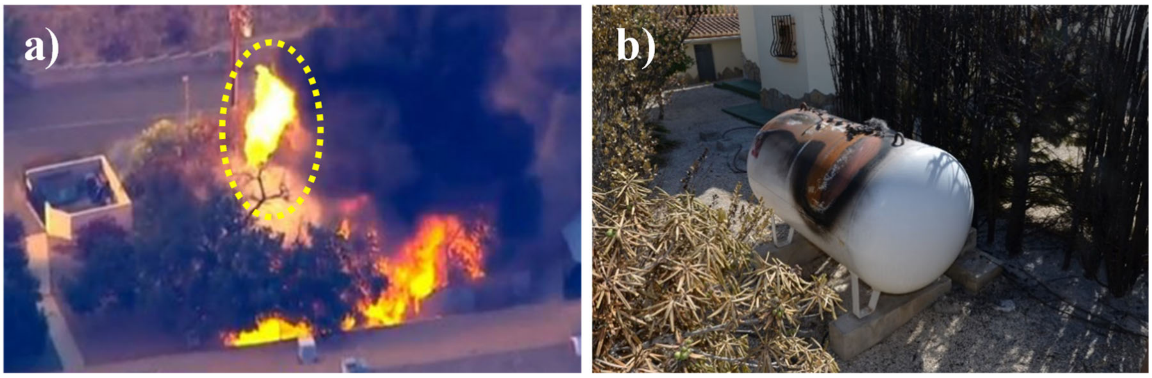

Figure 1. a) Calabassas fire (California, 2016 – credit KABC-TV). A propane jet fire can be observed at the center of the image (inside the yellow dotted ellipse). Flames from ornamental fuels are close to the tank. LPG infrastructure was inside a kindergarten; b) Domestic LPG tank in Benitatxell (Spain, 2016 - credit D. Caballero) damaged by a jet fire from the PRV. The tank was surrounded by an ornamental hedgerow that ignited by spotting.

This document presents a study of the problem of LPG domestic tanks exposure to WUI fire exposure. First, an analysis of the existent regulations in WUI-fire prone countries dealing with domestic LPG services is carried out, with the aim of detecting gaps, deficiencies and inconsistencies between regulations. The state of the art of experimental and modelling research dealing with the safety of LPG tanks in the framework of the WUI context is also reviewed. Finally, a methodology based on CFD (Computational Fluid Dynamics) modelling is presented as a tool to support the assessment of LPG tanks' integrity in WUI fire scenarios and proved useful to analyse patern scenarios as those described in previous WUVIEW deliverable D5.1.

2. Regulatory framework at European level

Worldwide the use and installation of domestic LPG tanks is not harmonized. In the European Union, different regulations are issued by each Member State (MS). Thus, prescription specifying, among others safety distances from the LPG supply unit to vulnerable elements, storage of flammable materials and sources of ignitions, may be extremely variable. A detailed and comprehensive analysis of all regulations is out of the scope of the present study. In the following, regulations from France (JORF, 1979), Greece (ΦΕΚ, 1993), Italy (GUDRI, 2004) Portugal (DRE, 2002), Spain (AENOR, 2008) and UK (HSE, 2016) will be considered for the sake of comparison and to analyze the specific case-studies.

Figure 2 shows a comparison of minimum safety distances from domestic above-ground LPG tanks according to the legislation of the European countries listed above. In general, it can be noted how prescriptions are not harmonized. Italy has the most conservative requirements, whereas Spain has the less restrictive ones. The Spanish regulation, for instance, indicates that for tanks with volume within 1 and 5 m^3 in volume, safety distances should be of 2m. This distance can be reduced by a 50% for smaller tanks. The Italian legislation prescribes a safety distance that is more than twice of that required in Spain for the same tank volumes. Thus, strong discrepancies are present in the standards, even within countries in the same geographical area and exposed to similar hazards. This alone should rise concern.

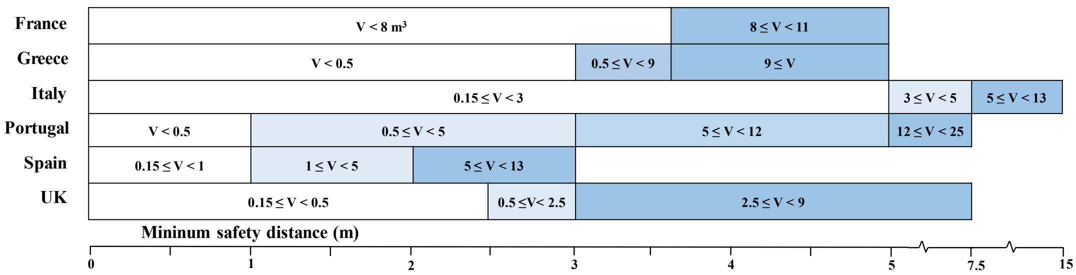

Figure 2: Minimum safety distances as a function of tank volume (in m^3) for different European countries.

Another important issue that is worth to remark is that not all the standards in the different countries listed in Figure 2 explicitly regulate the possible presence of vegetation in the proximity of the tank. The Greek regulation clearly states that "*the floor of the storage area must be kept clean and free of dry grass, grass and foreign objects*". Similarly, the HSE (UK) recommends that there should be no trees or shrubs within the safety distance reported in the standard. The Italian regulation requires that no vegetation is present in an area of 5 m around the tank. On the other hand, the Portuguese regulation has a more general statement, not allowing the presence of flammable products within the safety distance reported in Figure 2. The French regulations simply mention that no storage of flammable material can be present in the area defined by safety distance. Clearly enough, such statement does not cover the case of ornamental vegetation commonly placed in WUI microscale and that might be ignited in case of wildfires. The Spanish regulation does not address the issue of the possible presence of fuels in the proximity of LPG tanks.

Indeed, there are countries in which the potential hazard produced by the presence of vegetation in the proximity of LPG tanks is not properly considered. As shown in Figure 1, this regulatory gap may produce dangerous situations in case of WUI fires. Furthermore, even in the countries with a standard explicitly addressing the issue, situations such as those depicted in Figure 1 demonstrate that current prescriptions might be not sufficient to avoid escalation events involving domestic LPG tanks in the case of severe wildfires.

In the framework of such jeopardized scenario, the need clearly emerges to support regulators towards better-informed decision-making in the determination of safety distances.

3. State of the art on vulnerability assessment of LPG tanks exposed to fire

The response of LPG vessels to fire exposure was investigated since the sixties (Bray, 1964). Several fire test campaigns have been carried out by different research groups and institutions (most of which are summarized in the literature reviews presented by Moodie (1988) and Birk (2006), which allowed increasing the understanding of the physical phenomena involved in these scenarios (e.g. Aydemir et al., 1988; Sumathipala et al., 1992; Birk and Cunningham, 1996).

In parallel to experimental studies, more and more complex models were developed over the years, aimed at reproducing the phenomena occurring inside a vessel under fire exposure, and predicting pressurization rate, temperature distributions and time to failure. Early approaches are based on strong simplifying assumptions (Aydemir et al., 1988; Beynon et al., 1988; Birk, 1988, 1983; Gong et al., 2004; Graves, 1973; Johnson, 1998b, 1998a; Dancer and Sallet, 1990; Venart, 2000; Yu et al., 1992): the tank is divided in one or more zones (or nodes), for which integral mass and energy balances are solved. Such models rely on empirical expressions with a limited range of applications. Furthermore, they neglect key phenomena such as thermal stratification and boiling. More recently, approaches based on CFD codes were proposed (Bi et al., 2011; D'Aulisa et al., 2014; Hadjisophocleous et al., 1990; Scarponi et al., 2019, 2018a; Yoon and Birk, 2004).

Despite such advancements, the vast majority of the studies addressed the effects of hydrocarbon pool and jet fires (i.e. scenarios that are likely to occur in an industrial environment). So far, very little attention was dedicated to the analysis of pressure tanks exposed to fire in WUI scenarios. Heymes and co-workers (2013c, 2013b) recently carried out a study specifically addressing such framework, performing a set of fire tests on a 2.3 m^3 LPG tank exposed to a distant source of radiation, mimicking the effect of a forest fire. They considered a crown fire scenario with a 100 m wide by 40 m high fire front and average (and constant) emissive power of 90 kW/m^2, affecting a tank positioned at 50 m from the fire. They also provided a method to estimate safety distances (Heymes et al., 2013a) based on the guideline provided in the API 2501 (American Petroleum Institute, 2001). Few years later, Scarponi et al. (2018b) proposed a 2D CFD modelling setup able to reproduce with good accuracy the experimental results obtained by Heymes and co-workers (2013c, 2013b).

Although the above mentioned publications represent pioneering works in the field, a comprehensive analysis of the problems related to fire affecting pressure vessels at the WUI is still missing. As shown in past WUIVIEW deliverable D5.1, the presence of several kinds of fuels that may ignite in a WUI fire, such as vegetation from unmanaged plots, ornamental trees or non-natural materials (storage sheds, fences, pet houses, etc.), introduces a high level of complexity in terms of fire scenario characterization. The methodology developed in the present study aims at providing a systematic approach to the assessment of the response of domestic LPG storage vessels exposed to different typologies of fires that might occur in WUI areas.

4. CFD methodology for LPG tank vulnerability assessment in WUI

The task of assessing whether the response of an LPG tank exposed to a WUI fire scenario falls within acceptable safety limits is challenging, due to the complex physics and the diversity of the phenomena involved. Figure 3 shows a sketch of the problem addressed, together with the schematization of the assessment methodology proposed.

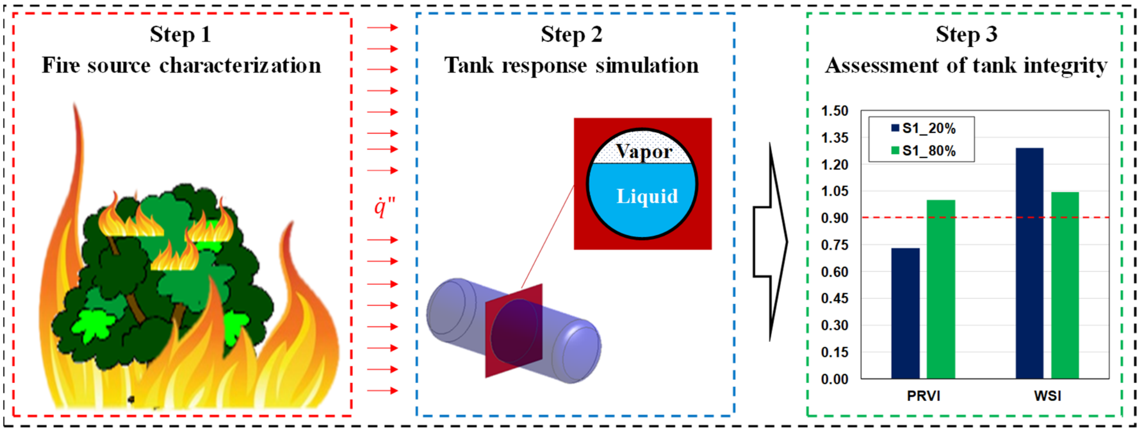

Figure 3: Schematization of the problem and of the methodological approach ($\dot{q}''$ is heat flux through the external surface of the tank).

The methodological approach at hand is divided in three blocks: the characterization of the fire source (e.g. flame shape, emissive power, transient behavior), the simulation of the tank response (e.g. pressurization rate, steel and lading temperatures) and the consequence assessment, in which it is evaluated whether the scenario under analysis can be considered safe or not. The following sections describe in detail the steps of the methodology.

4.1. Step 1 – Fire source characterization

The aim of the first step is to provide the input required for the analysis of the tank response. This means defining the heat load coming from the fire, namely the boundary condition assigned at the external surface of the tank wall in the CFD simulations carried out in Step 2. In the CFD approach developed, the boundary condition (at time t and at point $\vec{x}$ on the external tank wall) reproducing the radiative and convective heat transfer with the exterior of the tank is expressed as follows:

$$\dot{q}"(\vec{x},t) = \sigma\varepsilon_w\left(T_{BB,eq}(\vec{x},t)^4 - T_w(\vec{x},t)^4\right) + h_g(\vec{x},t)\left(T_g(\vec{x},t) - T_w(\vec{x},t)\right) \qquad \text{Eq. (1)}$$

where $\dot{q}"$ is the heat flux through the external surface of the tank wall, σ is the Stefan-Boltzman constant, ε_w is the emissivity of the wall, T_w is the wall temperature and $T_{BB,eq}$ is the equivalent black body temperature (representative of the incident radiation hitting the tank surface):

$$T_{BB,eq}(\vec{x},t) = \sqrt[4]{\frac{I(\vec{x},t)}{\sigma}} \qquad \text{Eq. (2)}$$

The values of the incident radiation I (representing the radiative contribution of both the fire and the ambient), the temperature of the gases T_g (air, flame, smoke) in contact with the tank surface and the convective heat transfer coefficient h_g need to be specified according to the fire scenario characteristics.

The definition of such parameters is the particular objective of the first step of the methodology (the red block in Figure 3). This can be performed by different approaches, depending on available data, accuracy required and organizational factors such as time, costs and computational resources. It is worth mentioning that, in cases where no direct impingement of the flames on the tank occurs, the convective term in Eq. (1) can be neglected. In these cases, this term would actually be negative (i.e. involving convective cooling of the tank surface), hence neglecting it results in a conservative approach from the safety standpoint, also considering the uncertainties in defining the fire scenario. Therefore, in scenario with no flame impingement, spatial and temporal distribution of the incident radiation is the only required input.

Table 1 presents an overview of the possible options to define the fire scenario. The table also specifies the main inputs and the tools required to apply each approach.

Option 1 represents the case in which the analyst already knows the heat load to be applied to the storage tank (e.g. when this comes from regulations, standards, prescriptions or experience). In this case it is possible to directly proceed with the definition of *I*, h_g and T_g (see Eq. (1) and Eq. (2)).

Table 1: Different strategies to characterize the fire sources considered.

Option	Main Inputs	Required tools
1) Direct definition	Expert judgment or prescriptions	None
2) Solid flame model	- Scenario geometry - Fire emissive power (as a function of time) or fire Heat Release Rate curve (and radiative fraction) - Fire shape	Tool for the calculation of view factors
3) Fire simulation	3.1 – Fire prescription - Scenario geometry - Fire HRR curve - Ambient conditions (temperature, humidity and wind) 3.1 – Fire prediction - Scenario geometry - Solid fuel composition, density, heat capacity and thermal conductivity - Solid fuel particle size distribution and moisture content (for vegetation) - Solid fuel pyrolysis curve - Ambient conditions (temperature, humidity and wind)	Fire simulation software (e.g. FDS)

Option 2 is based on the solid flame model concept (Eisenberg et al., 1975): the flame is considered as a solid body having defined shape and dimensions, with an emissive power *E.* Thus, the incident radiation *I* to remote points (e.g. the tank surface) is obtained using Eq. 3, where Γ is the air transmissivity (which is a function of the humidity and the concentration of the carbon dioxide in the atmosphere and can be calculated using empirical correlations) and *f* is the view factor between the remote point and the solid body representing the flame. Details about the calculation of the view factor under the assumption of uniform radiosity and that both the flame and the object surface emit and reflect diffusely can be found in the literature (Beatty, 2004; Eckert, 2004; Scarponi et al., 2018b; Heymes et al., 2013c; Modest, 2003).

$$I = \Gamma f E \quad \text{Eq. (3)}$$

An example of application of Option 2 is reported by Scarponi and Heymes (2018), who considered the situation of a LPG tank exposed to the front of a wildfire. In the study, the fire emissive power and the flame shape were defined according to real scale experimental measurements and only a view factor calculation was needed to obtain *I* (a unitary value of air transmissivity was assumed).

By this approach, a complete characterization of the incident radiation *I* is obtained. As for the temperature of the gas in contact with the tank wall and the related convective heat transfer coefficient (T_g and h_g in Eq. 1), it must be pointed out that the solid flame model is only valid for a distant fire source. This means that scenarios involving flame impingement can not be analyzed using this method and that the use of Option 2 is limited to fire scenarios in which the flame is not in contact with the wall of the tank. In such cases, the gas temperature T_g can be considered as the ambient temperature. The convective heat transfer coefficient h_g can be estimated through empirical correlations for the calculation of the natural convection heat transfer coefficient around a horizontal cylinder, as the one reported by Martynenko and Khramtsov (2005).

The last option to carry out the fire source characterization step is the use of a fire simulation software (Option 3), in which the scenario under analysis is reproduced and spatial and temporal distributions of *I*, h_g and T_g on the surface of the target object (in this case the LPG tank) are obtained. In the present methodology, the Fire Dynamic Simulator (FDS) by the National Institute of Standards and Technology (NIST) of the Unites States Department of Commerce is considered as the reference tool to carry out the simulations. The key point when considering Option 3 is how the fire is simulated. Two different options were defined to carry out the simulation: Option *3.1 – Fire Prescription*, and Option *3.2 - Fire Prediction*. The first option consists in simulating a burning element as a solid shape with an assigned HRR curve on its surface. The software models the fire as the ejection of a gaseous fuel from the surface that ignites, generating the flame. This procedure is similar to that of Option 2, with the important difference that *I*, h_g and T_g on the target are obtained by the fire simulator solving the transport equations for mass, momentum and energy (including radiation transport) through the problem domain.

Option 3.2 represents the most advanced approach to the simulation of a fire scenario, fully exploiting the capabilities of the fire simulation software in the modelling of the combustion of solid fuels. All the steps characterizing the combustion process of a solid fuel are considered (although applying some simplifying assumptions according to data availability and required level of detail): the heat-up phase, the pyrolysis process leading to the production of gaseous fuels and the final burning process (a comprehensive description of such processes can be found in Hurley et al. (1995). In other words, the heat released from the fuel surface is not prescribed (as it is in Option 3.1 using a HRR curve), but rather is predicted using the potentialities of the fire simulator.

4.2. Step 2 – Tank response analysis

The previous step allows obtaining the spatial and time varying maps of *I*, h_g and T_g on the tank surface. The setting of these parameters represents the boundary condition for the CFD simulation of the tank response when affected by a fire. In the methodology presented here, the analysis of the latter is carried out by a CFD analysis. The ANSYS® Fluent® 18.2.0 code was used, applying the CFD modelling setup proposed by Scarponi et al. (2019). The tank (both the steel wall and the lading) is discretized in a computational grid and governing equations for mass, momentum, energy and turbulent quantities are solved throughout the computational domain. According to the computational resources and the geometrical characteristics of the scenario to be analyzed (i.e. if *I*, h_g and T_g may be considered constant along the axial direction of the tank), a 2D or a 3D approach can be applied. Further details on the possible approaches to be applied in this step are reported in literature (Scarponi et al., 2019, 2018a; Tugnoli et al., 2019)

The application of the CFD procedure provides a large amount of data describing the thermo-fluid dynamic response of the vessel to fire exposure. In particular, it is possible to obtain pressurization curves, wall temperature profiles, temperature distribution in the liquid and vapor phases and evolution of the velocity field.

4.3. Step 3 – Assessment of tank integrity

In the last step of the methodology, the results of the CFD simulations are analyzed with the aim of understanding whether the fire scenarios under consideration may compromise tank integrity.

According to the API 2510 (American Petroleum Institute, 2001), the integrity of an LPG tank exposed to fire is not compromised as long as: i) the tank is equipped with a properly designed PRV (i.e. the PRV prevents the vessel pressure from rising more than 21% above the design pressure) and ii) the incident radiation is below 22 kW/m^2. This is a very useful indication and may even avoid the necessity of carrying out the second step of the methodology. In fact, the value of the incident radiation is already available after the fire characterization (Step 1).

However, assuming the threshold value suggested by API 2510 (22 kW/m^2) would often be over-conservative. Furthermore, the radiation threshold value provided was derived considering a distant fire source and is not valid in case of flame impingement.

Therefore, it is important to have alternatives to establish whether the tank integrity may be compromised by the fire scenario defined in step 1. This is done by introducing two indicators (the definition of which are presented in Table 2) that can be easily compared with threshold values, defining the limits within which a given schenario may be deemed safe. The first one, the "Weakened Surface Index" (WSI), aims at assessing the extension of mechanical weakening of the tank steel structure due to high temperature.

The second indicator (see Table 2), the "Pressure Relief Valve Index" (PRVI), highlights how close the pressure reached in the tank is to the PRV set point. In fact, although the PRV opening represents a safety measure to prevent the tank rupture, the jet fire resulting from the ignition of the fluid released by the valve increases the heat load to the tank and the surrounding and may contribute to worsen the consequences of the fire.

Table 2: Indicators for the assessment acceptability of the LPG tank response to fire.

Indicator	Definition	Notes
WSI: Weakened Surface Index	$WSI = \frac{S_{a,max}}{S_c}$	$S_{a,max}$: maximum (over simulation time) surface area where the temperature is higher than 400°C S_c: critical surface area (0.48 m^2)
PRVI: Pressure Relief Valve Index	$PRVI = \frac{p_{max}}{p_{PRV}}$	p_{max}: maximum pressure reached in the tank p_{PRV}: PRV set point

From the definitions presented in Table 2, fire scenarios resulting in values WSI and PRVI higher than 1 have the potential to compromise tank integrity and/or to result in an escalation of consequences. However, WSI and PRVI are only lumped indexes representative of potentially hazardous conditions. WSI depends on the value of S_c, that was derived by extrapolation of experimental observations and shall be considered as an indicative critical value rather than an exact threshold. On the other hand, the PRVI is based on the value of the PRV set point. However, due to the high temperature reached under fire exposure, the spring in the PRV may experience softening (Heymes et al., 2013b), resulting in an actual opening pressure lower than the design one. In this work, a safety coefficient of 0.9 was applied to identify scenarios not having the potential to compromise the integrity of LPG installations, considering both such factors of uncertainty.

5. Case studies

According to the idealized situations reported in WUIVIEW deliverable D5.1, 5 different scenarios are analysed here using the methodology presented above. For all of them, the reference target is a 1 m^3 LPG tank (diameter = 1000 mm, length = 1470 mm, wall thickness = 6 mm, with semi-elliptical ends). The selected scenarios are all representative of typical situation that may occur at the WUI. The analysis of the first 2 scenarios present a higher lever of details with respect to the last 3. This is done in order to provide the reader with a comprehensive description of how each single step is performed. In particular, with the aim of comparing the application of Option 3.1 and Option 3.2, the fire characterization step for Scenario 2 was carried out following both options.

5.1.1. Scenario description

Scenario 1 involves quite severe fire conditions, the characteristics of which were derived from fire experiment monitoring (Pastor et al., 2019b). In this fire test, a 13m by 6m fuel bed of *Pinus halepensis* slash was ignited with the aim of studding a fire front close to a vulnerable target. This scenario represented cases in which the neighboring plot to the one having the LPG tank is abandoned and accumulated unmanaged fuel able to burn. Such situation is actually frequent in Mediterranean WUI areas.

5.1.2. Fire source characterization

The fire characterization was carried out following Option 2, introducing a solid flame model and assigning a fire emissive power. As shown in Figure 4, it was assumed that the fire generated during the test could be approximated to a rectangle with constant shape and dimensions. The rectangle was considered to have an inclination of 60˚ with respect to simulate the effect of the wind. An emissive power varying according to the transient profile reported in Figure 5b was assumed (dotted red line).

Based on fire characterization, the incident radiation to the tank wall was calculated. First, the view factors between each of the points lying on the tank wall and the plane representing the fire were calculated following the approach reported in Scarponi et al. (2018c). Figure 5a shows the results of this calculation. Assuming conservatively a unitary air transmissivity (Γ = 1 in Eq. 3), the incident radiation (I_P) at point *P* on the tank surface was calculated.

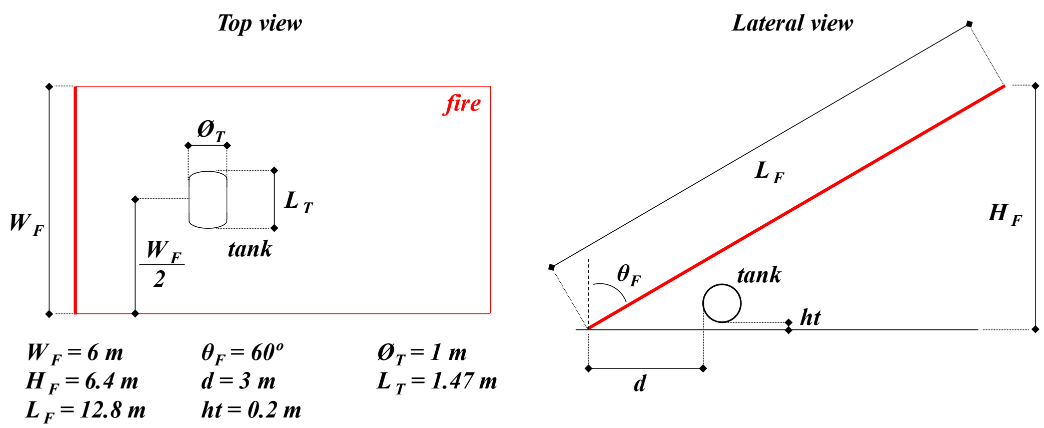

Figure 4: Geometric characteristics assumed for the fire and relative position with respect to the LPG tank for Scenario 1. The red rectangle represents the fire shape.

Figure 5b provides an example of how the incident radiation changes considering different points on the surface of the tank wall. It is interesting to note that the values of the incident radiation along the exposed wall (e.g. point A and B in Figure 5b) are well above the 22 kW/m^2 suggested as the incident heat flow by the API 2510 standard.

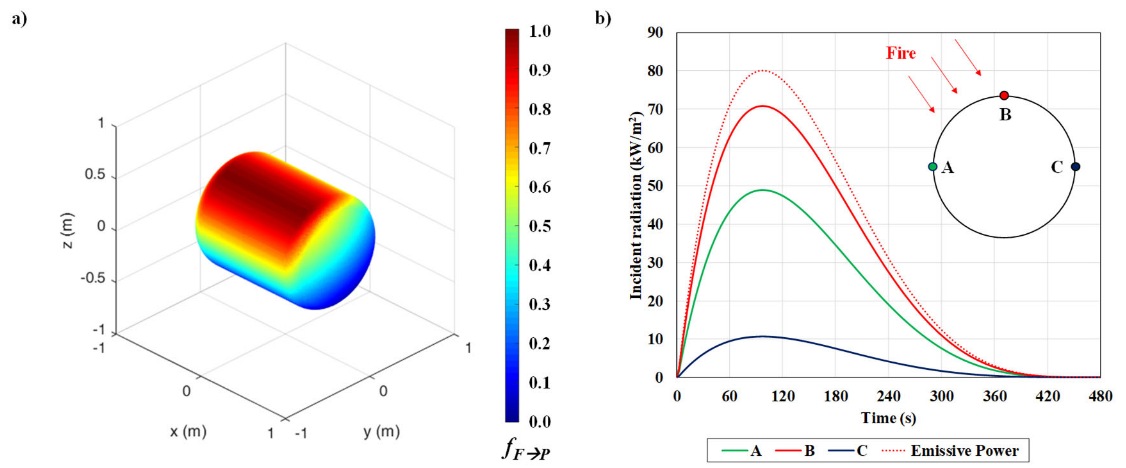

Figure 5: a) Contour plot of view factors calculated at tank surface for the lay out shown in figure 4; b) incident radiation vs. time in different positions of the external wall (at the central vertical section) considering an ambient temperature of 20 ºC.

As for T_g and h_g, the convective heat transfer between the tank and the surrounding air was not taken into account. This is a conservative assumption since it eliminates the cooling effect of air.

5.1.3. Tank response simulation

This step consists in the analysis of the tank response by means of CFD modelling. Since in this case study the lay-out is symmetric with respect to the vertical plane (perpendicular to the tank axis) cutting the tank center, only half of the tank was considered in order to save computational time (see Figure 6a). The problem domain (the tank solid wall and its internal volume, see Figure 6b) was discretized using an unstructured grid obtained as a combination of tetrahedrons and hexahedrons with a maximum edge size of 3 cm (2 cm for the cell lying onto the external wall). In order to achieve appropriate resolution in the proximity of the inner wall (see Figure 6c), where the gradients of temperature and velocity are high, the grid was refined defining an inflation region (25 layers with a volume growth rate of 1.1) with a first layer thickness of 0.2 mm. The resulting number of cells was 533,997.

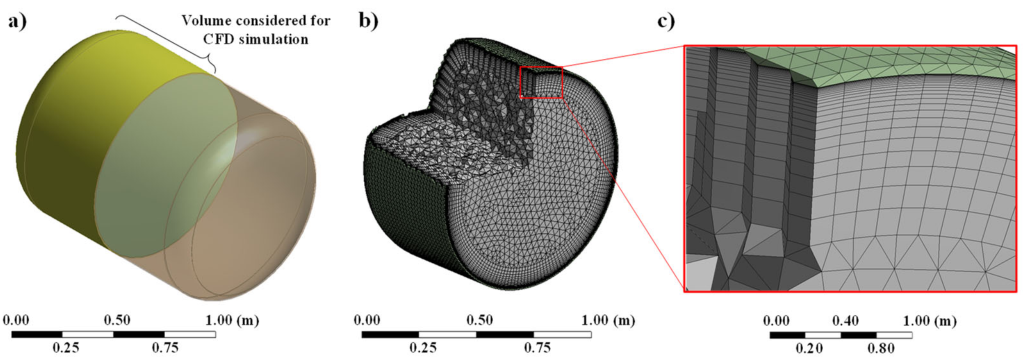

Figure 6: a) Tank portion considered for the CFD simulation of the tank response; b) overview of the computational grid; c) detail showing the increased grid resolution in the near wall region (grey and green cells refer to the fluid and the solid domains respectively).

The tank lading was assumed as pure propane, the material properties of which were defined as a function of temperature according to data reported by Liley et al., (1999). The thermal properties of carbon steel were considered for the tank wall (CEN - European Committee for Standardization, 1998). The boundary conditions along the outer wall were defined according to the results obtained in Step one. The no-slip condition was assigned to the inner wall. At the beginning of the simulation, the fluid was considered to be motionless, the temperature was set to 20 °C and the pressure at 8.36 bar (corresponding to the saturation of pure propane at 20 °C).

As for the degree of filling, two different cases where analyzed in order to study its effect on the tank response. In the first case, a 20% of liquid was considered (low filling level case, referred to as S1_20% in the following). In the second, an 80% filling level was considered (high filling level case, referred to as S1_80%). The opening pressure of the PRV was considered of 18 bar in both cases.

In the following, the analysis of the data provided by CFD simulations is carried out focusing on pressurization curves and wall temperature profiles that are the variables of interest when the tank integrity is of concern. A more detailed and fundamental study of CFD results considering, for instance, the temperature distribution in the liquid and vapor phases, evolution of the velocity field and liquid thermal expansion can be found in literature (D'Aulisa et al., 2014; Scarponi et al., 2019, 2018a, 2018b).

Figure 7a shows the results obtained for the internal pressure. The pressure rise is faster when the tank is 80% full of liquid. Higher values of pressure are attained in this case, where the PRV opens after about 400s. Differently, in the S1_20% case the pressure remains well below the PRV set point, reaching a maximum value of 13.1 bar.

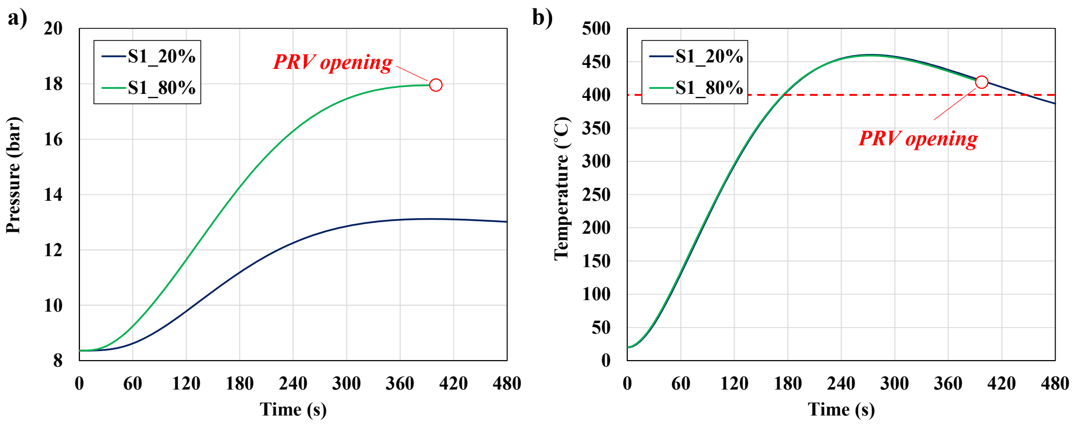

Figure 7: a) Pressure vs. time and b) maximum wall temperature obtained for different filling levels.

This difference is due to the contribution of the boiling liquid at the tank wall. In fact, in the case featuring the lowest filling degree, the shell portion wetted by the liquid is exposed to a quite low incident radiation and nucleate boiling occurs in a very limited part of the domain. On the other hand, when the tank is 80% full of liquid, the surface on which boiling takes place is much more extended, producing a fast increase in the vapor phase mass and speeding up the pressurization process. It is interesting to notice how the tank keeps pressurizing well beyond the instant of time in which the fire emissive power curve starts decreasing (see Figure 5, where the curve assumed for the fire emissive power vs. time is reported) and that the pressure inside the tank remains high even when the fire is almost extinguished.

Differently from pressure, Figure 7b shows that the maximum wall temperature is not influenced by the filling degree in the ranges allowed by national standards (filling degree should be equal or lower than 80 or 85% depending on the country). In fact, the two curves are coincident. In both cases, the peak wall temperature exceeds 400°C and remains above this threshold for several minutes. Analyzing the temperature distribution over the external wall, it evident that the region suffering mechanical weakening due to the high temperature is quite extended in both cases. This is clearly visible in Figure 8a and b, where the area of the wall featuring a temperature higher than 400 °C is highlighted in red (data after 240s of fire exposure are considered). A similar consideration can be made looking at Figure 8c and d, showing the temperature profiles at intervals of 120 s along the curve given by the intersection between the tank wall and the symmetry plane perpendicular to the tank axis. It is well visible how the liquid produces a cooling effect on the steel, limiting the temperature in the portion of the wall in contact with the condensed phase. Such behavior is more pronounced when the filling degree is higher.

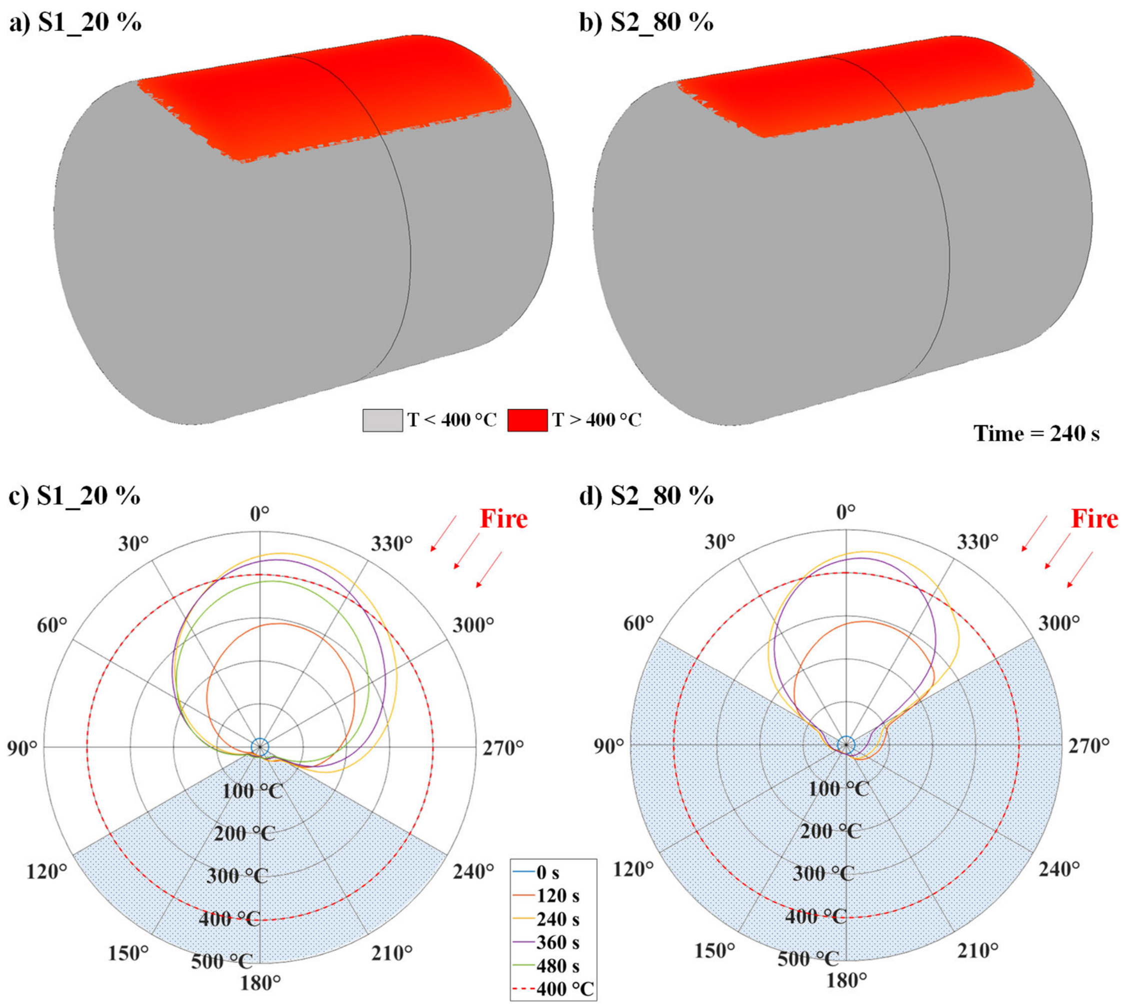

Figure 8: Region of the external wall with temperatures higher than 400 °C for a) S1_20%; and b) S1_80% cases (time = 240 s). External wall temperature profiles at the symmetry plane perpendicular to the tank axis at different intervals of time for c) S1_20% and the d) S1_80% cases. The shaded area in the polar plots highlights the portion of the wall wetted by the liquid.

5.1.4. Assessment of tank integrity

Figure 9 shows a comparison of the values calculated for the indicators (see Table 2) obtained for the two filling levels considered. The PRVI is equal to 1 for the case featuring the higher filling degree (S1_80%) and 0.73 for the other, suggesting that, even considering the uncertainties in the definition of the fire scenario, the risk of having a jet fire generated by the opening of the PRV is quite low for the latter case.

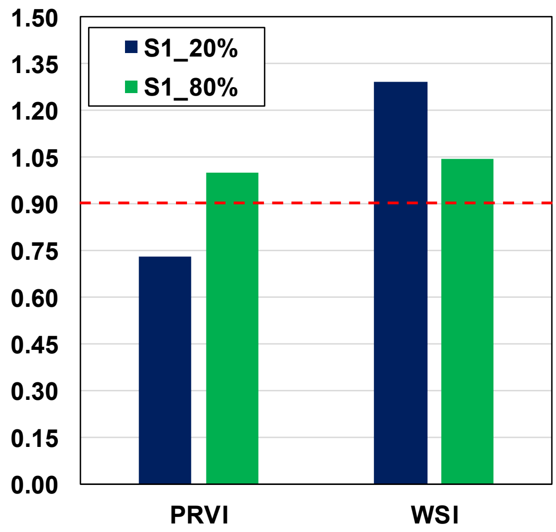

Figure 9: Comparison of the values of the indicators obtained for the S1_20 % (blue bars) and the S1_80 % case (green bars).

The WSI indicates that, in both cases, the maximum extension of the area experiencing this phenomenon is higher than the critical value S_C. The values obtained (1.04 and 1.29 for the SI_20% (WSI =1.04) and the SI_80% cases (WSI =1.29) are both higher than the acceptance criteria (0.9) suggested in the present study. It may be concluded that Scenario 1 represents a threat for the tank integrity, regardless to the filling degree.

5.2. Scenario 2

5.2.1. Scenario description

In the second scenario (Scenatio 2), the tank was exposed to a fire generated assuming a geometry based on a row of six Douglas fir trees catching fire. Figure 10 shows an overview of geometrical characteristics of Scenario 2, defined on the basis of the data reported by Mell et al. (2009). The trees were assumed 2.05m high (0.15m of clear trunk base and 1.90m of crown), with a conical canopy having a 1.6 m diameter base. The tank was positioned 3m away from the trees. Simulations were carried out in the absence of wind.

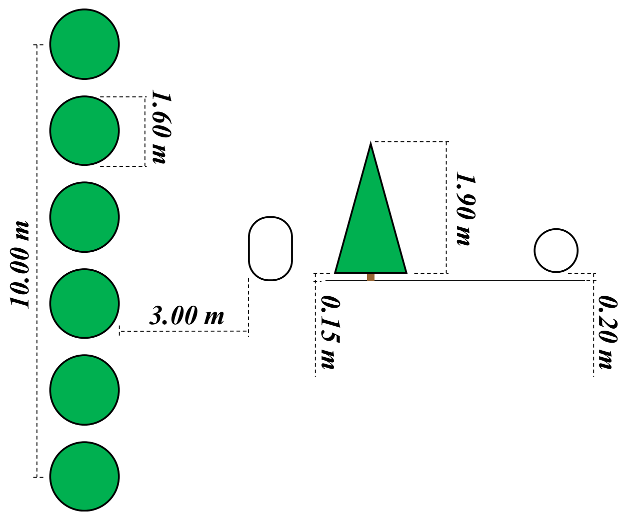

Figure 10: Lay out (left) and frontal view (right) of the trees and of the LPG tank in Scenario 2.

5.2.2. Fire source characterization

As mentioned above, the analysis of Scenario 2 aims at providing a detailed description of how to apply Option 3.1 and 3.2 for fire source characterization. In both cases, the geometric characteristics of Scenario 2 were reproduced using the FDS6.7.1 software (see Figure 11a).

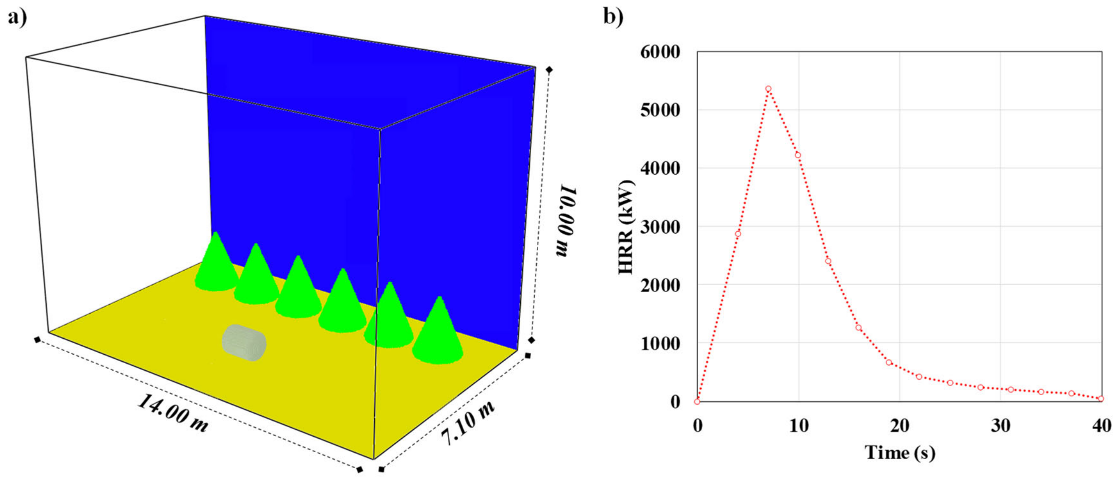

Figure 11: a) Computational domain considered for simulation of Scenario 2 using FDS; b) HRR curve for each of the Douglas fir trees in Scenario 2 obtained from (Mell et al., 2009)*.*

In Option 3.1, the trees were modelled as solid cones and the fire was simulated assuming the HRR curve reported in Figure 11b for the surface of each cone. In Option 3.2, the approach proposed by Mell et al. (2009) was applied (adapting the simulation setup from WFDS to FDS6.7.1). The tree crowns were modelled as distributed solid particles (according to experimental observations reported by Mell et al. (2009) into four size classes: foliage, roundwood of diameter < 3 mm, roundwood of diameter between 3 and 6 mm and roundwood with a diameter between 6 and 10 mm. The total mass burned was assumed of 3.9 kg (dry mass). For all vegetation types, the following parameters were assumed: moisture on a dry weight basis of 14%, dry and wet bulk densities of 2.98 kg/m^3 and 3.4 kg/m^3 respectively.

Given a heat source (simulated introducing a ring hot spot at the base of each tree, which induced a buoyant hot flow), the particles temperature increases and the moisture is removed. Then, the pyrolysis starts and fuel vapors are generated. Finally, the remaining char undergoes an oxidation process. For the sake of brevity, equations describing the pyrolysis process as well as other details on the simulation setup are not reported here. The reader is referenced to the paper of Mell et al. (2009) for the full details on the simulation approach.

Figure 12 reports a series of snapshots showing the characteristics of the fire simulations.

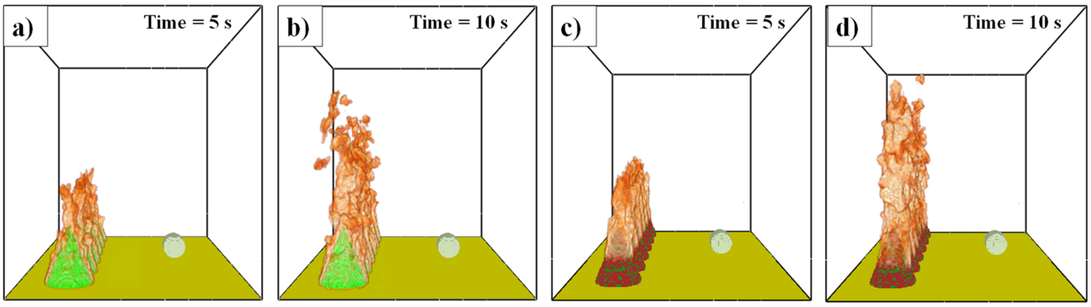

Figure 12: Characteristics of the fire after 5 (a and c) and 10 s (b and d) obtained from the fire simulator following Option 3.1 (a and b) Option 3.2 (c and d) for the definition of the fire source.

The two modelling approaches provide similar results, with the most complex approach (Option 3.2) producing a slightly higher flame. Actually, when particles are used to model the trees (Option 3.2), air can flow through the crowns, helping the development of the flame, whereas in Option 3.1 the trees behave as solid obstacle to the flux of air. This effect is expected to be exacerbated when wind is present.

The fire characteristics observed in Figure 12 result in a heat load to which the tank is exposed. This is visible in Figure 13a, where the distribution of the incident radiation onto the tank side facing the fire (after 10s of simulation) is shown. Option 3.1 and 3.2 produce very similar results, as observed also in Figure 13b, reporting the incident radiation vs time curves at the center of the tank side facing the fire. In both cases, the incident radiation is always lower than 22 kW/m^2. Therefore, according to the API 2510, Scenario 2 would not represent a threat for tank integrity.

5.2.3. Tank response simulation

The tank response step was carried out using the same setup and computational grid considered for the simulation of Scenario 1. The filling degree was set to 80%. Two different cases were considered. In the first (S2_3.1), the boundary condition was defined according to the spatial and temporal distributions of I, h_g and T_g obtained using Option 3.1. In the second (S2_3.2), the output generated by Option 3.2 was considered.

Figure 14a shows that, in both cases, the pressure increase in the tank is very limited. The maximum pressure (8.45 bar) is obtained for the S1_3.2 case and is only 0.09 bar higher than the initial pressure. The curves describing the maximum wall temperature in the two cases (Figure 14b) show a limited temperature increase (about 8°C).

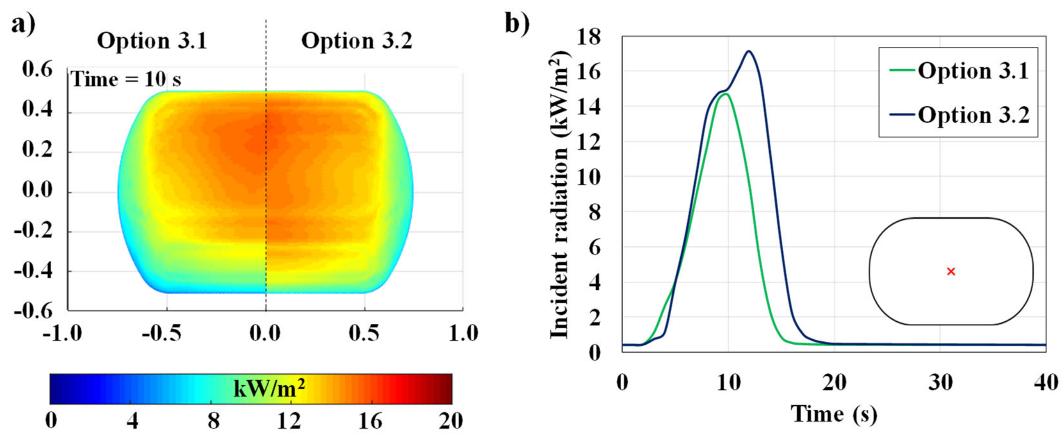

Figure 13: a) Distribution of the incident radiation onto the tank side facing the fire (after 10s of simulation) obtained applying Option 3.1 and 3.2; b) incident radiation as a function of time at a point located at the center of the tank side facing the fire (red cross on tank shell).

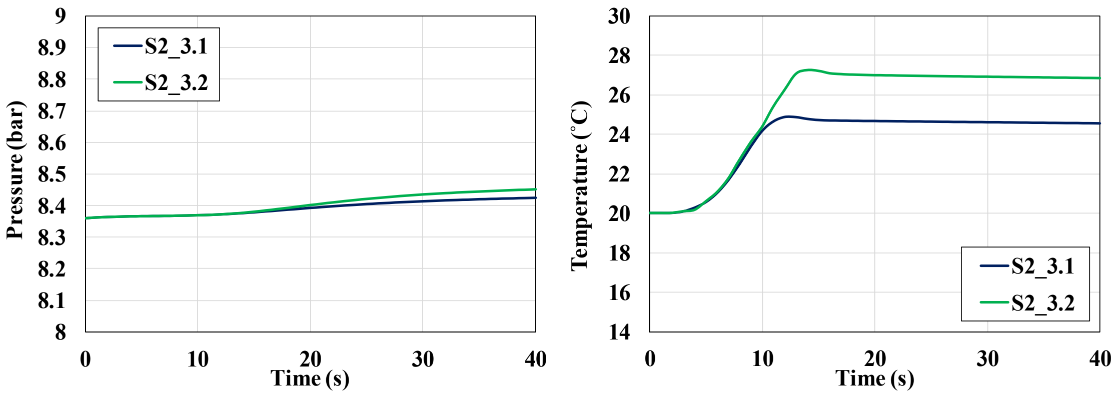

Figure 14: a) Pressure curves and b) maximum wall temperature obtained for the S2_3.1 (blue line) and the S2_3.2 (green line) cases.

5.2.4. Assessment of tank integrity

The results reported in Figure 14 show that Scenario 2 produces negligible effects in terms of pressure increase and temperature rise. This is reflected by the values of the KPIs calculated in Step 3 of the methodology. The PRVI indicator results 0.469 and 0.468 respectively for the S2_3.1 and the S2_3.2 scenarios, whereas the WSI is null for both cases. Thus, it is possible to conclude that this scenario does not represent a threat for the tank integrity. The results confirms the assumption made after comparing the values of incident radiation in Figure 13 with the threshold value of 22 kW/m^2 suggested by the API 2510.

5.3. Scenario 3

5.3.1. Scenario description

In Scenario 3 (see Figure 15), the LPG tank was exposed to the combustion of a stack of 9 pine pallets (80 x 120 x 144 cm), placed in contact with the tank.

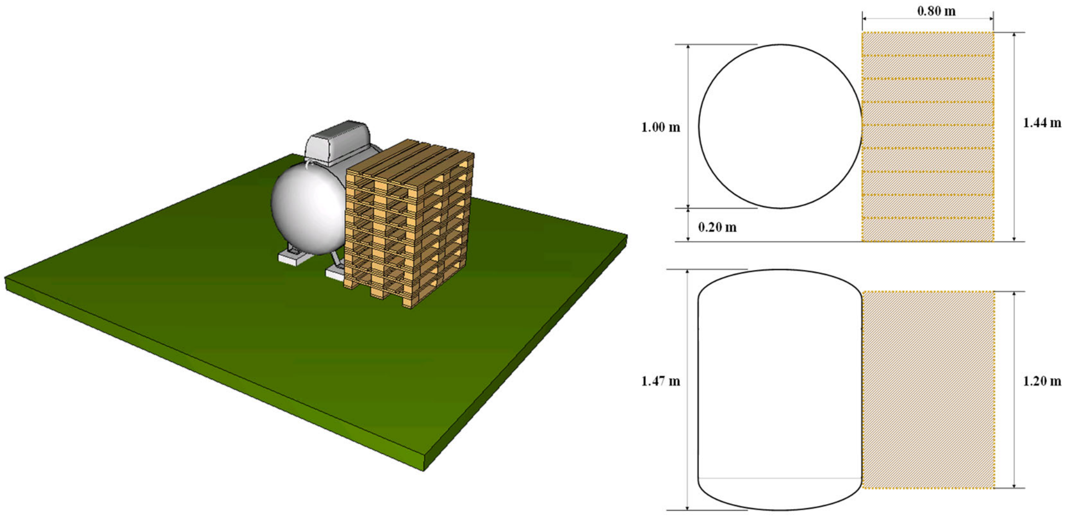

Figure 15: Overview of the geometric characteristics of Scenario 3.

5.3.2. Fire source characterization

The fire characterization step was carried out using Option 2. The combustion of the pallets was simulated by creating a 120 x 80 cm vent on the grownd with an assigned HRR curve (see Figure 16a). This is taken from chapter 3 of the book Enclosure Fire Dynamics (Karlsson and Quintiere, 2000), which reports data from fire experiments on pallet staks. Figure 16b shows the characteristics of the fire after 250 s of simulation.

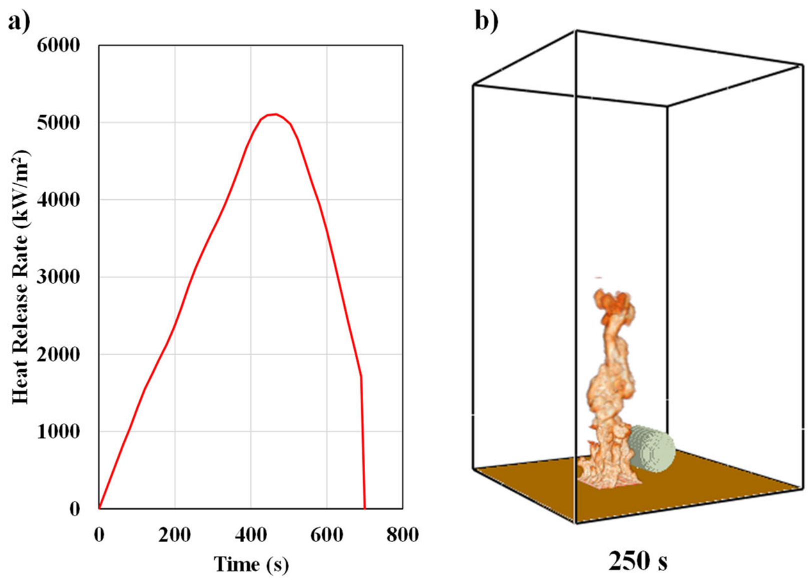

Figure 16: a) HRR curve used to simulate the fire; fire scenario after 250 s of simulation in calm (a) and windy (b) conditions.

5.3.3. Tank response simulation

The tank response step was carried out using the same setup and computational grid considered for the simulation of Scenario 1. Two different cases where analyzed in order to study its effect on the tank response. In the first case, a 20% of liquid was considered (low filling level case, referred to as S3_20% in the following). In the second, an 80% filling level was considered (high filling level case, referred to as S3_80%). The opening pressure of the PRV was considered of 18 bar in both cases.

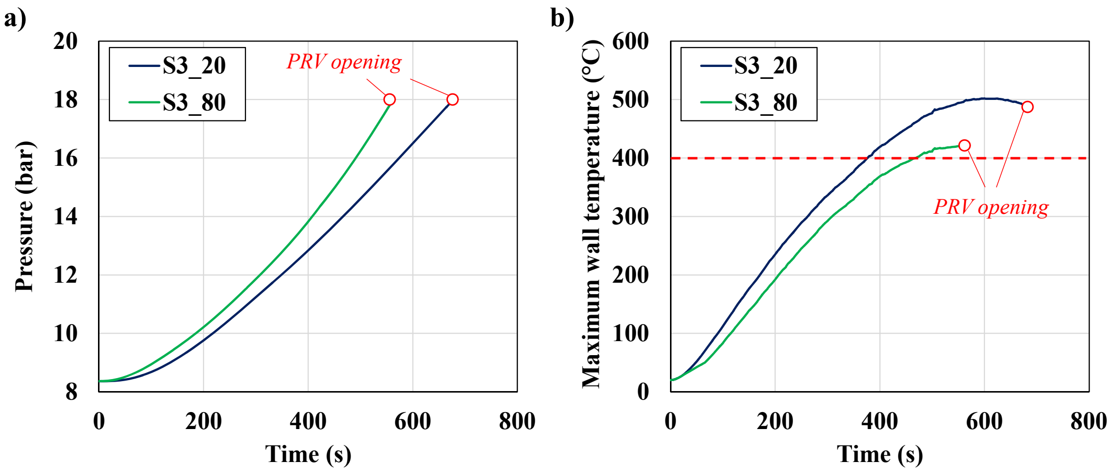

Figure 17: Pressurization curves (a) and maximum wall temperature (b) obtained for Scenario 4.

Figure 17 reports the results of this step in terms of pressurization curves (Figure 22Figure 14) and maximum wall temperature (Figure 22Figure 14). In both cases, the PRV set point is reached and the maximum wall temperature exceeds 400 °C. As observed for Scenario 1, the pressurization is faster for the higher filling level case. On the other hand, higher wall temperature is attained when the tank is 20 % full of liquid.

5.3.4. Assessment of tank integrity

Figure 18 shows a comparison of the values calculated for the indicators obtained for the two filling levels considered. Since for both cases the PRV opening set point is reached, the PRVI is equal to 1. This shows that, regardless the filling degree considered, this scenario has the potential to trigger a jet fire due to the release caused by the PRV opening.

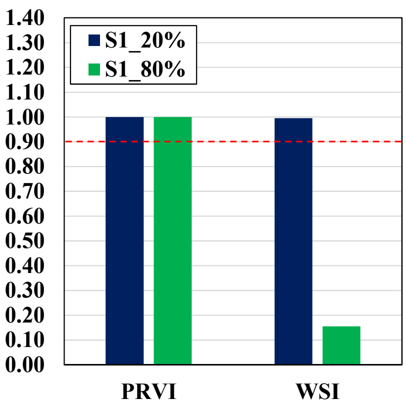

Figure 18: Comparison of the values of the indicators obtained for the S1_20 % (blue bars) and the S1_80 % case (green bars).

On the other hand, the WSI indicates that the maximum extension of the area experiencing mechanical weakening is critical only for the 20 % filling degree case, for which a value of the WSI close to unity (0.994) is obtained. In the case with the higher filling degree, the value of the WSI is equal to 0.155, quite fare from the threshold value of 0.9.

Looking at both indicators, it may be concluded that Scenario 3 does not fall within the safety limits defined by the methodology presented in this document.

5.4. Scenario 4

5.4.1. Scenario description

In Scenario 4 (see Figure 19Figure 15), the LPG tank was exposed to the combustion of a 300 x 300 x 40 cm bed of flashy cured grass. Two wind conditions were considered: absence of wind and 20 km/h (at 10 m) wind blowing from right to left and the grass patch is ignited at one of the corners as indicated in see Figure 19.

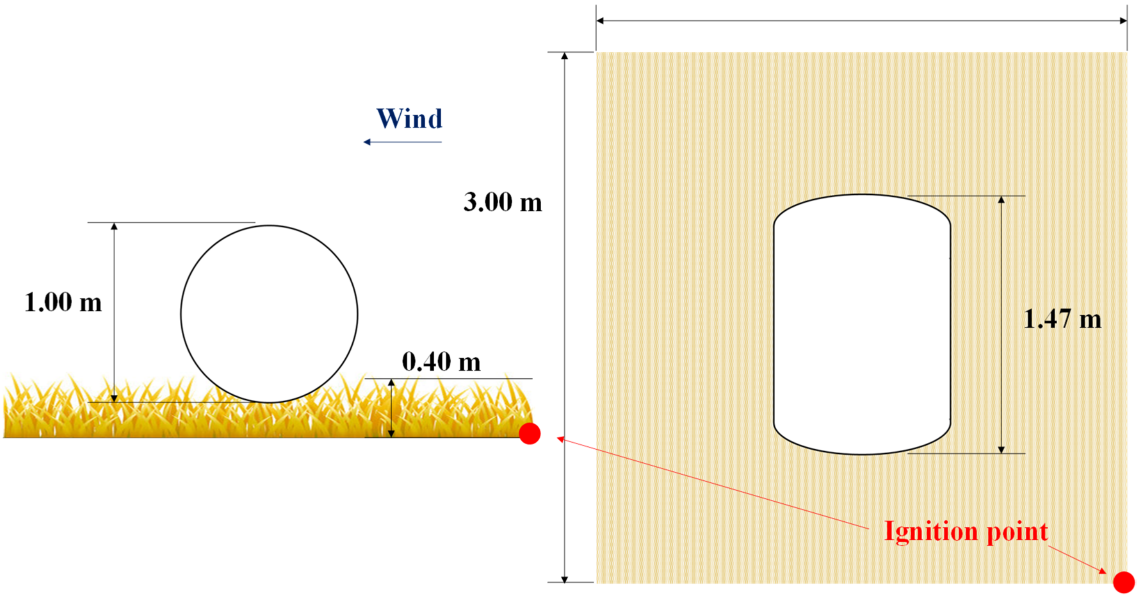

Figure 19: Overview of the geometric characteristics of Scenario 4.

5.4.2. Fire source characterization

The fire characterization step was carried out using Option 2. The combustion of the cured grass was simulated by creating a 300 x 300 cm vent on the ground with assigned HRRPUA and spread rate taken from experimental data on cured grass ((Cheney et al., 1993; Cheney and Gould, 1995).

Figure 20 shows the evolution of the fire in calm and windy conditions. In both cases, the fire estinguishes within about 15 s. Although the fire duration is very limited, the incident radiation to the tank is high. As illustrated by Figure 21, a peak of around 100 kW/m^2 is reached in windy conditions. It must be taken in mind that this represents only a fraction of the total heat flux to the tank. In fact, the curves in Figure 21 do not take into account the convective contribution of the flame that is in contact with the tank wall. From the above it appears that Scenario 4 is representative of those situations in which the tank is exposed to a quite strong fire for a very small amount of time.

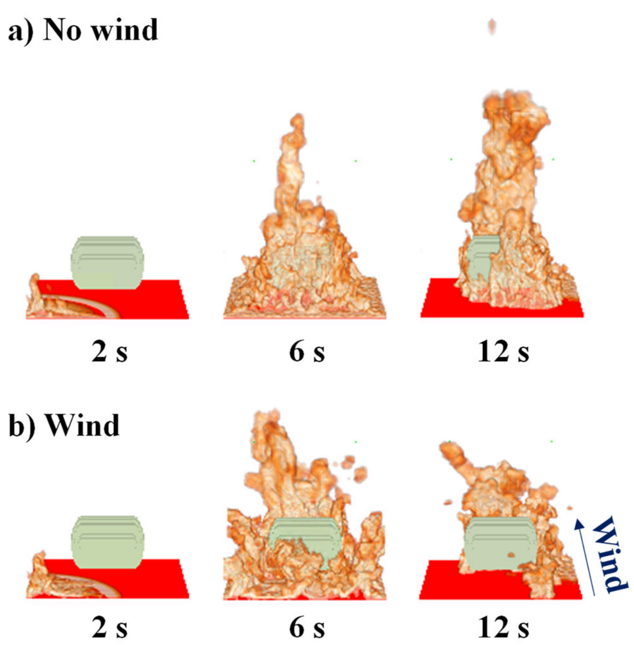

Figure 20: Fire evolution at different instant of time for calm (a) and windy (b) conditions.

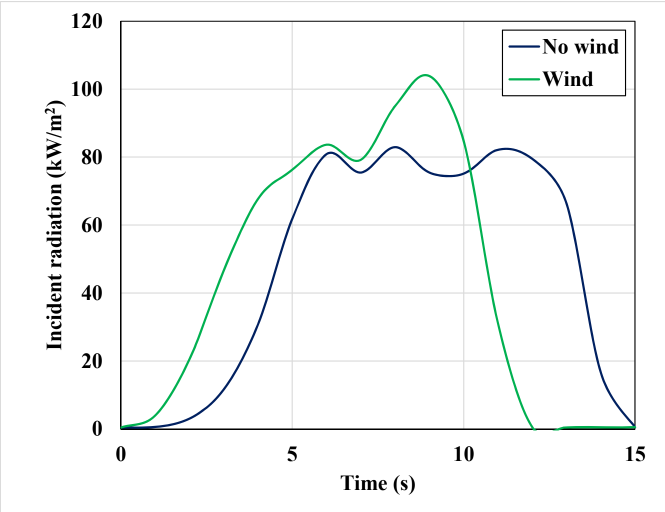

Figure 21: Maximum incident radiation to the tank surface as a function of time in calm and windy conditions.

5.4.3. Tank response simulation

The tank response step was carried out using the same setup and computational grid considered for the simulation of Scenario 1. The filling degree was set to 80%. Figure 22Figure 14 reports the results of this step in terms of pressurization curves (Figure 22Figure 14) and maximum wall temperature (Figure 22Figure 14). It clearly appears that, regardless the presence of the wind, Scenario 4 produces a neglegible increase in both pressure and wall temperature.

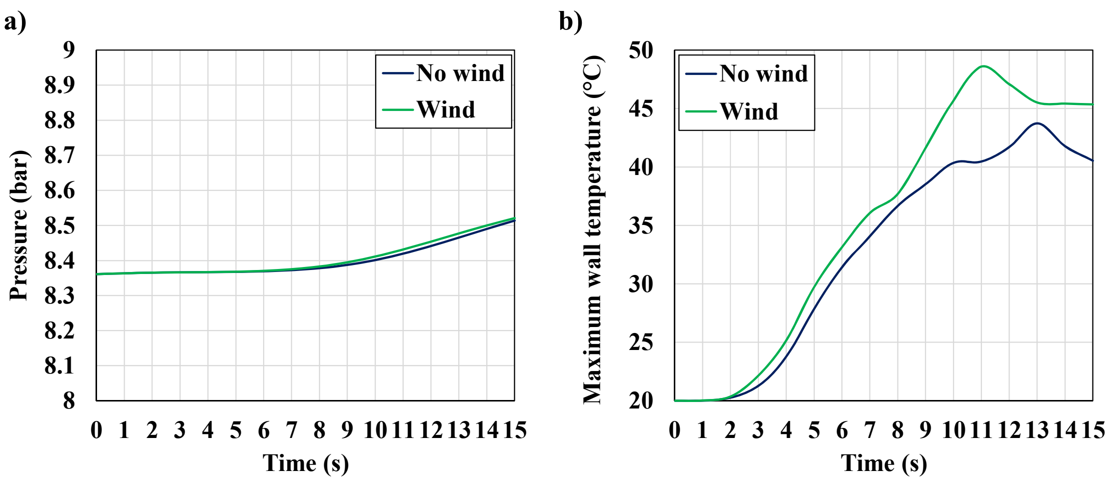

Figure 22: Pressurization curves (a) and maximum wall temperature (b) obtained for Scenario 4 in calm and windy conditions.

5.4.4. Assessment of tank integrity

Looking at the results in Figure 22, it It can be concluded that Scenario 4 does not represent a threat for the tank integrity. This is reflected by the values of the indicators calculated in Step 3 of the methodology. The PRVI is 0.47 both for calm and windy conditions, whereas the WSI is always null. This result is a direct consequence of the very short duration of the fire.

5.5. Scenario 5

5.5.1. Scenario description

In Scenario 5 (see Figure 23Figure 15), the LPG tank was exposed to the combustion of 300 x 150 x 1000 cm hedge of Cupressus arizonica placed at 2 m from the tank. Two wind conditions were considered: absence of wind and 20 km/h (at 10 m) wind blowing from the fuel pack towords the tank.

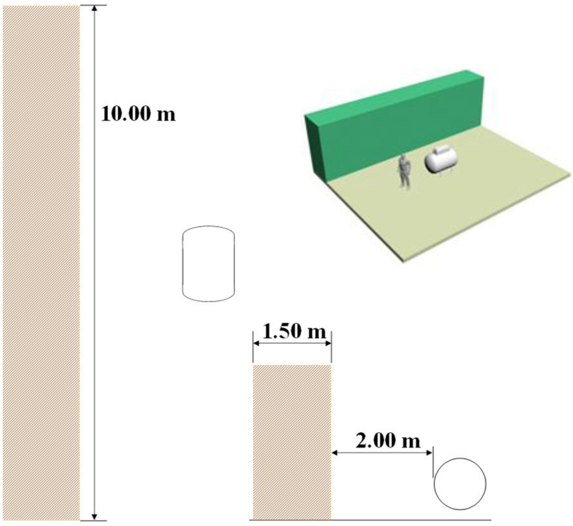

Figure 23: Overview of the geometric characteristics of Scenario 5.

5.5.2. Fire source characterization

The fire characterization step for scenario 5 was carried out according to Option 3.2. The hedge was modelled as distributed solid particles belonging to five size classes: foliage, wood with a diameter (d) smaller than 3 mm, wood with 3 < d < 6 mm, wood with 6 < d < 10 mm, and d > 10 mm. The wood is devided further in two sub-classes: live wood and dead wood. The foliage is concentrated in the outer parts of the hedge, the dead roundwood in the center. The live roundwood is distributed evenly across the entire volume of the hedge.

As can be observed by comparing Figure 24a and b, the presence of the wind has a strong effect on the flame geometry. In both cases, the fire extinguishes within less than 30 s and the incident radiation to the tank is always very small (see Figure 24c).

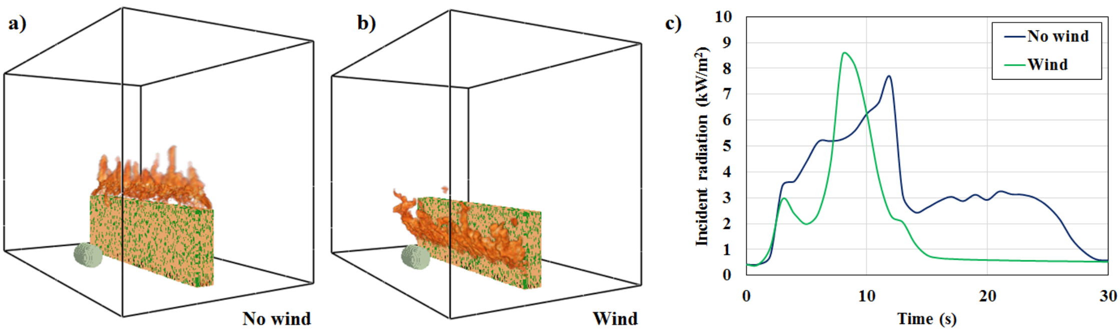

Figure 24: Fire characteristics after 15 s of simualtion in calm (a) and windy (b) conditions; (c) maximum incident radiation on the tank as a function of time.

5.5.3. Assessment of tank integrity

Since the incident radiation to the tank is well below the threshold proposed by the API 2510 (22 kW/m^2) for the entire duration of the fire, Scenario 5 can be deemed safe without the need of performing a CFD simulation of the tank response. For this reason, step 2 of the methodology was not performed for this scenario.

6. Concluding remarks

Preventing and mitigating the consequences of forest fires at the WUI is a challenging task due to the inherent complexity of the WUI environment. Safety measures have to be implemented at different scales (macro, meso and micro scale) to ensure the success of population and structures protection strategies. The present document focused on the home owner scale identifying in the possible presence of LPG tanks a potential additional threat in case of fire.

Recent accidents have demonstrated that the risk associated with this type of installations is real, but often disregarded by residents. The survey of regulations detailed in the present study provides evidence of a lack of harmonization throughout European countries. Moreover, important gaps have been highlighted in specific provisions, particularly those referred to the presence of fuels near domestic LPG tanks. Furthermore, there is no general agreement in the definition of safety distances. A 3-step methodology was developed to assess if the integrity of a domestic LPG tank exposed to WUI fire scenarios may be affected.

The methodology was applied to analyse 5 different scenarios, representative of situations that may tipically be found at the WUI. The results obtained for case study 2, 4 and 5 show that the scenarios analysed may produce only negligible effects from the safety point of view. On the other hand, it was demonstrated that both Scenario 1 and Scenario 3 represents a threat for the tank integrity due to the high wall temperatures induced by the fire. Furthermore, it was shown that for high filling degrees (80 %), the fire exposure leads to the PRV opening for both scenarios. The same is true for the lower filling degree case (20 %) in Scenario 3. As mentioned in Section 4.3, this shall be considered as an unwanted event since the jet fire resulting from the ignition of the fluid released by the valve increases the heat load to the tank and may contribute to worsen the consequences of the fire, creating the potential for an escalation of consequences.

It is important to remark that the layout considered in Scenario 1 (tank placed at 3 m from a 13x6 m fuel bed of pine slash) is compatible with the requirements of regulations adopted in Portugal, Spain and UK. Therefore, the results obtained raise some concern about the adequacy of safety distances indicated in the regulations of several European countries.

On the other hand, Scenario 4 (LPG tank exposed to the combustion of a stack of 9 pine pallets (80 x 120 x 14.4 cm), placed in contact with the tank), does not meet any EU regulation. However, it is representative of many observed cases of homeowner negligence in the management of the space dedicated to the installation of domestic LPG tanks. The results obtained from the analysis of this case stress once more the importance of increasing the awareness of WUI communities about the hazard related with LPG installations.

In the light of the present document, it can be concluded that work shall be devoted to the identification and the analysis of additional WUI fire scenarios involving LPG tanks, in order to carry a more comprehensive assessment of current prescriptions related to this kind of installation and highlight possible gaps in safety regulations. Outcomes from this modelling approach are envisaged to be the basis of scientific-based recommendations for future policy improvements.

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