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# A Dynamic Assessment of Safety Barriers Effectiveness in Fire Protection of Cryogenic Storage Tanks

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Liquid hydrogen (LH2) is believed to play a pivotal role in the energy transition. The main issue of this technology is the boil-off of the cryogenic liquid, particularly in the presence of critical heat sources, such as an external fire. Typically, in addition to the insulation system, safety barriers, such as water deluge systems and water curtains, are introduced as shields to protect the vessel from the fire radiation. Thus, the heat received from the cryogenic equipment depends on the effectiveness of those barriers.
The present study aims at providing a dynamic quantification of the time to failure of an LH2 cryogenic tank, based on the performance of the abovementioned safety barriers. The results of this analysis highlight how different parameters affect the effectiveness of the safety systems, suggesting how to implement the most effective configurations. Moreover, the results obtained in terms of heat fluxes are precious input data useful for the definition of the boundary conditions in mathematical models (e.g., analytical and computational fluid dynamic models) used to investigate the behavior of cryogenic tanks engulfed in a fire.

## 1. Introduction

Liquid hydrogen ($LH_2$) is regarded as an essential element in the energy transition. One of the main issues of this technology is the formation of the so-called boil-off gas (BOG) that results from the vaporization of the liquid. The heat transfer to the tank is regarded as its primary cause, particularly for stationary applications (Godula-Jopek et al., 2012). This is promoted by the significant temperature difference between the warm external environment and the cryogenic fluid, and cannot be completely avoided (Al Ghafri et al., 2022). Clearly, the presence of an external fire in the proximity of the tank is a critical situation. In fact, in this scenario, the driving force of the heat transfer (i.e., the temperature difference between the environment and the cold stored liquid) is significantly increased, leading to a faster pressurization of the equipment (Perez et al., 2021). For example, considering a hydrocarbon fire with mean flame temperature of around 1000 K (Pehr, 1996), the temperature difference rises from 273 K (calculated considering a $LH_2$ storage temperature of 20 K and an ambient temperature of 293 K) up to 980 K. To mitigate the fire attack, a series of safety barriers (SBs), is installed to shield the fire radiation (Rausand, 2011) and avoid, or at least postpone, the tank failure. As a consequence, the probability of incident escalation (i.e., domino effect) (Hankinson & Lowesmith, 2004) is also reduced and a longer time is available for the emergency response (Roberts, 2004a). Water deluge systems (WDS) and/or water curtains are extensively used for fire protection of cryogenic tanks. Previous studies proved the effectiveness of water curtains (Lowesmith et al., 2007; Wen et al., 2008; Zhou et al., 2023) and water deluge systems (Hankinson & Lowesmith, 2004; Roberts, 2004a; Shirvill, 2004) in fire protection against pool fires and jet fires. The influence of the most relevant parameters, such as the operating pressure, number of nozzles, stand-off distance (i.e., the distance between the nozzles and the tank), and activation time, has been assessed through the estimation of the radiation reduction and maximum tank wall temperature with different configuration.

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In this work, the effectiveness of different configurations of WDS and water curtains for fire protection is evaluated through the estimation of the time to failure (i.e., the time after which the equipment fails) of the cryogenic equipment protected by the systems. A percentage reduction of the radiated heat provided from the fire is assigned to each configuration and used to calculate the time to failure (TTF) of the tank by means of a lumped model developed by Ustolin et al. (2021). The results of this study provide useful information for safety studies, giving an insight on the most critical parameters that impact the performance of the fire protection systems of interest. Moreover, they are a valuable support for modelling activities (e.g., Computational Fluid Dynamic, CFD, and analytical models) aimed at the reproduction of the behaviour of cryogenic tanks exposed to fires. For instance, the data obtained in terms of heat radiation can be used as input for the models to define the boundary conditions, allowing to simulate a variety of scenarios and obtained a comprehensive overview of the tank performance.

## 2. State of art

Water deluge systems and water curtains are designed according to standards, such as NFPA 13 (National Fire Protection Association, 2019), NFPA15 (National Fire and Protection Association, 2017), API RP 2030 (American Petroleum Institute, 2005), ISO 6182 (International Organization for Standardization, 2014) and the Tentative Rules (Fire Officies' Committee, 1979). Among them, the NFPA 15 and the Tentative Rules are the most used, with the second providing more detailed guidance (Roberts, 2004b).
In the design phase, the parameters (column 1 and 3 in Table 1) that strongly affect the system performance (Davies & Nolan, 2004; Roberts, 2004c) due to their influence on the water distribution on the target, must be chosen so that their combination ensures at least the minimum application rate (i.e., delivery rate to the nozzle/surface area) defined in the codes (e.g., 10 $dm^3$ $min^{-1}$ $m^{-2}$ and 10.2 $dm^3$ $min^{-1}$ $m^{-2}$ according to the Tentative Rules and NFPA 15, respectively).
Table 1 summarizes the features of the most common configurations of WDS for the fire protection of horizontal cylindrical vessels containing flammable liquids (Hankinson & Lowesmith, 2004; Roberts, 2004a, 2004b; Shirvill, 2004) designed according to the abovementioned codes. Regarding water curtains, a more limited number of information is available. Typically, the same type of nozzle of WDS is used, but with a different arrangement (i.e., rows of nozzles above the target rather than around it); water flow rates are in the range between 12 $dm^3$ $min^{-1}$ $m^{-2}$ and 24 $dm^3$ $min^{-1}$ $m^{-2}$, and the number of nozzles rows is between 1 and 3 (Lowesmith et al., 2007).

*Table 1: Features of the most common water deluge systems for fire protection of horizontal cylindrical vessels containing flammable liquids.*

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Spray nozzle type | Medium velocity (MV57) | Number of blocked nozzles | 0 |
| Discharge pressure (barg) | 1.4 – 3.5 | Nozzle stand-off distance (m) | 0.55 – 3 |
| Nozzles rows | 3 | Nozzle distance (m) | 1.5 (longitudinal) |
| Activation time (s) | 0 – 30 | Nozzle bore diameter (mm) | 4.7 – 50 |
| Efficiency (%) | 25 – 45 | Nozzle angle (°) | 45 – 120 |

Different combinations of parameters in Table 1 have been investigated to assess the most effective configuration of WDS for fire protection of storage tanks. It was proved that systems designed to give the minimum application rate are not efficient for the vessel protection (Roberts, 2004a, 2004b) because, even if the minimum requirements are met, the water coverage of the tank is not sufficient to avoid the formation of dry spots and limit the shell temperature below 100-120 °C, regarded as the maximum shell temperatures above which critical conditions for the failure of the water film are reached (Roberts, 2004a; Shirvill, 2004). In fact, considering the efficiency of these type of systems (25-45% (Roberts, 2004c)), the application rate as defined above, does not represent the amount of water that actually protects the tank because it does account for water losses. On the other hand, if the minimum requirement of around 10 $dm^3$ $min^{-1}$ $m^{-2}$ is interpreted as surface water flow rate (i.e., water flow that reaches the tank/surface area), the target is successfully protected from the impact of the fire. This can be achieved by increasing the minimum application rate by four times (i.e., 40 $dm^3$ $min^{-1}$ $m^{-2}$) (Roberts, 2004b). Generally, the increase of the discharge pressure is beneficial in terms of radiation reduction, while large delays in the activation of the system can significantly compromise its performance, leading the tank shell to exceed 600 °C, with consequent possible failure of the equipment (Roberts, 2004b). Moreover, the block of nozzles, especially if adjacent, can result into the vessel failure due to the formation of large dry patches (Roberts, 2004b). Overall, WDS proved to be more effective in reducing the heat radiation in the part of the vessel not directed impacted by the jet fire, while their efficacy on the other zones is significantly reduced. This performance gap can be compensated combining WDS with area deluge systems. For instance,

the reduction of the radiated heat received by the tank on the top and front sections can be increased from an average value of 20% up to 60% (Hankinson & Lowesmith, 2004).
The effectiveness of water curtains has been assessed considering the sole variations of the water flow rate and nozzle rows. Their performance improves with the increase in the discharge pressure and number of nozzle rows (Lowesmith et al., 2007).

## 3. Case study

The aim of the present study is to investigate how the performance of WDS, and water curtains affects the TTF of cryogenic tanks exposed to an external fire. Particularly, the influence of the most relevant parameters (see Section 2) is assessed by exploring different SBs configurations. For the present study, a 10 $m^3$ cryogenic tank (internal diameter of 1.5, length of 6 m and 50% filling degree) for medium-scale hydrogen storage is considered. The tank is insulated with a multi-layer insulation (MLI), able to reduce the incident heat flux of 80% (Zheng et al., 2019) when perfectly working. The pressure relief valve (PRV) is designed according to the ISO 21013-3:2016 (International Organization for Standardization, 2016) with an opening pressure of 4 bar. A radiated heat around 250 kW $m^{-2}$ is calculated considering a propane fire with a burning rate of 2 kg $s^{-1}$ with an average combustion energy of 50 MJ $kg^{-1}$. Assuming a distance of 5 m between the fire and the tank, a constant heat flux of 75 kW/$m^2$ is received from the vessel when no safety barrier is present. It is assumed that the MLI undergoes a completely degradation due to the fire exposure (Camplese et al., 2023; Eberwein et al., 2023).
First, the basic performance of the safety barriers has been defined by designing a reference configuration according to the Tentative Rules. For both WDS and water curtains, medium velocity nozzles MV57 have been selected and an efficiency of 35% is assumed. The WDS is able to provide a surface flow rate of 10.6 $dm^3$ $min^{-1}$ $m^{-2}$, just above the limit (see Section 2), that corresponds to an application rate of 40 $dm^3$ $min^{-1}$ $m^{-2}$ (nozzle K-factor is 28). For water curtains, an intermediate flow rate of 18 $dm^3$ $min^{-1}$ $m^{-2}$ has been selected. The base performances of the two systems are able to limit the shell temperature below 100 °C, ensuring a percentage reduction of the radiated heat of 50% for WDS (row 1 in Table 2) and 40% for water curtains.
Then, parameters have been varied and the corresponding reduction of the radiated heat of the overall systems have been estimated. For WDS, four variations have been considered starting from the reference case: increase and decrease of the discharge pressure (V1), increase of the activation time (i.e., delayed activation) (V2), increase in the number of blocked nozzles (V3) and increase and decrease of the stand-off distance (V5). The percentage reduction of the radiated heat has been defined based on the maximum tank shell temperature (Table 2). For variations from 1 to 3, data have been obtained from (Roberts, 2004b), while for variation 4 the maximum shell temperatures are derived considering the heating rate of the tank provided in (Roberts, 2004a).

*Table 2: Variations of the most relevant parameters affecting the performance of water deluge systems considered in the present study.*

| Case | Discharge pressure (barg) | Activation time (s) | Number of blocked nozzles | Stand-off distance (m) | Radiated heat reduction (%) |
|---|---|---|---|---|---|
| Reference | 2 | 0 | 0 | 1.5 | 50% |
| Variation 1_1 (V1_1) | 1.4 | 0 | 0 | 1.5 | 40% |
| Variation 1_2 (V1_2) | 3.5 | 0 | 0 | 1.5 | 60% |
| Variation 2_1 (V2_1) | 2 | 30 | 0 | 1.5 | 25% |
| Variation 2_2 (V2_2) | 2 | 160 | 0 | 1.5 | 0% |
| Variation 3_1 (V3_1) | 2 | 0 | 1 | 1.5 | 30% |
| Variation 3_2 (V3_2) | 2 | 0 | 2 | 1.5 | 10% |
| Variation 3_3 (V3_3) | 2 | 0 | 3 | 1.5 | 0% |
| Variation 4_1 (V4_1) | 2 | 0 | 0 | 0.55 | 60% |
| Variation 4_2 (V4_2) | 2 | 0 | 0 | 3 | 25% |

In addition to the variations listed in Table 1, the combinations of the WDS with an additional area deluge system with an application rate of 12 $dm^3$ $min^{-1}$ $m^{-2}$ (V5_1) and 24 $dm^3$ $min^{-1}$ $m^{-2}$ (V5_2) were also considered. It is worth mentioning that in these cases the application rate was defined not accounting for the water losses (i.e., delivery rate to the nozzle/surface area).
For water curtains, literature data have been used. In this case, only three variations have been considered (Table 3): increase and decrease of the application rate (V1), increase and decrease of the number of nozzle rows (V2) and their combination (V3). Again, the application rate considered for this system did not consider water losses.

Finally, the TTF of the cryogenic tank was estimated by means of a lumped model (Ustolin et al., 2021), already validated for $LH_2$ applications.

*Table 3: Variations of the most relevant parameters affecting the performance of water curtains considered in the present study.*

| Case | Water flow rate ($dm^3\ min^{-1}\ m^{-2}$) | Number of nozzle rows | Radiated heat reduction (%) |
|---|---|---|---|
| Reference | 18 | 2 | 40% |
| Variation 1_1 (V1_1) | 12 | 2 | 30% |
| Variation 1_2 (V1_2) | 24 | 2 | 70% |
| Variation 1_3 (V1_3) | 40 | 2 | 90% |
| Variation 2_1 (V2_1) | 18 | 1 | 25% |
| Variation 2_2 (V2_2) | 18 | 3 | 60% |
| Variation 3_1 (V3_1) | 12 | 1 | 15% |
| Variation 3_2 (V3_2) | 12 | 3 | 45% |
| Variation 3_3 (V3_3) | 24 | 1 | 50% |
| Variation 3_4 (V3_4) | 24 | 3 | 85% |

## 4. Results and discussion

For all the cases considered in the present work, the failure of the cryogenic tank does not occur regardless of the performance of both the safety systems. Thus, the different effectiveness of WDS and water curtains can only affect the required time to empty (TTE) the equipment through the PRV. Clearly, the maximum values are obtained when the barriers show the best performance because, in these cases, the boil-off of the liquid phase is the slowest due to the highest reduction of the heat flux. These are the configurations consists into the combination of the WDS with an area deluge system with a water flow rate of 24 $dm^3\ min^{-1}\ m^{-2}$ (V5_2) and in the use of water curtains with an application rate of 40 $dm^3\ min^{-1}\ m^{-2}$ (V1_3); the corresponding time required to empty the vessel is 19 minutes.

From a safety standpoint, the increase of the TTE is beneficial because it allows to reduce the hydrogen concentration in the atmosphere, reducing the severity of possible accidental scenarios such as fires or explosions.

However, if the PRV is not designed correctly or, in the worst case, not working, the performance of the safety barriers has an impact on the TTF of the tank. Similar results have been obtained considering a reduction of 50% of the PRV opening area and its complete failure. For this reason, only the results relative to the second case are presented. Figure 1 shows the results obtained for the different performance of the WDS (see Table 2 in Section 3).

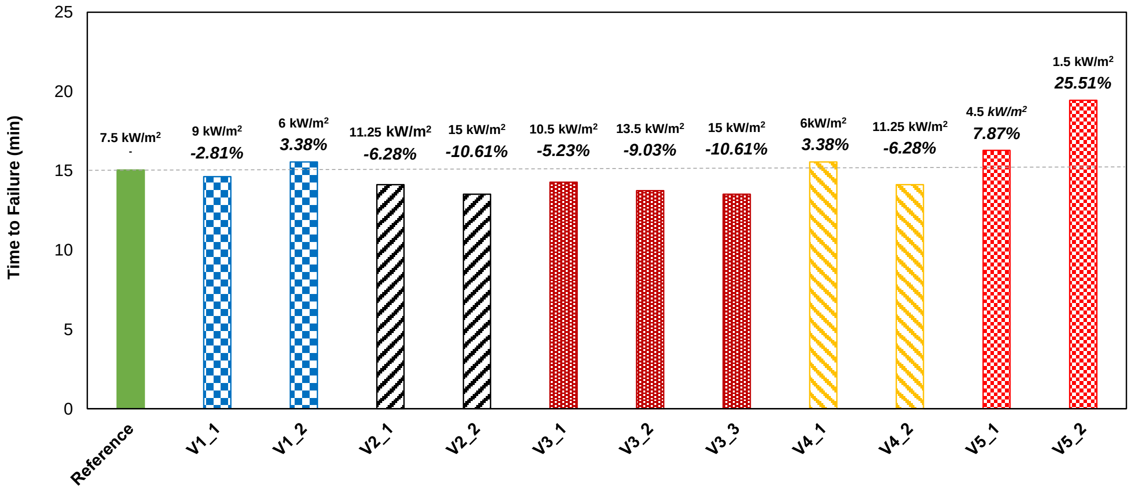


*Figure 1: Variation of the time to failure (TTF) of the $LH_2$ cryogenic tank according to the performance of the water deluge system; percentage values are referred to the percentage variation of the TTF.*

Overall, the TTF remains around 15 minutes as calculated for the reference case. The combination of the WDS with an additional area deluge system is the most effective configuration that leads to an increase of more than 25% of the TTF. The increase of the discharge pressure (V1_2) and the reduction of the stand-off distance (V4_2) have exactly the same effect. In cases V2_2 (activation time of 160 s) and V3_3 (3 adjacent blocked nozzles), despite the WDS is completely ineffective, the reduction of the TTF is only around 10%.
The results obtained for water curtains are showed in Figure 2. With the basic performance of the system the TTF is the same as before. Here the maximum increase of the TTF (around 28%) is achieved by increasing the water flow rate up to 40 $dm^3$ $min^{-1}$ $m^{-2}$. The second best performance (+21% of the TTF) is reached increasing by one the number of nozzle rows and the water flow rate to 24 $dm^3$ $min^{-1}$ $m^{-2}$ at the same time (V3_4). The same increase of the sole water flow rate (V1_2) allows to increment the TTF of more than 16% and is more effective than the addition of one nozzle rows (V2_2), for which the TTF increment is slightly more than 6%. Furthermore, the reduction of the water flow rate from 18 $dm^3$ $min^{-1}$ $m^{-2}$ (Reference) to 12 $dm^3$ $min^{-1}$ $m^{-2}$ (V1_1) is worse than using only one row of nozzles, keeping the same water rate of 18 $dm^3$ $min^{-1}$ $m^{-2}$.

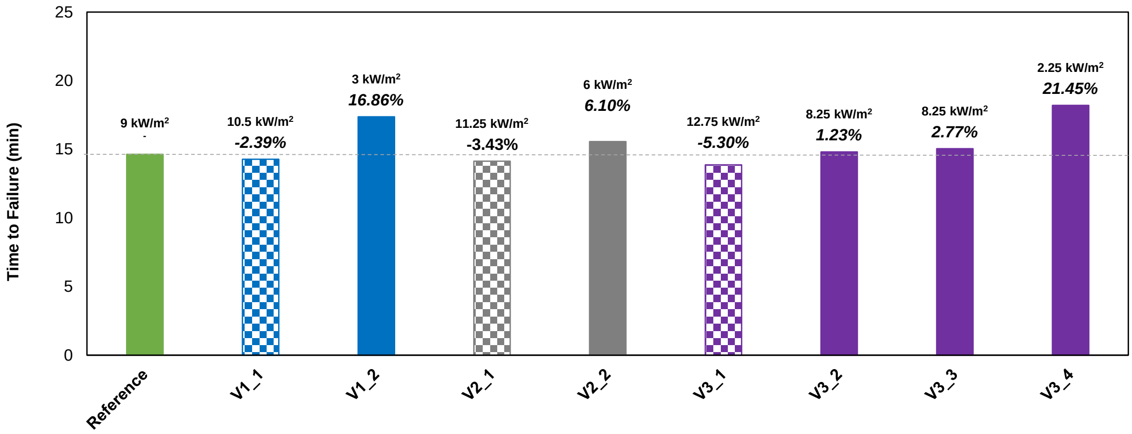


*Figure 2: Variation of the time to failure of the $LH_2$ cryogenic tank according to the performance of the water curtains; percentage values are referred to the percentage variation of the TTF.*

Overall, considering the variations of the parameters within the ranges defined in this study, the performance of the SBs have not a strong impact on the time to failure of the tank. Moreover, even when the effectiveness of the systems is reduced with respect to the reference case, the radiation levels are still below the thresholds of 15 kW/$m^2$ and 40 kW/$m^2$, defined as minimum radiation intensities, respectively for atmospheric and pressurized tanks, capable to lead to the escalation of the accident scenario and involve adjacent equipment items (Cozzani et al., 2006).

## 5. Conclusions

In the present study the influence of the performance of water deluge systems and water curtains used in fire protection of $LH_2$ cryogenic tanks has been assessed through the estimation of their time to failure. The results obtained show that, if the pressure relief device installed on the tank is working, the safety systems can prevent the equipment failure, otherwise the vessel fails after approximately 15 minutes. However, even in the worst cases, the barriers can avoid the accident escalation. The results can be used to define the boundary conditions in mathematical models used to simulate the fire engulfment of cryogenic tanks and contribute to deepen the knowledge regarding liquid hydrogen applications. Moreover, starting from this study, the performance of the safety barriers can be further analysed considering the variation of the radiated heat flux received by the tank during the fire exposure including the influence of the degradation of the insulation system, not accounted in the present analysis.

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