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Safety distances for storage tanks to prevent fire damage in Wildland-Industrial Interface

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ABSTRACT

Wildfire occurrence frequency is increasing worldwide, generating more and more concern, especially in Wildland-Urban interfaces (WUI) and Wildland-Industrial Interfaces (WII) areas. Wildfires approaching WII can cause severe damage to people and industrial assets. In these scenarios, storage tanks present in industrial installations are among the most vulnerable pieces of equipment, since they are usually located in the proximity of the plant boundary. If hazardous substances are stored, tank damage caused by the fire can lead to loss of containment and trigger technological accident scenarios, escalating the consequences. Preserving the integrity of this type of equipment in case of wildfires is of paramount importance. The present study proposes a stepwise methodology for the evaluation of safety distances between storage tanks and vegetation that may be affected by a wildfire. According to the available data on the wildfire, on the lay-out and on the tanks that are likely to be affected, the methodology provides safety distances that may be applied to design fuel-reduced fringes around the industrial facility. The methodology proposed represents a quantitative tool for the calculation of safety distances that can guide industrial managers and assist regulators in the definition of more reliable standards. The comparison of the safety distances resulting from the present study with regulations and guidelines currently in use in different countries rises concern about the possible underestimation of required safety distances in the case of severe wildfires.

1. Introduction

Forest fires are uncontrolled fires involving the combustion of wild vegetation. When this type of event approaches anthropic settlements (e.g. urban and industrial areas) at the so called Wildland-Urban Interface (WUI) it becomes a potential threat for humans, civil structures and industrial facilities (Argañaraz et al., 2017), posing complex management challenges in terms of civil protection and fire mitigation (Manzello et al., 2018).

The concern about forest fires reaching the WUI has been growing over the last years for two main reasons. On one hand, global warming increases the frequency of occurrence of extreme fires, promoting the conditions for ignition and rapid spread (Dimitrakopoulos et al., 2011; Flannigan et al., 2016). On the other hand, the fast urbanization and the industrial development in rural areas is increasing the extension of the WUI, making it more likely for forest fires to come in contact with anthropic structures (Paveglio et al., 2015; Wigtil et al., 2016).

In Johnston and Flannigan (2018), three different types of interfaces are identified between wildland and human built areas (wildland-human interface):

i) Wildland-Urban Interface: an area where homes, public buildings and commercial structures meet with or are dispersed within wildland vegetation;
ii) Wildland-Infrastructure Interface: an area where infrastructures (e.g. roads, railways, or powerlines) meet with or are dispersed within wildland vegetation;
iii) Wildland-Industrial Interface (WII): an area where industrial facilities (e.g. chemical plants, oil depots, warehouses) meet with or are dispersed within wildland vegetation.

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Nomenclature

Symbol	
D	Fire-target distance (m)
E	Emissive power (W/m^2)
F_{view}	View factor (-)
H_v	Vegetation height (m)
I	Incident radiation (W/m^2)
I_B	Byram's fireline intensity (W/m)
L_f	Flame length (m)
RT	Reference time (min)
t_e	Exposure time to wildfire (min)
T_f	Flame temperature (K)
t_r	Response time of rescue teams (min)
TTF	Time to failure (s)
V	Tank volume (m^3)
W_f	Fire front width (m)
ε_f	Flame emissivity (-)
θ	Flame tilt angle (°)
σ	Stefan-Boltzmann constant (W/m^2K^4)
τ_a	Atmospheric transmissivity (-)

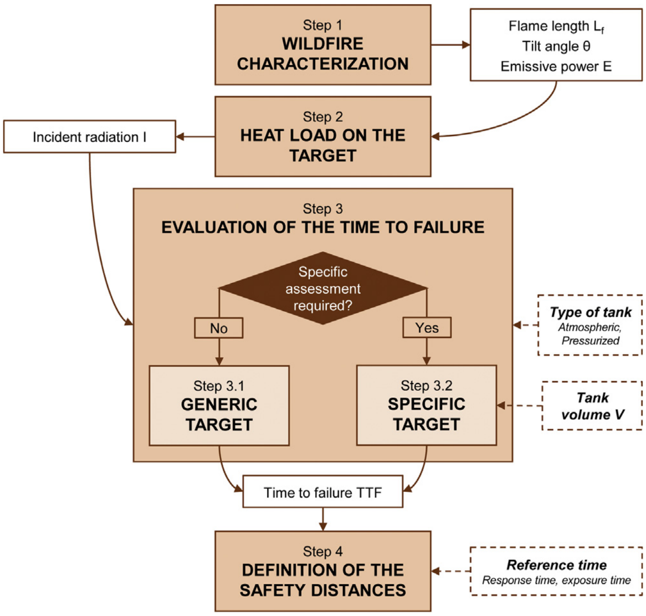

Fig. 1. Overview of the methodology for the definition of safety distances for wildfires.

Recent wildfire events, some of which quite extreme such as those occurred in California in 2020 (Healy et al., 2020), Canada in 2015 and 2016 (Khakzad, 2019), Portugal in 2017 (Viegas et al., 2017) and Greece in 2018 (Efthimiou et al., 2020), have shown how all the aforementioned types of interface may suffer devastating consequences when hit by the fire front. This has promoted the investigation on safety-related aspects of the interaction of forest fires with human structures. In the last decade, many researchers focused on the WUI (e.g. Murphy et al., 2007; Pastor et al., 2019; Rehm and Mell, 2009; Scarponi et al., 2020a, 2020b; Vacca et al., 2020). On the contrary, the WII has only recently started to attract attention. Especially in chemical industries or oil refineries, where large inventory of hazardous compounds is present, the fire exposure (e.g. exposure to a wildfire front) may lead to catastrophic events (Abbasi and Abbasi, 2007; Birk and Cunningham, 1994; Leslie and Birk, 1991; McDevitt et al., 1990; Moodie et al., 1985) and even trigger domino effects (Landucci et al., 2009), worsening the consequences of the wildfire alone. Pioneering studies to quantify the risk posed by wildfires to industrial activities were carried out by Khakzad and co-workers (Khakzad, 2019; Khakzad et al., 2018), indicating the loss of revenue due to industrial operations shutdown as one of the most critical aspects, and stressing the importance of considering wildfire risk for industrial facilities at the WII.

In this framework, storage tanks are among the most vulnerable pieces of equipment since they are usually located in the proximity of the plant boundary. Experimental (Heymes et al., 2013) and modelling (Scarponi et al., 2018) studies have shown how this kind of equipment can be seriously affected by the exposure to a wildfire front. Also considering the large amount of hazardous substances that a storage tank may contain, it is clear that the preservation of their integrity is paramount. This may be achieved by the provision of adequate separation (or safety) distances between storage tanks and the vegetation.

In the current industrial practice and in available regulations, the definition of separation distances for industrial storage tanks exposed to wildfires is often limited to rules-of-thumb based on empirical values (e.g. FireSmart Guideb. oil gas Ind., 2008), not based on specific quantitative assessments considering the fire radiation and the resistance of the structure. To the best of the authors' knowledge, no systematic and quantitative approach is currently available to establish appropriate safety distances based on sound technical criteria.

The present study aims at filling this gap, proposing a methodology for the evaluation of safety distances between storage tanks and vegetation that may be affected by a wildfire (Section 2). The methodology is based on the characterization of the wildfire scenario according to the type of vegetation involved and on the application of simplified vulnerability models to assess the survivability of specific categories of tanks (pressurized or atmospheric), also considering their geometrical features. The application of the methodology and the resulting safety distances are described in Section 3. Strengths and limitations of the proposed approach are discussed in Section 4. Conclusions are presented in Section 5.

The outcomes of the present study are envisaged to rise concern about empirical safety distances currently adopted at WII and to provide a conservative and physically sound approach for their definition.

2. Methodology for the assessment of safety distances

A methodology was developed with the aim at assessing safety distances to prevent the failure of a tank exposed to radiation from a wildfire front. The methodology is based on four main steps, as shown in Fig. 1: i) wildfire scenario characterization (emissive power and fire front shape and dimension); ii) definition of the heat load to the target tank (namely the incident radiation on the tank wall); iii) calculation of the time to failure; and iv) calculation of the safety distance. In the following, each of these steps is described in detail.

2.1. Step 1: wildfire characterization

The aim of the first step of the methodology is to characterize the fire scenario, providing the inputs for the calculation of the heat load on the target under analysis. The potential damage of structures caused by an approaching wildfire front mainly occurs due to thermal radiation and convection (Gettle et al., 2002; Zárate et al., 2008). In the specific case of tanks present inside industrial facilities, the contribution of convection is usually negligible. In fact, for safety and security reasons, a clearance area is commonly present

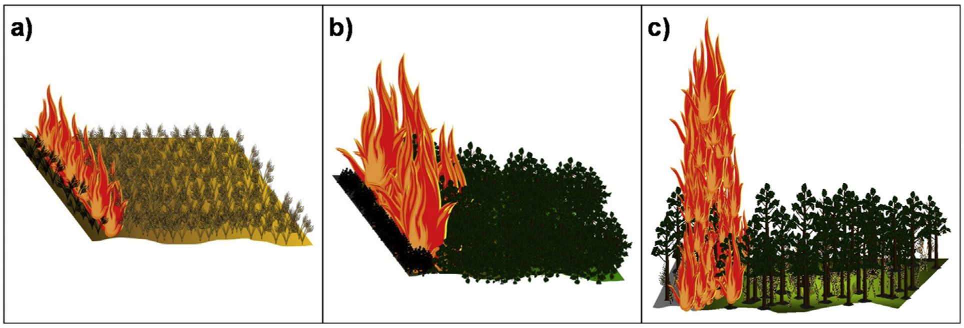

Fig. 2. Representation of the three different type of wildfire considered in the present study: a) grassfire; b) shrubfire; c) active crown fire.

around the facility where no vegetation is allowed. Thus, direct contact of tanks and other process items with flames from a wildfire is unlikely. For this reason, the problem of determining the heat transfer between the fire and the target can be addressed following a solid flame model approach (Eisenberg et al., 1975), as suggested in previous studies (Butler and Cohen, 1998; Gettle et al., 2002; Rossi et al., 2011; Zárate et al., 2008). The flame is modelled as a solid body of defined shape and dimensions, with an emissive power E. The aim of Step 1 is to characterize the fire scenario according to these three parameters.

The emissive power depends on the intensity of the fire and on the radiative fraction of the heat released by the fire. In the case of wildfires, the fire intensity is usually represented by the parameter I_B (called Byram's fireline intensity (Byram, 1959)). The value of the Byram's fireline intensity strongly depends on the type and load of burning vegetation, on weather conditions, and on terrain and fuel characteristics that directly influence wildfire spread (e.g. slope, wind speed, fuel moisture content (Rothermel, 1972)). As for the radiative fraction of the heat generated, this is affected by several factors as well, with the combustion rate, the size and the shape of the burning area being the main ones (Byram, 1959). Byram (1959) suggests that radiative fraction may vary in the range between 3 and 30 % of the total heat generated. The variability of the fire intensity and of the radiative fraction, together with the uncertainties related with their estimation, suggest that basing the definition of safety distances on this couple of variables only could lead to flawed results.

Wildfire behaviour modelling is usually carried out using specialized software (Sullivan, 2009), such as FARSITE (Finney, 1998), PROMETHEUS (Barber et al., 2007), SPARK (Hilton et al., 2014), only to mention a few. These software tools implement models that are specifically developed to characterize fire spread throughout vast areas in terms of fire spread rate and intensity. They also incorporate flame geometry models to obtain information on flame length and tilt angle. In order to perform fire spread simulations, these tools require several specific inputs, such as the type of the burning vegetation, the slope of the terrain, distribution and load of the fuel and weather variables (temperature, relative humidity, wind, etc.). For this reason, simulations results are extremely specific, depending on site and meteorological conditions, and, therefore, not useful for the purpose of the present study, that aims at providing a generalized approach for safety distance definition. Furthermore, as reported by Murphy et al. (2007), wildfire behaviour may change considerably when the fire front approaches the wildland-human interface, where local variations in the type and spatial distribution of fuel have an effect on the wind profile and hence play an important role in fire spread and structures damage (Rehm and Mell, 2009). Therefore, caution shall be used when applying such models to simulate a fire front approaching an industrial site.

Thus, a different strategy for the fire characterization was applied, based on an approach proposed in several previous studies (Billaud et al., 2011; Butler and Cohen, 1998; Zárate et al., 2008). According to the Stefan-Boltzmann law, the emissive power of a grey body (a wild fire front may be represented as such) can be calculated as:

$$E = \varepsilon_f \sigma T_f^4 \tag{1}$$

Where E is the emissive power (W/m^2), ε_f is the emissivity of the flames, T_f is the flame temperature (K) and σ is the Stefan-Boltzmann constant ($5.67\ 10^{-8}\ W/m^2\ K^4$).

The flame temperature and emissivity are highly variable across the flame profile (e.g. Àgueda et al., 2010; Cruz et al., 2011). However, several authors agree on the fact that assuming a fire black body temperature of 1200 K (i.e. posing $\varepsilon_f = 1$ and $T_f = 1200$ K) is a reasonable and conservative choice to estimate the fire emissive power in the definition of safety distances for people and civil structures facing a wildfire front (Billaud et al., 2011; Butler and Cohen, 1998; Zárate et al., 2008). Thus, a value of 118 kW/m^2 (resulting from Eq. (1) when $\varepsilon_f = 1$ and $T_f = 1200$ K) is conservatively assumed as the emissive power for the fire front in the present approach.

To define the shape and dimension of the fire front, a distinction is made with respect to the type of burning wildlands, whether they are grasslands, shrublands or woodlands/forests. According to wildfire behaviour research and terminology, grasslands and shrublands are considered surface fuels and, when ignited, give rise to grassfires and shrubfires respectively. These two type of fires fall under the definition of surface fires, which are characterized by moderate flame length (usually higher for shrubfires than grassfires) and fast rate of spread (Heward, 2019). In case of fire in forests, combustion can either be limited to understorey fuels only or involve tree canopies as well. In the first case, the resulting type of fire is categorized as surface fire. In the second one, the phenomenon takes the name of crown fire. Crown fires can be passive or active. Passive crown fires are those in which the canopy of a single tree or a small group of trees catches fire from the base (i.e. from the understorey surface fire) to the top, without the flame being maintained in the canopy. In active crown fires, instead, the flame is sustained also in the canopies and the surface and crown phases of the fire travel together generating a solid wall of flame (Xanthopoulos and Athanasiou, 2020). Active crown fires are characterized by high values of flame length and represent a more severe scenario with respect to passive crown fires as well as to surface fires involving understory. For this reason, as a conservative choice, only active crown fires are considered in the present methodology when the vegetation around the plant site is a forest. A graphical representation of the three different types of fire considered in the present study is reported in Fig. 2.

Both surface and crown fires can be modelled as a plane of dimensions equal to the flame length L_f and the fire front width W_f, inclined according to the flame tilt angle θ as shown in Fig. 3. The estimation of the flame length L_f for crown fires can be obtained by the indications provided by experienced firefighters, who sug-

Table 1
Maximum flame length registered for grassfires and shrubfires (both considering prescribed fires and wildfires) reported in specialized literature.

Grassfires		Shrubfires	
Reference	Maximum flame length[a] (m)	Reference	Maximum flame length[a] (m)
(Clark, 1983)	4.2	(Catchpole et al., 1998)	13
(Cruz et al., 2018)	4.5	(Vega et al., 1998)	6.5
(Cheney and Gould, 1995)	7.5	(Fernandes et al., 2009)	3
(Sneeuwjagt and Frandsen, 1977)	3	(Cruz et al., 2011)	≈ 7–8
		(Van Wilgen et al., 1985)	4.5

[a] Not considering possible outliers.

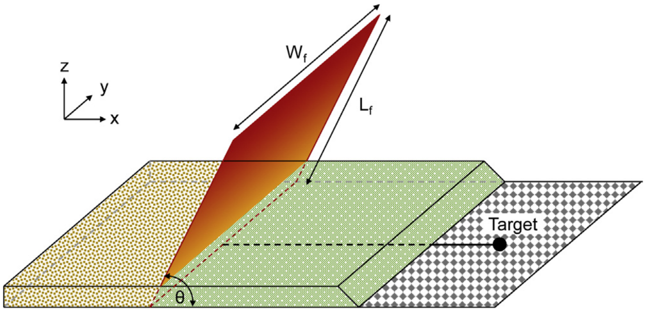

Fig. 3. Scheme of flame shape and geometrical parameters used to model radiation from a wildfire scenario.

gest that a value ranging from 2.5 to 3.5 times (Zárate et al., 2008) the height of the trees can be assumed for trees higher than 4 m. Butler (2014) reports the observation of a flame length up to 3 times the tree height in crown fires. Thus, in the present study, the flame height for crown fires is conservatively assumed as 3.5 times the height of the vegetation, H_v. As for surface fires, they behave differently with respect to crown fires. Therefore, the same rule for the estimation of the flame length cannot be applied. In this case, a conservative yet realistic estimation of L_f is possible considering data and observations of actual prescribed (Duff et al., 2018) and wildfires reported in specialized literature. Table 1 summarizes the results of a literature review of peer-reviewed papers analysing grassfires and shrubfires behaviour (considering data from both wildfires and prescribed fires), showing the maximum values of flame length reported in each reference. It can be noted that, for grassfires, L_f never exceeds the value of 7.5 m. For shrubfires, the maximum reported value of L_f is 13 m. Applying again a conservative approach, these two values are chosen for the flame length, L_f, for grassfires and shrubfires respectively.

In summary, the following rule (Eq. (2)) is adopted in the present approach for the evaluation of the flame length according to the type of fire expected from the vegetation in the proximity of the plant boundary:

$$L_f(\mathrm{m}) = \begin{cases} 7.5\ \mathrm{m\,Grassland\ fires}\ (GR) \\ 13.0\ \mathrm{m\,Shrubland\ fires}\ (SF) \\ 3.5 \cdot H_v\ \mathrm{Crown\ fires}\ (CF) \end{cases} \tag{2}$$

where H_v is the height of vegetation. The second dimension defining the plane representing the fire front in Fig. 3 is the fire width, W_f. This depends on the distribution of the fuel, on the terrain configuration, on the weather conditions and on the spatial (and transient) evolution of the wildfire, which are all specific to a particular wildfire event. For this reason, it is not possible to provide a simple and general procedure for its estimation. Therefore, as a conservative assumption, an infinite value of W_f is considered in the present methodology.

The last parameter defining the fire front geometry is the flame tilt angle θ. This is defined as the angle between the fire front and the terrain (see Fig. 3). Many empirical expressions are available in the literature for the evaluation of θ (Anderson et al., 2006), most of which were specifically derived from observations of surface fires. Such expressions are usually based on the values of I_B and on the wind velocity at a given altitude (generally 10 m), that are site specific and may vary considerably (especially wind velocity) during a wildfire event. A more generic approach is applied in the present methodology with the aim of defining a worst-case scenario: the value of θ maximizing the view factor at each fire front-target distance is considered. Thus, a value of θ changing according to the flame length L_f and the fire-target distance D is selected (this assumption is better clarified in Section 2.2). This value tends to 90° for long distances, regardless the flame length.

2.2. Step 2: definition of the heat load on the target

The second step aims at evaluating the heat load on the target tank, providing the input required for the analysis of the tank response. As introduced in the previous sections, the heat load on a target when considering a WII fire is given only by the incident radiation, being the engulfment and the direct contact with flames unlikely. According to the solid flame model approach (Eisenberg et al., 1975), the incident radiation I reaching the tank as a consequence of the exposure to the fire front can be expressed as follows:

$$I = E\,F_{view}\,\tau_a \tag{3}$$

where E is the emissive power of the flame (as evaluated in Step 1), τ_a is the atmospheric transmissivity and F_{view} is the view factor between the target surface and the solid body representing the flame.

The view factor F_{view} is a geometrical parameter that accounts for the fraction of the flame emissive power that reaches the target surface per unit area. It depends on the flame shape and size, and on the relative position and orientation between fire and target. When the geometry of the problem is simple, the view factor can be calculated using analytical expressions (Mannan, 2005; Van den Bosch et al., 1997). For a flat radiator with a tilt angle θ, as the fire front schematized in Fig. 3, the view factor can be obtained using the expression proposed by Mudan (1987). The flame tilt angle considered is the one that maximizes the view factor F_{view} (thus the incident radiation I) at each distance D and each flame length L_f.

The atmospheric transmissivity τ_a accounts for the portion of the emitted radiation that passes through the atmosphere and reaches the target. It is a function of the relative humidity and of the concentration of the carbon dioxide in the atmosphere and it can be calculated using empirical correlations. In the present study, as a conservative assumption, atmospheric transmissivity was assumed equal to one.

2.3. Step 3: evaluation of time to failure

Once the incident radiation on the tank is estimated, it is possible to calculate the time to failure (Step 3) using vulnerability models for the equipment item of concern. In the framework of the present methodology, this step is based on the approach proposed by Landucci et al. (2009), who developed a lumped model for the assessment of the response of storage tanks to fire exposure. In the model, the target equipment is discretized in thermal nodes for which material and energy balances are solved. The time to failure is then obtained comparing the mechanical stresses at which each zone of the vessel shell is subjected with the admissible tensile strength at the average temperature of the shell, thus taking into account thermal weakening. The model was tuned on values of time to failure obtained from an extended set of experimental data available for atmospheric and pressurized steel tanks (both carbon steel and stainless steel) containing water solutions or hydrocarbons (e.g. LPG, gasoline, etc.). The experimental data set was further extended by the use of a 3D finite element model specifically implemented for this purpose and validated on the available experimental data. By this procedure, Landucci et al. (2009) derived specific envelope correlations providing conservative values of the time to failure (TTF), depending on the type of tank only (atmospheric or pressurized). These correlations are based on a fitting the TTF minima versus the incident radiation:

$$\ln TTF_{atm} = -1.13\ln I + 9.43 \tag{4}$$

$$\ln TTF_{press} = -0.95\ln I + 9.31 \tag{5}$$

where TTF (s) is the time to failure and I (kW/m^2) the incident radiation. Eq. (4) applies to atmospheric tanks, while Eq. (5) applies to pressurized ones. The correlations were developed for cone roof atmospheric tanks featuring a volume between 25 and 17,500 m^3 and pressurized horizontal vessels with volume between 5 and 250 m^3 and a design pressure between 1.5 and 2.5 MPa. It should be remarked that the above correlations provide the minimum values of TTF given the incident radiation and do not consider protections, as fireproofing coatings.

Eqs. (4) and (5) provide conservative values for the TTF as a function of the incident radiation, not dependent on tank geometry or other geometrical details or structural detail. If less conservative values are required, depending either on the purpose of the assessment or on results of Step 3.1 (e.g. if a critically low TTF value is obtained in Step 3.1 for the position of a tank), more specific correlations may be considered to assess the time to failure (Step 3.2). In particular, if the volume of the tank is known, specific correlations obtained by the same procedure outlined above, but considering the tank volume in the fitting of the TTF minima are provided by Landucci et al. (2009):

$$\ln TTF_{atm} = -1.13\ln I - 2.67\,10^{-5}\,V + 9.9 \tag{6}$$

$$\ln TTF_{press} = -0.95\ln I + 8.845\,V^{0.032} \tag{7}$$

where V is the tank volume (m^3). Eq. (6) applies to cone roof atmospheric tanks, and Eq. (7) applies for pressurized horizontal vessels. These equations are obtained by the same procedure as that used to derive Eqs. (4) and (5), but the introduction of the tank volume in the data fitting results in less conservative outcomes. The limits of validity of the above correlations are the same of Eqs. (4) and (5) and also in this case no protection is considered.

2.4. Step 4: definition of safety distances

The definition of safety distances (i.e. the separation distance between a tank and the vegetation that may fuel the fire) is a safety measure aimed at ensuring the integrity of a piece of equipment (storage tanks in this case) in case of fire. Following the approach proposed by Cozzani et al. (2006, 2007), safety distances may be related to the value of the TTF calculated for the specific scenario of interest, also considering the type of vegetation surrounding the plant. Actually, in Step 2, the value of the incident radiation as a function of the view factor is obtained. It should be remarked, however, that the view factor critically depends on the fire-target distance. Step 3 provides a correlation that links the incident radiation to the time to failure. It is thus possible to derive a relationship between the fire-target distance and the time to failure, combining the results of Step 3 and Step 2. In particular, the higher the fire-target distance, the higher will be the interval of time between the fire start and the tank failure (namely the TTF). In order to avoid tank failure, a safety distance between the tank and the vegetation should be present. The safety distance is a fire-target distance (i.e. a separation distance of the tank with respect to the vegetation) high enough to ensure that the TTF is higher than the duration of the fire exposure or of the time required to deploy emergency response teams (Cozzani et al., 2006, 2007). The safety distance can thus be defined as the minimum value of the distance between tank and vegetation that satisfies the following condition:

$$TTF < RT \tag{8}$$

$$RT = \min(t_e, t_r) \tag{9}$$

where RT is the reference time that must be compared with the time to failure of the tank, t_e is the exposure time to the wildfire (i.e. the amount of time considered for tank exposure to the thermal radiation from the fire front) and t_r is the maximum response time of the emergency teams to the wildfire in the industrial facility under consideration (i.e. the time needed for the team to reach the site and protect the exposed tanks using fire monitors).

Exposure time t_e is a function of the fire spread rate and residence time, which in turn depend on many factors (among others, the meteorological conditions, the slope of the terrain and the type and characteristics of the vegetation that fuels the fire). These parameters are site-specific and may vary considerably along the year (and from one year to another), thus a general estimate of t_e is difficult. Limited information is available in literature on fire residence time (e.g. see Burrows (2001)). Furthermore, reported values refer to situations in which the fire spreads through uniformly distributed vegetation. This is not true for the scenarios considered here, where the fire front burns in the proximity of the plant boundary. Such condition is known to affect both the fire spread and residence time (Alexander and Cruz, 2012; Van Wagner, 1977). Nevertheless, according to the indications provided by experienced firefighters, the exposure time might not exceed 15 min even when the fire is at the edge of the vegetation. Therefore, a reference value of 15 min can be considered for the exposure time, leading to a conservative estimation of safety distances.

The response time t_r, although site-specific as t_e, is an easier parameter to obtain. In fact, this is usually reported in the emergency response plans of the facility. Furthermore, even without plant specific information, a plausible estimation of t_r can be based on experience, current practice and technical guidelines. Indeed, response times higher than 30 min as well as lower than 5 min are not credible (Scandella, 2012). The upper value represents the situation of an isolated depot (for example fuel depots used to load tankers for the distribution of fuel to service stations) or small industrial sites where there is no internal fire brigade. On the contrary, the lower value is valid for industrial sites where dedicated firefighter teams are present, together with specific safety barriers as fire sprinklers and permanent fire monitors.

Once the incident radiation on the tank has been evaluated as a function of the fire-target distance D (using Eq. (3)) for a given fire scenario (Steps 1 and 2), the TTF can be calculated using Eqs. (4) or (5), or applying Eqs. (6) or (7) if a specific target is assessed (Step 3). Hence, the TTF can be compared with the reference time RT, which is the minimum between t_e and t_r (according to Eq. (9)). Finally, the safety distance results as the minimum value of the distance for which the TTF is higher than the reference time RT (Eq. (8)).

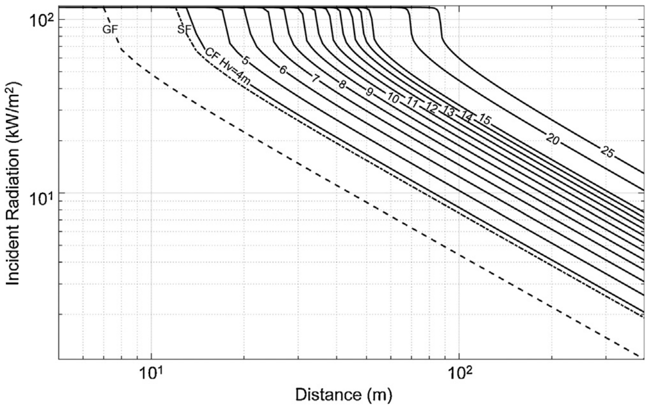

Fig. 4. Incident radiation as function of the distance considering the three type of vegetation. GF: Grassfire. SF: Shrubfire. CF: Crown fire.

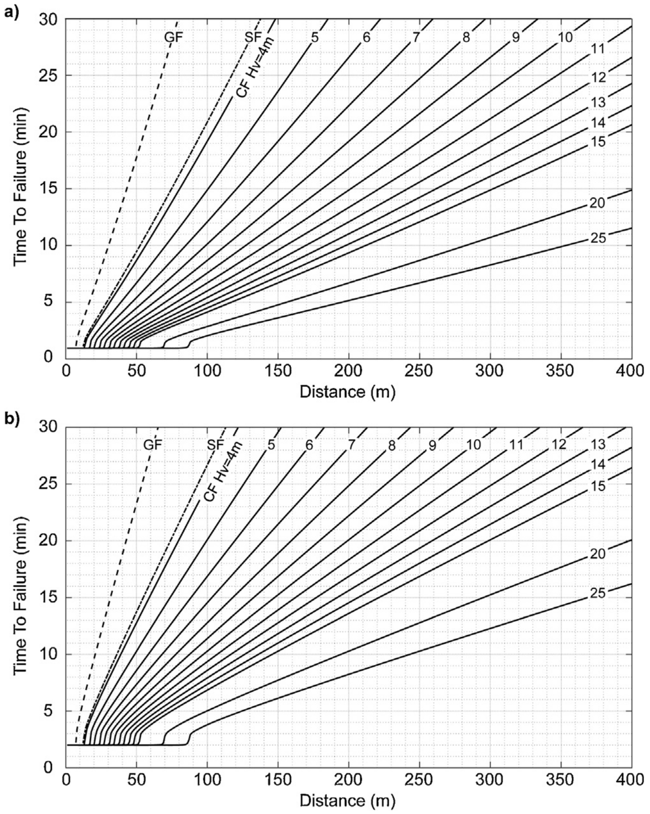

Fig. 5. Time to failure as a function of distance for different vegetation heights obtained for (a) atmospheric tanks and (b) pressurized tanks. GF: Grassfire. SF: Shrubfire. CF: Crown fire.

3. Results

Fig. 4 reports the values calculated for the incident radiation as function of the fire-target distance D, evaluated using the assumptions discussed in Section 2.1. In the case of crown fires, values of the vegetation height ranging from 4 to 25 m were considered. The lower limit is imposed by the rule of thumb introduced in Section 2.1, while the upper one was selected in accordance with the average height of the trees of Mediterranean forests (NASA, 2015).

Fig. 5 reports the conservative generic values of the time to failure obtained from Eqs. (4) and (5) by the approach described in Section 2.3, considering the values of incident radiation reported in Fig. 4. Table 2 summarizes the values of the safety distances calculated for generic targets exposed to grassfires, shrubfires and crown fires with vegetation height 5, 10, 15, 20 and 25 m. The safety distances were calculated by the approach described in Section 2.4, considering two different values, 5 and 15 min, for the reference time, RT. The table points out the strong correlation between the reference time considered in the analysis and the resulting safety distance.

Table 3 reports a selection of significant tank geometries and wildfire scenarios selected for the assessment of specific values of time to failure (Step 3.2 of the methodology). Fig. 6 reports the specific values of the time to failure calculated for the four specific tanks and the four wildfire scenarios summarized in Table 3.

Fig. 7 shows the safety distances calculated for the specific cases listed in Table 3, considering the values of 5 and 15 min for the reference time. The figure clearly shows that atmospheric tanks, having a higher vulnerability, require higher values of safety distance. This is due to the fact that the structural features of atmospheric tanks (lower shell thickness due to the absence of internal pressure apart from that generated by liquid head) causes a lower resistance to local stresses generated by differential thermal dilatation in case of exposure to external fire. Pressurised vessels, having higher shell thicknesses, usually have a higher resistance to the effects of fire exposure (Gubinelli, 2005).

The influence of the fire scenario is also evident in both panels of Fig. 7, highlighting the effect of the flame length. Actually, safety distances obtained for surface fires are roughly one order of magnitude lower than those calculated for crown fires. Finally, it is important to notice that for the pressurized tank featuring the maximum value of volume (200 m^3) in Table 3 the time to failure is always higher than 5 min. Therefore, as shown in Fig. 7, when a RT value of 5 min is assumed, a null value for the safety distance is obtained. This represents an extreme situation, in which the incident radiation from the fire does not represent a treat for the tank integrity. Still, it is advisable to provide a minimal distance between the tank and the vegetation so that flame impingement is avoided. In this case, in fact, also thermal convection (disregarded in the present approach) plays a role in the fire to tank heat transfer.

4. Discussion

The methodology developed provides an approach to the estimation of the safety distance between vegetation and storage tanks in industrial facilities, with the aim of preventing tank failure and escalation leading to technological accident scenarios in the case of wildfires. In each step of the procedure developed, simplifying assumptions were adopted, allowed the definition of a straightforward, yet technically sound, approach to the assessment of safety distances. Obviously, the simplifying assumptions introduced in the methodology may be interpreted as limitations to the field of application of the analysis and to its results. Table 4 provides a summary of the main strengths and limitations identified for the methodology developed.

From a general point of view, it is worth to stress that the safety distances obtained applying the present methodology are always conservative. These may be used as guidelines in lay-out definition, to provide adequate separation distances from the vegetation since the early design stages. Furthermore, when considering a given layout, the application of the methodology allows identifying the most vulnerable areas and equipment items, driving decision making on the adoption of protection and mitigation systems for critical tanks (e.g. the installation of fireproofing, remotely activated sprinklers or water curtains) and the improvement of emergency response plans in the case of wildfire, prioritizing the interventions of the rescue teams towards the most critical sections of the plant.

It is important to remark that the safety distances obtained for generic targets are often higher than those proposed by technical

Table 2
Safety distances obtained assuming a reference time of: (a) 5 min and (b) 15 min.

Wildfire scenario	Type of tank	Generic safety distances[a] (m)	
		RT =5 min	RT = 15 min
Grassfire	Atmospheric	20	45
	Pressurized	15	35
Shrubfire	Atmospheric	30	75
	Pressurized	20	55
Crown fire, H_v =5 m	Atmospheric	40	105
	Pressurized	25	75
Crown fire, H_v = 10 m	Atmospheric	80	205
	Pressurized	50	150
Crown fire, H_v = 15 m	Atmospheric	120	305
	Pressurized	75	225
Crown fire, H_v =20 m	Atmospheric	160	405
	Pressurized	100	300
Crown fire, H_v =25 m	Atmospheric	195	505
	Pressurized	125	370

[a] Values are rounded to the next multiple of 5.

Table 3
Significant combination of tank geometries and wildfire scenarios considered for the specific assessment of TTF (Step 3.2 of the methodology). The tags in the table are used to identify the TTF values reported in Figs. 6 and 7 for the specific tank/wildfire scenario combination considered.

Type of tank	Volume m^3	Grassfire GF L_f = 7.5 m	Shrubfire SF L_f=13 m	Crown fire CF1 H_v=10 m	Crown fire CF2 H_v=15 m
Atmospheric	50	A50_GF	A50_SF	A50_CF1	A50_CF2
	14,000	A14000_GF	A14000_SF	A14000_CF1	A14000_CF2
Pressurized	15	P15_GF	P15_SF	P15_CF1	P15_CF2
	200	P200_GF	P200_SF	P200_CF1	P200_CF2

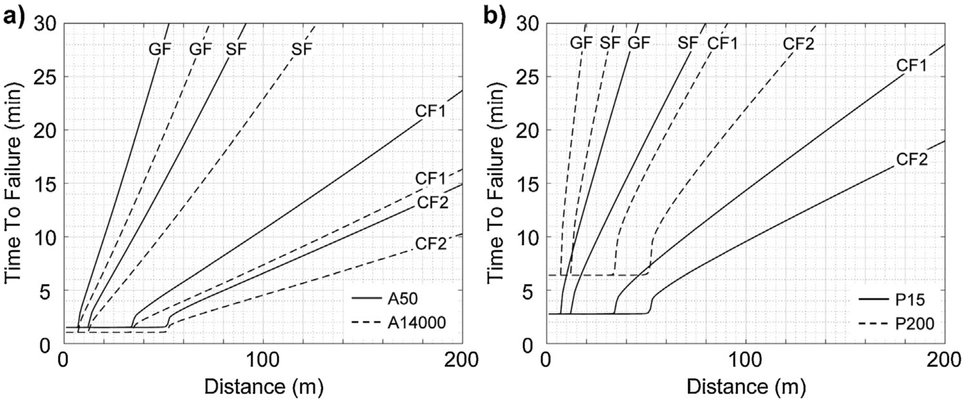

Fig. 6. Time to failure as function of distance for the tanks and wildfire scenarios listed in Table 3: (a) cone roof atmospheric tanks: (b) pressurized horizontal vessel. The key to the tags of the different curves is reported in Table 3.

standards and legislations. For instance, in the case of atmospheric tanks, the Italian legislation (GURI, 1934) states that the maximum separation distance shall be 20 m. This distance represents the minimum distance between storage tanks and plant boundary when the total storage capacity of flammable substances in the area is higher than 3500 m^3 (lower values are recommended for lower overall storage capacities). The Spanish legislation for petrochemical installation (BOE, 1994) prescribes a separation distance between tanks (regardless the type) and plant boundary of 30 m. The Health and Safety Executive (HSE), in the guidelines “Storage of flammable liquids in tanks” (HSE, 2015), suggests that the distance between tanks and plant boundary should be 15 m for tanks with volumes larger than 250 m^3. In the USA, the National Fire Protection Association (NFPA) provides guidelines for the distance between atmospheric tanks and Third-Party properties (NFPA, 2018). Such distance depends on the characteristics of the tank, both with respect to dimension and type (e.g. floating roof, cone roof, etc.). The maximum distance suggested is 105 m, that corresponds to horizontal and vertical tanks with emergency relief venting to limit pressure to 17 kPa and no other protection system.

As for pressurized tanks, the Italian legislation (GURI, 1994) provides separation distances for LPG storage tanks, which must be not less than 40 m for tanks featuring a volume higher than 300 m^3. For the same volumes and type of tanks, the Greek legislation (ΦEK, 1993) prescribes a safety distance between tanks and plant boundary of 30 m.

It should be remarked that all the safety distances reported by the above-mentioned regulations and guidelines are lower than the safety distances obtained for generic targets in the present study and reported in Table 2, with differences as high as an order of magnitude. Even considering that all the assumptions at the base of the methodology are conservative, this rises some concern about the appropriateness of the separation distances from vegetation used in the current practice in areas where severe wildfire scenarios are possible.

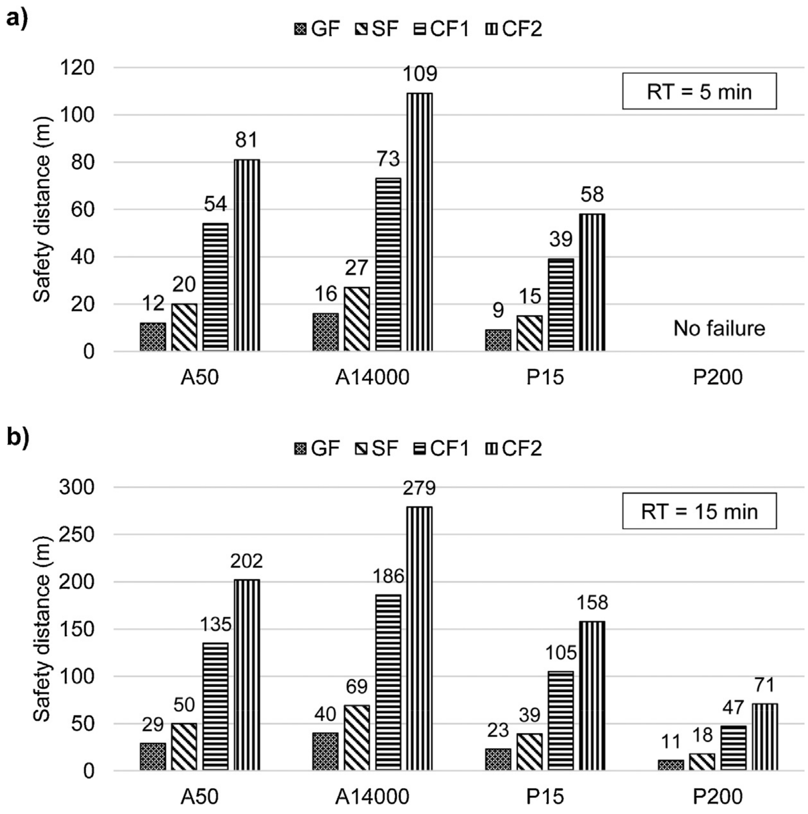

Fig. 7. Safety distances calculated for the tanks and wildfire scenarios described in Table 3, obtained assuming a reference time of (a) 5 min and (b) 15 min. Table 3 reports the key to the x-axis captions.

Table 4
Main strengths and limitations identified for each step of the methodology developed for the calculation of safety distances.

Step	Strengths	Limitations
Step 1 Wildfire characterization	• Does not require the use of specialized fire spread modelling software • It is based on a straightforward estimation of fire front characteristics, resulting in a conservative assessment	• To date, no accurate model exists allowing the calculation of the fire front flame length for crown fires. The rule of thumb adopted for its estimation is very conservative • The possible effect of firebrands is not considered
Step 2 Heat load on the target	• Heat load calculation is based on the solid flame model, which is consolidated and was used by several authors to assess incident radiation on targets from wildfire fronts (e.g. Billaud et al., 2011; Butler and Cohen, 1998; Zárate et al., 2008)	• As a conservative simplifying assumption, the maximum value of the view factor between the fire and the target tank is applied to the entire tank surface • Possible flame impingement or engulfment is not considered • Protection deriving from safety barriers (e.g. fireproofing, fire deluges, etc.) is not considered
Step 3 Evaluation of the rime to failure	• The reduced number of input values simplifies the use of the methodology, that may be applied since the early design stages • The normographs in Fig. 5 are easy to use and do not require to perform any further calculation	• The range of application of the equations used for the calculation of the time to failure is limited to the tank geometries used for their validation. For atmospheric (cone roof) tanks: –25 m^3 <Tank volume <17,500 m^3 For pressurized (horizontal) tanks: –5 m^3 <Tank volume <250 m^3 – 1.5 MPa < Tank pressure <2.5 MPa
Step 4 Definition of the safety distances	• It is possible to consider site-specific values for the local emergency team response time	• To date, no model is available to assess wildfire duration in a wildland-human interface

5. Conclusions

The increasing number of extreme wildfires, together with the growing extension of the WII, poses concerns on the potential consequences deriving from wildfires affecting WIIs. Wildfires facing an industrial site where relevant quantities of hazardous substances are stored or processed can trigger major technological accidents, which may escalate the consequences of the wildfire. The approach developed in the present study allows for the definition of safety distances based on a technically sound approach. The safety distance values obtained may be applied both in the design of the layout of new plants and in the safety management of existing facilities. In particular, the approach supports the management of the vegetation clearance area around the plant and allows the identification of the most vulnerable targets, assisting the setup of emergency plans and highlighting the need for the implementation of fire protection measures and safety barriers.

The comparison between safety distances resulting from the present study and the empirical values for safety distances adopted in regulations and guidelines applied in several countries highlights that the safety distances used in industrial practice might not be sufficient for asset protection and escalation prevention, raising concern about the current approaches to the protection of industrial sites from wildfires.

Future work shall be devoted to perform a systematic identification of typical WUI fire scenarios involving industrial farm tanks and sites where storage tanks are present, in order to carry out a critical assessment of the current prescriptions related to this type of installation and highlighting possible gaps in safety regulations.

In perspective, the proposed approach may be extended to include the effect of safety barriers and of emergency response management in the assessment of safety distances. This shold pave the way to integrate technological accidents caused by wildfires in the quantitative risk assessment framework of industrial sites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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