Domino effect triggered by fire: performance assessment of safety barriers in harsh environmental conditions

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Accidental fires may lead to damages to equipment with severe consequences and escalation events in the framework of process facilities. Safety barriers such as hardware systems, procedural measures and emergency response are critical elements aimed at preventing the propagation of accidents among units, but their performance may be strongly affected by external factors, such as harsh environmental conditions. The present study is aimed at defining a structured approach to the quantitative performance assessment safety barriers for facilities operating in harsh environment. A specific scoring system allows penalizing external factors associated with harsh environmental conditions determining simplified relationships for availability and effectiveness of safety barriers. The so obtained barriers performance data are input to a specific event tree analysis in order to support the quantitative assessment of accident frequency associated to cascading events. The approach is tested by its application to a case study, aimed at the assessment of the influence of harsh environmental conditions on the risk due to cascading events in an industrial site.

Keywords: Domino effect; cascading events; fire protection; safety barriers; harsh environment; escalation.

Introduction

Cascading events triggered by the escalation of fires and explosions were responsible of severe accidents that affected the chemical and process industry. Past accident data analysis showed secondary targets more frequently affected by escalation were pressurized tanks, atmospheric tanks, process vessels and pipelines (Reniers and Cozzani, 2013). The awareness of the hazards posed by domino effect led to the introduction of several technical standards that recommend the use of protective systems or barriers to reduce the possibility of fire escalation. Safety barriers, such as interlocks, fireproofing, firefighting systems, etc., are critical elements aimed at preventing the propagation of accidents among units and to ensure the integrity of the facility. These may be considered as "hardware" barriers, since they require activation (active protections) or are permanently in place (passive protections) (CCPS - Center of Chemical Process Safety, 2001). However, procedural and emergency measures play also a key role in the interruption of accident chains (Lees, 1996).

The performance of safety barriers or protective layers against the propagation of cascading events may be strongly affected by external factors, in particular if the facility of interest is located in harsh environments. Harsh environments refer to those climatic conditions which may lead to difficulties for people to work and for process plants to be operated, with possible reduction of operational performance and system availability (Bercha et al., 2003; Gao et al., 2010; Khan et al., 2015). In recent years, the exploitation of natural resources in harsh, remote and sensitive areas (such as Arctic and sub-Arctic regions) increased (Barabadi et al., 2015; Naseri and Barabady, 2013). This raised concerns about safety and environmental issues, also considering the limited amount of data and methodologies able to support structured analyses in this type of environment, which are critical to define a risk-based design framework to the safety enhancement of operations (Gao et al., 2010; Paik et al., 2011; Vinnem, 2014).

The present study is aimed at defining a structured approach to support the quantitative risk assessment of cascading events, accounting for the influence of harsh environmental conditions on the effectiveness and availability of safety barriers, with particular reference to installations located in Arctic and sub-Arctic regions. Relevant phenomena associated with the degradation of hardware barriers due to extreme weather conditions are considered in the method. The specific role of emergency teams, and the possible delayed intervention and increment of human error probability due to extremely cold environments were also determined.

The approach was tested by a case study aimed at determining the influence of harsh environment on the risk profile of industrial facilities.

Methodology

Overview

The aim of the present methodology is to account for the influence of harsh environmental conditions on the frequency of cascading events, through a specific analysis of the effects on the expected safety barrier performance. The methodology consists of the following steps:

- Step 0: Characterization of safety barriers performance in harsh environment
- Step 1: Determination of harsh environment score (HES)
- Step 2: Quantitative assessment of safety barriers performance in harsh environment
- Step 3: Probabilistic assessment of mitigated cascading events

Step 0 is a preliminary step aimed at the characterization of the safety barriers performance, with particular reference to the prevention and mitigation of cascading events triggered by fire. Three categories of barriers are considered (CCPS - Center of Chemical Process Safety, 2001): i) active protection systems, ii) passive protection systems and iii) procedural and emergency measures. This step is based on the application of a previously developed methodology (Landucci et al., 2016a, 2015), in which the evaluation of safety barriers performance in the framework of escalation is aimed at quantifying:

- availability, defined as the probability of failure on demand (PFD) of the safety barriers;
- effectiveness (η), defined as the probability that the safety barrier, once successfully activated, will be able to prevent the escalation.

Once the parameters needed to support the quantitative evaluation of safety barriers are defined, the influence of harsh environmental conditions on their protection performance is inferred on the basis of the analysis and of the systematization of previous studies and literature data. In particular, the outcomes of studies related to harsh environmental conditions influence on human factors (Bercha et al., 2003; Musharraf et al., 2013; Song et al., 2016) and statistical studies devoted to emergency response time modelling (Matteson et al., 2011; Taylor, 2016) were adopted in order to determine emergency teams performance data. On the other side, specific approaches recently developed for reliability and maintainability studies in Arctic and sub-Arctic regions (Gao et al., 2010) were adapted in order to model the performance of "hardware" barriers (e.g., both passive and active barriers).

In order to systematically account for the effect harsh environmental conditions, such as temperature, wind, snow, waves, etc., a "Harsh Environmental Score" (HES) is defined (Step 1, see Section 2.2). The score is based on a weighted combination of penalties associated with external factors induced by harsh environment, which may have an impact on procedural and hardware measures. The scoring of weather parameters to determine the severity of environmental conditions is based on the commonly applied indexes in weather forecasting (Spellman, 2013), which consist of a weighted summation of atmospheric parameters, such as wind speed, ambient temperature, humidity, etc. and were taken into account as a methodological basis for the development of the HES score.

Starting from the estimated value of HES, the modification of availability and effectiveness of the barriers is carried out (Step 2), based on the tailoring of several models and approaches available in the literature. Finally, in Step 3 of the methodology the escalation frequency and probability values are evaluated according to a modified event tree analysis (Landucci et al., 2016a, 2015).

Definition of the Harsh Environment Score (step 1)

In order to systematically account for the external factors associated to environmental conditions, a harsh environment score (HES) is defined. HES is a score function of the features of the environment where the facility under analysis is located, and of site-specific information.

HES is primarily adopted as a reference metric to evaluate the severity of environmental conditions. The metric is then used to account for the influence of external factors on the availability and effectiveness of procedural and emergency measures according to the rules described in Section 2.3. Applying a conservative approach, the same metric is also adopted to identify whether or not environmental conditions are critical for hardware barriers (see Section 2.3).

More details on the definition of HES are reported elsewhere (Landucci et al., 2016b), hereby the main elements are summarized. HES is based on the identification of "stressors", which mostly affect the human performance when operations are carried out in harsh environment. A collection and taxonomy of generic stressors and performance shaping factors (PSF) is reported by Kim and Jung (Kim and Jung, 2003). Musharraf et al. (Musharraf et al., 2013) report a summary of the most relevant stressors associated with harsh environment, based on the outcomes of previous studies (Bercha et al., 2003; Bercha, 2006). These stressors are summarized in Table 1 and are taken as reference in the present study.

To each stressor, one or more external factors (EF) are associated. Each EF represents a climate or environmental condition, which can be measured or quantified for the site under analysis and has an impact associated to the correspondent stressor. On the basis of the EF value, a score is assigned. The score for the i-th EF (named S_i, ranging from 0 to 1) represents the relative distance from "favourable" environmental conditions, being 0 the indication of "good" conditions and "1" the worst case.

The ranges of the parameters aimed at determining the external factor penalties were derived from a literature survey focused on the effect of extreme temperatures (American Petroleum Institute, 2000), visibility (Holejko and Nowak, 1997), waves, and other adverse meteorological conditions (Bercha, 2006; PAFA Consulting Engineers, 2001) on plant operation performance. Landucci et al. (2016b) discuss in detail the procedure for the determination of the penalties, which are summarized in Table 1.

<table>
<tr><th>Stressor (Musharraf et al., 2013)</th><th>External factor</th><th>Range</th><th>Penalty</th></tr>
<tr><td rowspan="6">Coldness or warmth;
Ice for slippery
Difficulty in breathing</td><td rowspan="6">1) Environmental temperature</td><td>>45°C</td><td>0.4</td></tr>
<tr><td>4 – 45°C</td><td>0</td></tr>
<tr><td>-4 – 4°C</td><td>0.2</td></tr>
<tr><td>-10 – -4°C</td><td>0.6</td></tr>
<tr><td>-30 – -10°C</td><td>0.8</td></tr>
<tr><td>< -30°C</td><td>1</td></tr>
<tr><td rowspan="18">Combined weather effect</td><td rowspan="6">2) Extreme wind speed</td><td>0 – 3.3 m/s</td><td>0</td></tr>
<tr><td>3.3 – 5.5 m/s</td><td>0.2</td></tr>
<tr><td>5.5 – 8 m/s</td><td>0.4</td></tr>
<tr><td>8 – 10.8 m/s</td><td>0.6</td></tr>
<tr><td>10.8 – 13.9 m/s</td><td>0.8</td></tr>
<tr><td>>13.9 m/s</td><td>1</td></tr>
<tr><td rowspan="6">3) Waves height</td><td>< 0.1 m</td><td>0</td></tr>
<tr><td>0.1 – 0.5 m</td><td>0.2</td></tr>
<tr><td>0.5 – 1.25 m</td><td>0.4</td></tr>
<tr><td>1.25 – 2.5 m</td><td>0.6</td></tr>
<tr><td>2.5 – 4 m</td><td>0.8</td></tr>
<tr><td>>4 m</td><td>1</td></tr>
<tr><td rowspan="6">4) Snow (annual precipitation)</td><td>0 – 0.125 m</td><td>0</td></tr>
<tr><td>0.125 – 0.5 m</td><td>0.2</td></tr>
<tr><td>0.5 – 1 m</td><td>0.4</td></tr>
<tr><td>1 – 1.5 m</td><td>0.6</td></tr>
<tr><td>1.5 – 2 m</td><td>0.8</td></tr>
<tr><td>> 2 m</td><td>1</td></tr>
<tr><td rowspan="12">Low visibility</td><td rowspan="6">5) Fog (visibility)</td><td>< 50 m</td><td>1</td></tr>
<tr><td>50 – 200 m</td><td>0.8</td></tr>
<tr><td>200 - 500 m</td><td>0.6</td></tr>
<tr><td>500 – 1,000 m</td><td>0.4</td></tr>
<tr><td>1,000 – 2,000 m</td><td>0.2</td></tr>
<tr><td>> 2,000 m</td><td>0</td></tr>
<tr><td rowspan="6">6) Sunlight hours (for visibility)</td><td><1,200 h/y</td><td>1</td></tr>
<tr><td>1,200 – 1,600 h/y</td><td>0.8</td></tr>
<tr><td>1,600 – 2,000 h/y</td><td>0.6</td></tr>
<tr><td>2,000 – 2,400 h/y</td><td>0.4</td></tr>
<tr><td>2,400 – 3,000 h/y</td><td>0.2</td></tr>
<tr><td>>3,000 h/y</td><td>0</td></tr>
<tr><td rowspan="2">Remoteness</td><td rowspan="2">7) Distance from home, fear of unknown</td><td>Low</td><td>0</td></tr>
<tr><td>High</td><td>1</td></tr>
</table>

Table 1. Summary of the stressors, external factors and penalties defined for the evaluation of the Harsh Environment Score (HES). Adapted from (Landucci et al., 2016b).

A weight (w_i) is assigned to each score. Weights are specifically defined by the assessors, also on the basis of interviews to workers and managers of the Company operating the facility. Such consultation is aimed at determining the importance of the considered EF and, in turn, of the correspondent stressor. Single stressor values are used to evaluate the HES, which is defined as weighted sum of the N assigned scores:

$$HES=\sum_{i=1}^{N} w_i S_i \qquad (1)$$

The choice of adopting the weighted summation is in line with the multi-criteria analysis (Goodwin and Wright, 1998), in which a set of decision variables (e.g., the scores in this case) are combined through weighted summation in order to establish their relative importance. The "importance" is representative of the view of decision makers and, in this particular case, reflects the outcomes of the Company decision. An example of weighting is discussed in Section 3 for the analysis of a specific case study.

Performance data of safety barriers for facilities operating in harsh environments (step 2)

The availability and effectiveness for emergency teams' response and hardware barriers are estimated on the basis of the HES parameter; more details are reported in a previous study (Landucci et al., 2016b).

In order to evaluate the decrement in the availability (e.g., increment of PFD) of emergency response in the presence of harsh environmental conditions, the framework proposed in the SLIM (Success Likelihood Index Methodology) method is adopted (Rosa et al., 1985). In particular, the HES score defined in Section 2.2 is assumed as a simplified and straightforward ranking of the stressors affecting the emergency response in harsh environment. The higher the HSE value, associated with the considered location under analysis, the lower the likelihood of success for the emergency response task, obtaining the following simplified PFD expression:

$$\log_{10}(\mathrm{PFD})=a\times\left(1-\mathrm{HES}\right)+b \qquad (2)$$

where a = -0.954 and b = -0.046. The numerical values of "a" and "b" are determined assuming reference PFD associated with two given values of HES. In particular, in the case of favourable environmental conditions (e.g., HES = 0), PFD = 0.1, which is the value adopted for standard emergency team intervention in a previous work (Landucci et al., 2015); in the case of worst environmental conditions (e.g., maximum penalty HES = 1), PFD = 0.9, which is the value conservatively assumed as maximum human error probability, according to (Musharraf et al., 2013).

The effectiveness of emergency measures was evaluated following the approach proposed by Landucci et al. (2015), in which a time scale for emergency intervention is defined for onshore plants and adopted as a possible metric for effectiveness. The time scale was based on the different actions required to perform the fire mitigation (alerting, deploying on-site measures, provide required amount of water, etc.), which contribute to the evaluation of the time for final mitigation (TFM). In the present study, simplified rules to assess the expected delay in the emergency response time are defined in Figure 1.

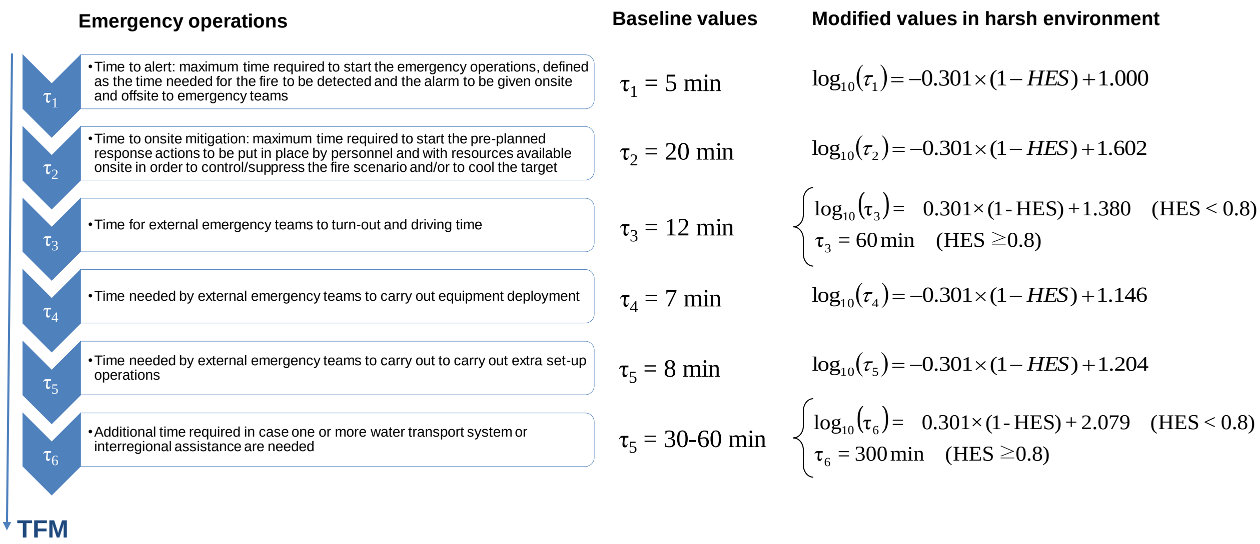


Figure 1. Definition of time scale for emergency operations and simplified relationship for the estimation of time increment due to harsh environmental conditions for onshore plants. Adapted from (Landucci et al., 2016b). TFM is obtained as the sum of each time contribution τ_i.

Each operation involved in the emergency response is associated with a characteristic time (τ), which baseline values (e.g., for "normal" environments) were gathered from a previous study (Landucci et al., 2015) and are shown in Figure 1. Then, in order to account for the delaying effect of harsh environment on emergency response, the following relationship is adopted:

$$\log_{10}(\tau)=c\times(1\text{-HES})+d \tag{3}$$

A logarithmic relationship was adopted to scale the intervention time as a function of environmental conditions in Eq. (3) in order to introduce an increase in the response time even for a limited worsening of environmental conditions (represented by the HES score). The logarithmic relation also allows considering that when higher values of HES are associated to a facility, the change in the response time levels out, due to logistic delays, unavailability of firefighting water resources, operator's difficulties in performing the tasks, etc. (Shelley et al., 2007). The coefficients "c" and "d" in Eq. (3) (see Figure 1) were tuned considering that the time for each operation in harsh environmental conditions is doubled with respect to normal environment, according to fire brigade statistics published for cold weather areas of North America (Flynn, 2009; U.S. Fire Administration, 2006). For both the time needed to reach the location (τ_3 in Figure 1) and the time needed for the deployment of additional water supply (τ_6 in Figure 1), constant values five times higher than the baseline values are conservatively assumed for HES>0.8 (e.g., τ_3 = 60 min and τ_6 = 300 min), based on the consideration that in the case of a high HES value, remoteness and high difficulties in reaching the area under analysis may be assumed, such to impair the external emergency response.

After the estimation of the time scale for the emergency, in order to establish the value of effectiveness η, the TFM value is compared against the time which the target equipment may withstand before losing its integrity due to the heat-up induced by fire (namely, the time to failure, TTF):

- if the emergency response is activated but TFM results higher than TTF, the emergency team actions come too late to prevent escalation and a mitigated escalation scenario occurs (η=0)
- if the emergency response is activated and TFM is lower than TTF, the mitigation action is successful and the fire escalation is prevented (η=1).

Next, the effect of harsh environment is also evaluated on hardware barriers (both active and passive). In this work, it is assumed that extreme environmental conditions may seriously affect the availability characteristics of the components (Gao et al., 2010; Li et al., 2015), but effectiveness is not influenced (in other words, once a barrier is either activated or is in place starting to perform its protective action, then the effectiveness is not altered by harsh environmental conditions).

In order to determine whether or not the environmental conditions may affect hardware performance, it is assumed that cold weather problems are directly related only to the environmental temperature, following the considerations reported in API standard 581 (American Petroleum Institute, 2000). The environmental temperature is penalized in HES estimation with a specific penalty ("external temperature" factor in Table 1), indicated as "S_1" in the following. Therefore, in order to determine whether environmental conditions might have or not an effect on the availability of hardware protections, a threshold limit was adopted for S_1. In particular, for $S_1 \leq 0.6$, it is assumed that no relevant modification affects the performance of components, thus the baseline performance data may be adopted (Landucci et al., 2015); while for S_1>0.6 the depletion of availability due to harsh environment is accounted by a specific approach.

The approach is based on the work of Gao et al. (Gao et al., 2010), which applied the "proportional hazard model" introduced by Cox (Cox, 1972) in order to modify reliability data in Artic environment. Figure 2 summarizes the procedure for the determination of hardware barriers PFD.

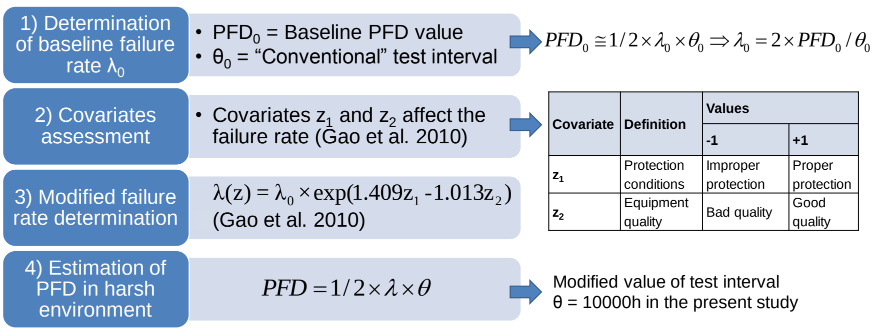


Figure 2. Approach for the modification of availability of hardware protection systems operating in harsh environment.

Evaluation of escalation probability and frequency (step 3)

The availability and effectiveness values obtained for emergency measures and the modified availability values for hardware barriers are then used to quantify the specific gates introduced in a modified event tree analysis proposed by Landucci et al. (2015). The gates associated with different types of protection barriers are summarized in Table 2.

Section 3 discusses the data used to quantify the event trees, both considering normal or harsh environmental conditions. In order to apply the "fragility gate" (see Table 2), in which the probability of failure of the equipment (P_d) is computed based on a given fire condition and on the possible mitigation due to one or more safety barriers, fragility models based on probit models (Landucci et al., 2013, 2009) may be used. Table 3 summarizes the probit correlation, input data needed and the procedure for the calculation of failure probability. In the original formulation of the method, probit coefficients were derived assuming a log-normal distribution of failure probability, associating 90% probability of failure for TTF value equal to the time required to start the emergency operations onsite (which is considered equal to the time to alert, see Figure 1), and a 10% probability of failure for TTF equal to the time to start the mitigation actions (e.g., the time for onsite mitigation, see Figure 1). Keeping the same assumptions, probit coefficients may be modified on the basis of the delayed response times in harsh environment, applying the rules described in Table 3.

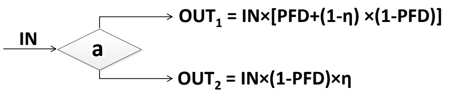
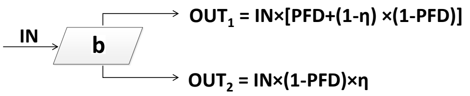
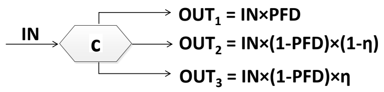
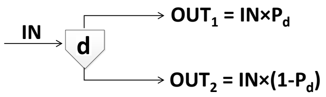
Gate type	**Graphical representation**	**Description**
a		Simple composite probability: availability, expressed as the probability of failure on demand, is multiplied by a single probability value expressing the probability of barrier success in the prevention of the escalation
b		Composite probability distribution (gate type “b”): availability, expressed as the probability of failure on demand, is multiplied by a probability distribution expressing the probability of barrier success in the prevention of escalation, thus obtaining a composite probability of barrier failure on demand
c		Discrete probability distribution (gate type “c”): depending on barrier effectiveness, three or more events may originate from the gate describing barrier performance
d		Vessel fragility gate: based on the status of the target equipment (e.g., received heat load, status of protections etc.), the failure probabily is computed through equipment vulnerabiltiy models based on probit functions (see Table 3)

Table 2. Definition of gate types and associated operators for the event tree analysis of mitigated fired domino events. PFD: probability of failure on demand; η: effectiveness; P_d: equipment failure probability computed trough fragility models (see Table 3).

Item	Definition	Value/Equation
Y	Probit value obtained through the fragility modela	$Y = k_1 \times \ln(TTF) + k_2$
k_1	First probit coefficient	$k_1 = [3.718\ln(\tau_1) - 6.283\ln(\tau_2)]/[\ln(\tau_1) - \ln(\tau_2)]$
k_2	Second probit coefficient	$k_2 = 2.565/[\ln(\tau_1) - \ln(\tau_2)]$
τ_1	Time to alert	See Figure 1
τ_2	Time to onsite mitigation	See Figure 1
TTF	Time to failure of unprotected tank (min)	Simplified correlation for pressurized vessels (Landucci et al., 2009): $\mathrm{TTF} = 2.783\times10^4 \times \exp\left(8.845V^{0.032} - 0.95\ln(Q_{HL})\right)$
		Simplified correlation for atmospheric vessels (Landucci et al., 2009): $\mathrm{TTF} = 2.783\times10^4 \times \exp\left(\ 2.67\times10^5 V - 1.13\ln(Q_{HL}) + 9.877\right)$
Q_{HL}	Heat load due to the fire (kW/m²)	Q_{HL} is evaluated considering that active protections may mitigate the fire and/or shield the target (Landucci et al., 2015).
V	Vessel volume in m³	-

Table 3. Fragility models and input parameters for the calculation of failure probability of pressurized and atmospheric tanks due to fire exposure. Probit is converted into probability according to the procedure shown in (Lees, 1996).

Definition of the case study

In order to exemplify the methodology, a case study is analysed. The layout of the case study is reported in Figure 3. A storage area of a hypothetical onshore Oil&Gas facility was selected. As shown in Figure 3, the storage area features a large atmospheric crude oil tank (V2) and a pressurized vessel (V1); the features of both tanks are summarized in Table 4.

The jet fire following a 4” rupture in tank V1 is considered as primary event affecting the target tank V2. The event frequency is equal to 1×10^{-5} 1/y, assuming the failure frequency derived from API 581 (American Petroleum Institute, 2000) for a 4” leak in a generic pressurized vessel and 100% ignition probability. Conventional integral models were adopted in order to perform the consequence assessment of the jet fire (Lees, 1996), obtaining a maximum value of heat radiation Q_{HL} = 21 kW/m² on the surface of the target tank V2. Several safety barriers are in place in order to protect V2 against potential fire escalation. The barriers and their performance assessment are discussed in Section 4.1.

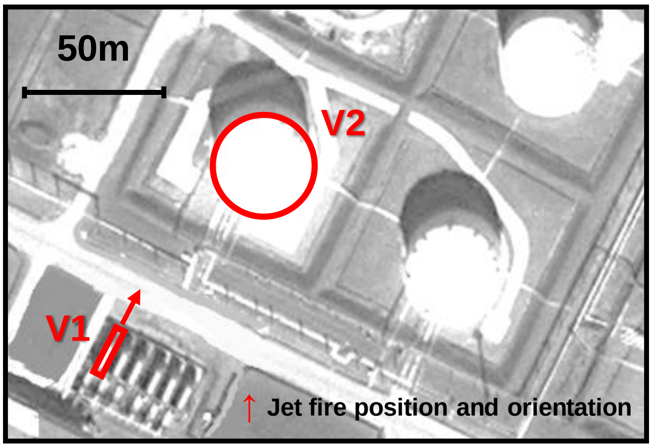


Figure 3. Layout considered for the case study; the features of the vessels are summarized in Table 4.

Vessel	Type	Substance	Inventory (t)	Diameter (m)	Length/height (m)	Design pressure (barg)
V1	Pressurized	Propane	50	3	18	19
V2	Atmospheric	Crude oil	4600	36	5.4	0.02

Table 4. Main features of the vessels considered in the case study.

External factor	Value for the considered location	Weight w_i	Score S_i
1) Environmental temperature	Average temperature -15°C (low temperature peaks <-35°C)	0.25	0.8
2) Extreme wind speed	Typical conditions feature wind speed greater than 13.9 m/s	0.25	1
3) Waves height	Not relevant (onshore plant)	0	-
4) Snow	1.7 m/y annual average	0.15	0.8
5) Fog effects	80 m visibility when relevant fog effects are present	0.15	0.8
6) Sunlight hours	1,200-1,600 h /y	0.15	0.8
7) Distance from home; Fear of unknown	Location is not remote	0	0

Table 5. Characterization of the environmental conditions considered for the case study: summary of external factors, scores and weights adopted for the calculation of HES. Scores are assigned on the basis of the rules reported in Table 1.

In order to exemplify the methodology and to obtain conservative estimations, the onshore plant is assumed as an old facility, with low quality equipment and protection devices (hence, the covariates shown in Figure 2 are set to the minimum values). The facility was assumed to be located in a Sub-Arctic region, featuring low temperatures and severe wind conditions. Table 5 summarizes the meteorological data in order to provide an example of the level of detail needed to apply the present methodology. Data were gathered from the meteorological database of US weather service and are adopted for the calculation of HES. Table 5 shows also the weighs adopted for the present study, which were based on the indications reported in a previous study (Landucci et al., 2016b).

The methodology described in Section 2 is adopted in order to evaluate the escalation frequency in presence of safety barriers, accounting for the effect of harsh environment. A cut-off value of 1×10^{-10} 1/y is assumed for the frequency in order to exclude the less credible escalation scenarios. For the sake of comparison, the results obtained in normal environment (i.e., following the methodology proposed by (Landucci et al., 2015)) and in the absence of safety barriers (i.e., according to the procedure by (Landucci et al., 2009)) are also reported and discussed in Section 4.2.

Results and discussion

Performance assessment of safety barriers in harsh environment

In order to assess the performance data of the safety barriers, the preliminary step of the procedure presented in Section 2 addresses the characterization of the environmental conditions through the calculation of the HES scores. The scores and weights reported in Table 5 are adopted in order to apply Eq. (1). A HES value of 0.85 is obtained for the site considered for the case-study. The HES score is then adopted in order to update the barriers performance data as summarized in Table 6.

The availability of emergency measures is evaluated applying the procedure summarized in Section 2.3 obtaining a PFD value more than six times higher than the baseline value. This reflects the relevant influence of harsh environment on human factors, documented in several previous studies (Musharraf et al., 2013).

In order to determine the efficiency of emergency and procedural measures, on the basis of vessel geometry and fire scenario features, the necessary amount of water is determined by the procedure proposed in (Landucci et al., 2015). Additional external water resources are needed in the case-study, leading to TFM = 80 min in normal environmental conditions. The time-scale of emergency is then delayed as a function of HES, according to the rules summarized in Figure 1, obtaining TFM = 300 min, which is the ceiling value due to the HES value exceeding the threshold limit of 0.8 (see Figure 1). Either in normal or harsh environment the evaluated TFM is much higher than the TTF of the target equipment. In fact, applying the simplified correlation reported in Table 3, TTF = 9 min for V2 exposed to the considered fire scenario, therefore the emergency team intervention is not able to exclude the escalation (e.g., η=0), but only provides a mitigation effect, with possible attenuation of secondary effects.

For what concerns active and passive barriers, the relationships summarized in Figure 2 are applied to calculate the modified PFDs reported in Table 6, while no relevant change in the effectiveness is assumed (see Section 2). As shown in Table 6, a relevant decrement of components availability is obtained, with a difference of one order of magnitude among performance in normal and in harsh environmental conditions. It is worth to mention that such figures were obtained assuming worst-case values of the covariates affecting the failure rate in harsh environment (e.g., z_1 = z_2 = -1 in the procedure schematized in Figure 2). The identification of critical elements affecting the protection performance may lead to select adequate equipment and protections in order to improve the performance in harsh environmental conditions.

Safety barrier	Gate type (Table 2)	PFD		Effectiveness	
		Normal environment (HES = 0)	**Harsh environment (HES = 0.85)**	**Normal environment (HES = 0)**	**Harsh environment (HES = 0.85)**
Pressure Safety Valve (PSV)	a	1.00×10^{-2}	1.29×10^{-1}	1	1
Foam-water sprinkler system	b	5.43×10^{-3}	6.98×10^{-2}	0.954	0.954
External emergency intervention	c	1.00×10^{-1}	6.50×10^{-1}	0	0

Table 6. Summary of the data adopted for the quantification of the event trees for the analysis of the case studies. Data for normal environment (HES = 0) were collected from (Landucci et al., 2015). Data for HES = 0.85 were modified according to the rules summarized in Section 2.

Probabilistic assessment of cascading events

On the basis of the frequency and consequence assessment of the primary scenario considered in the case study, e.g. the jet fire from tank V1 affecting tank V2, the application of event tree analysis (ETA) described in Section 2.4 is carried out. ETA performed for harsh environment (HES = 0.85) is shown in Figure 4; a similar ETA structure is obtained for normal environment conditions (HES = 0) and is not reported for the sake of brevity.

ETA allows determining the secondary final outcomes and quantifying their probabilities and frequencies (see an example of detailed results in Figure 4). Figure 5 summarizes the overall results obtained in the analysis of the case study, either considering harsh and normal environment. Moreover, for the sake of comparison, the probability and frequency obtained neglecting the presence of safety barriers following the approach suggested in (Landucci et al., 2009) are reported (data labelled with “no safety barriers” in Figure 5).

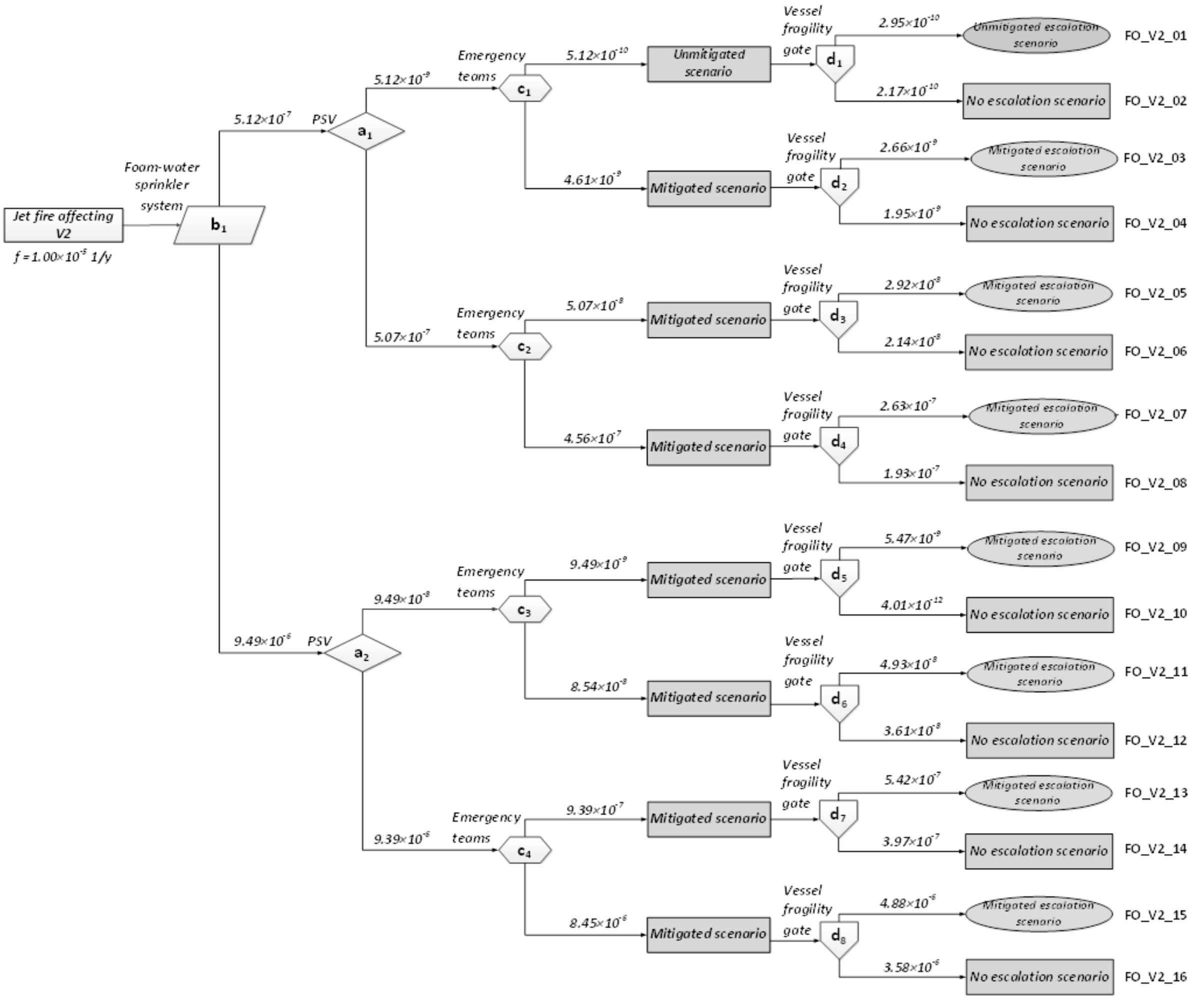


Figure 4. Event tree analysis carried out for the atmospheric vessel V2 considered as target equipment for the case study assuming harsh environmental conditions. Each branch of the event tree is quantified according to the rules summarized in Table 2, adopting the quantitative data summarized in Table 6 for HES=0.85. Frequencies are reported in 1/y.

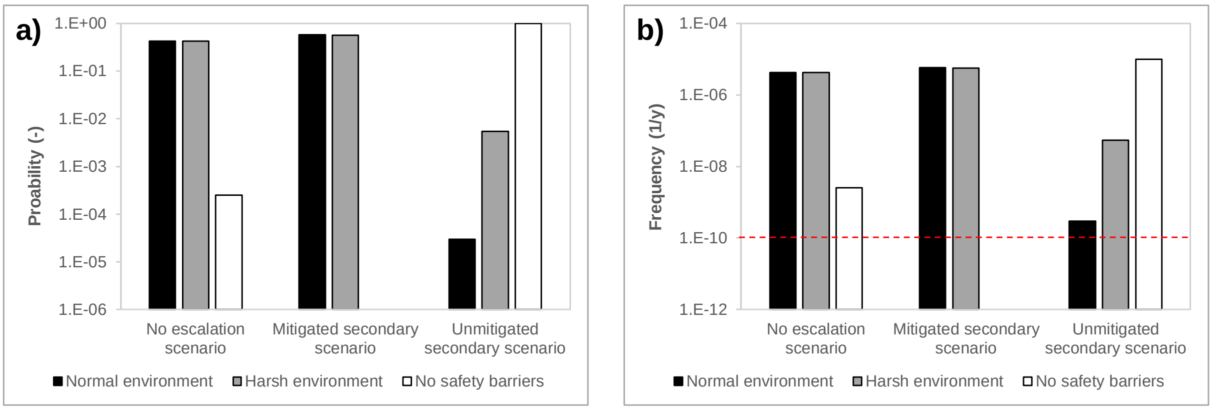


Figure 5. Summary the results of obtained for the considered case study: a) probability and b) frequency of secondary scenarios. Dashed line in panel b represents the cut-off value for the frequency considered in the present study (1×10^{-10} 1/y).

As shown in Figure 5, the analysis allows determining the possible occurrence of three different types of scenarios, all caused by the escalation of a primary fire event affecting a target process unit: i) unmitigated secondary scenario, which represents a domino scenario without the effective activation of the safety barriers in place; ii) no escalation scenario, in which the escalation is avoided, breaking the domino chain; iii) mitigated secondary scenario, in which the secondary scenario caused by escalation may be mitigated by the partial or ineffective activation of one or more barriers, leading to potentially attenuated consequences following target vessel rupture. Clearly enough, even in case absence or partial mitigation, the target vessel may resist to the fire conditions with no safety-relevant consequences. Hence, in such cases, the escalation is excluded as well.

The results obtained in absence of safety barriers, show that the escalation probability approaches 1 for all the cases considered, thus resulting in escalation frequencies comparable with those of the primary scenarios. When barriers are considered in the assessment, the unmitigated domino scenario becomes the less credible, ether in normal or harsh environment. Due to the relevant discrepancy among TFM and TTF (see Section 4.1) none of the safety barriers considered is able to suppress the domino chain, but the mitigation provided by emergency team may significantly reduce the severity of domino scenarios. In the case of harsh environment, the performance deterioration of the procedural and hardware barriers leads to a relevant increment of the frequency of the unmitigated escalation scenario, which increases by two orders of magnitude with respect to the previous case. Hence, both the frequencies of unmitigated and mitigated domino scenarios are increased with respect to those calculated in normal environmental conditions.

Discussion

The analysis of the present case study evidenced the potentialities of the present method in providing probabilistic input data aimed at supporting quantitative risk assessment (QRA) studies. In fact, the probability and frequency results shown in Section 4.2 may be implemented in QRA frameworks (Landucci et al., 2017), in order to obtain a more detailed risk assessment of escalation leading to domino effect in presence of harsh environmental conditions.

Moreover, the identification of criticalities in the barriers performance which emerges from the present analysis (see Section 4.1), possibly due to the poor selection of equipment, insufficient shielding against adverse climate conditions, poor maintenance and inspection, may be addressed in order to drive the design of equipment or procedure modification for facilities operating in harsh environment.

Relevant uncertainties may affect the input data needed to apply the present methodology, that is necessarily based on conservative and somewhat oversimplifying assumptions, which may be useful for a preliminary assessment of the influence of harsh environmental conditions on the site of interest. Availability and effectiveness determined from specific data gathered from on-field experience may be used if available, obtaining improved frequency and probability estimates. The growing experience of operation in Artic or Sub-Artic regions (Barabadi et al., 2015) may be the premise to provide more specific data to improve the present methodology.

Conclusions

The present study is aimed at the development of a structured approach to the quantitative assessment of cascading events, accounting for the influence of harsh environmental conditions on the safety barriers performance. A specific metric is defined, aimed at assessing the influence of harsh environmental conditions on both hardware barriers and emergency response and determining the frequency of escalation scenarios. The outcomes of the present analysis may drive the improvement in the design and operation of hardware safety devices, in order to limit the likelihood of critical escalation scenarios. The analysis also highlights the need of effective emergency training and response in order to improve the risk profile of industrial facilities operating in harsh environment.

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