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Reducing the Consequences of Accidental Fires in Oil & Gas Facilities: a Risk-Based Procedure for Identification of the Fireproofing Zones

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Accidental fires in Oil&Gas facilities have a significant potential for severe consequences, endangering personnel safety, environment, asset integrity, production continuity and company reputation. Moreover, in-plant accident propagation (domino effects) may further increase the outcomes of fires. Fireproofing is a crucial safety barrier in preventing the escalation of fire scenarios. Maintenance and cost considerations require the application of such protection only where an actual risk of severe fire scenarios is present. Available methodologies for the identification of fireproofing zones in on-shore installations are based on simplified assumptions and do not consider the effect of jet-fire scenarios. Experience has tragically shown though the importance of including such scenarios (e.g. Valero accident in 2007).
In the present study, a risk-based methodology for the identification of fireproofing zones was developed. The procedure addresses both the prevention of domino effect and the mitigation of asset damage due to the primary fire scenario (pool and jet fires), taking into account the specific issues of on-shore applications. Specific criteria were introduced to assess escalation hazard. A risk-based identification of the reference accident scenarios was developed, allowing a more detailed definition of the plant items that should be considered for fireproofing application. The method is mainly oriented to early design application, allowing the identification of fireproofing zones in the initial lay-out definition. The potential outcomes of the methodology are investigated by applying them to case-studies of industrial interest.

1. Introduction

Several past accidents in Oil&Gas facilities involved the escalation of initially moderate fires into extremely severe accidents. In particular, fire may trigger the catastrophic failure of process equipment (as in the Mexico City accident in 1984 (Mannan, 2005)) or of support structures (as in the Valero accident in 2007 (US-CSB, 2008)), leading to domino propagation phenomena with severe tolls in terms of human life, asset value and company reputation. Active and passive protections are usually provided to prevent or mitigate such events. Among passive protections, fireproofing is widely applied. Fireproofing delays the temperature rise of structural elements exposed to fire (CCPS, 2003), providing additional time for the implementation of effective mitigation measures (firefighting, depressurization, etc.).
Although fireproofing is an effective safety barrier, it may delay the detection of corrosion or of leaks and it may require costly maintenance operations. The integrity of fireproofing is a key issue and loss of water-tight integrity has been found to generate problems of accelerated corrosion on ageing installations (CCPS, 2003). Even if several strategies may be adopted to manage and mitigate this problem (UKOOA, 2007), this may be seen as a major drawback. Thus, fireproofing installation should be considered only where actual hazard of fire escalation or fire damage is present. In on-shore plants, alternatives to passive fire protection are possible in particular when the design of new plants is considered (e.g. inherent safety,

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spacing, active protection measures, etc. (Khan and Amyotte, 2003; Mannan, 2005; Tugnoli et al., 2008)). A detailed analysis is advisable, therefore, to correctly identify the best solution for fire protection and the actual need for passive fire protection. Specific technical standards report criteria for the application of fireproofing in onshore chemical and process plants (API, 1999, 2001). Nevertheless, the possible damage due to jet-fires is usually neglected and deterministic approaches are used for the assessment of fire damage potential. Moreover, existing standards do not address the protection from fire escalation hazard caused by the failure of structural elements of process equipment (e.g. vessel shells).
The present paper reports the results obtained in the further development and extension of an innovative methodology for the identification of fireproofing zones that takes into account the specific issues of on-shore application. The study, carried out in a more general framework aimed at the development of risk-based criteria for fireproofing application in on-shore facilities (Di Padova et al., 2011; Tugnoli et al., 2012), addressed the specific issue of the mitigation of escalation potential of pool and jet fires. Specific criteria were introduced to assess escalation hazard as well. The risk-based procedures allows for the identification of the plant items that should be considered for fireproofing application in on-shore facilities. The potential outcomes of the methodology were investigated by the application of a case-study.

2. The proposed methodology

The goal of the proposed methodology is the identification of the zones where the application of fireproofing is critical for safety due to the high risks related to equipment damage and possible domino propagation. The methodology is applicable to on-shore plant processing flammable materials. Typical input data include information on process and equipment, as well as on lay-out and already present safety barriers (catch basins, emergency shut-down systems, etc.). The procedure consists of eight steps:

1) Definition of the criteria for structural damage
2) Collection of input data and identification of targets
3) Identification of isolable sections
4) Identification of relevant loss of containment events and final outcomes
5) Consequence assessment
6) Definition of the frequencies of final scenarios
7) Selection of reference LOCs
8) Identification of the fireproofing zones

The first three steps should be applied simultaneously to the entire installation considered, while the following steps should be recursively applied to each of the isolable sections defined in step 3.
In step 1 the categories of targets of concern in the fireproofing design are identified and the damage criteria is characterized. In particular three categories of potential targets (support structures, atmospheric equipment, pressure vessels) were considered in the current study. The damage from fire is usually dependent on two criteria: radiation threshold and minimum duration of the reference fire scenario. A detailed assessment of the potential for damage during a fire scenario would require the complex modelling of steel wall temperature and induced stress transients (see e.g. Gomez-Mares et al. (2012a,b), Heidarpour and Bradford (2009), Landucci et al. (2009), Lien et al. (2010)). Computational resources and data needed to carry out such an assessment are not affordable if the design of a complex and extended installation is considered. Thus, simplified criteria need to be applied for radiation damage. Table 1 proposes criteria for the identification of four main damage zones. Further details on threshold definition can be found elsewhere (Cozzani et al. 2009).
In the second step, relevant input data is collected. In particular, the sensitive escalation targets (SET) are identified as the items that, if damaged by the primary fire, may cause an escalation of the event.
In step 3 of the methodology “isolable sections” (IS) are identified. These are defined as sections that may be completely isolated at shut-down (e.g. by emergency shut-down valves, by check valves, etc.). Only isolable sections where flammable substances are present should be further considered in steps 4 to 8.
One or more than one “reference stream” (RS) is defined for each IS in step 4. A RS identifies the phase, the composition and the operating conditions (temperature and pressure) of any release stream that may be caused by a loss of containment (LOC) in the unit. All possible loss of containment (LOC) events involving flammable RS should be then identified. The release categories suggested by API 581 standard (API, 2000) were applied in the present study, but alternative approaches may be adopted as well. Several alternative final outcomes (FOs) may follow a LOC event, depending on safety barriers present, release features and presence of ignition sources. Event trees should be defined for each LOC event. In the present framework, only pool fires and jet fires are considered relevant FOs.
In step 5 the consequences of the relevant FOs identified in step 4 should be assessed. Validated consequence analysis models should be used for this purpose (e.g. Mannan (2005), Van Den Bosch and

Weterings, (2005)). The total amount of flammable substances that may be released (also considering the time of activation of emergency responses) should be accounted. For each of the four damage categories listed in Table 1 the maximum damage distances in the horizontal and vertical direction (worst case scenarios) are calculated.

In step 6 the expected frequency of the relevant FOs should be estimated. The assessment of LOC frequency and the quantified analysis of the post-release event tree defined in step 4 allows for the estimation of the expected frequency of the unmitigated FOs. Examples of the procedure are provided by Di Padova et al. (2011).

In step 7 the reference LOCs should be identified by a simplified risk-based procedure. The severity classification is based on a preliminary analysis of the consequences of the final non-mitigated scenarios present in the event tree. The worst-case damage distance calculated in step 5 is used to identify the potential damage area for each relevant FO that is defined, adding the damage distance to the more remote release point for the isolable section of interest. The items (units, buildings, structures, etc.) present within this area are then considered. Figure 1 reports an example of severity ranks. Damage severity should be assessed, accounting for both: i) the direct damage from the primary fire scenario; and ii) the damage from escalation consequences, which should be assessed if the damage of a SET is possible in the fire damage area. When considering primary fire damage, the worst possible consequence among the target categories (people, environment, assets) from the non-mitigated scenarios is considered. The reference LOC events are screened for severity and frequency using the matrix reported in Figure 1. The LOC events belonging to the zones where “risk reducing measures are needed” or where the risk is “not acceptable” should be considered as the reference LOCs. The LOC events that fall in the “acceptable” zone are not further considered. If more than one LOC for the same IS and RS falls into the same frequency class, only the one having the higher severity class should be retained for further assessment.

In step 8, the envelopes corresponding to the four damage categories calculated for the reference LOCs are plotted and used to identify the zones where fireproofing should be considered for application.

	Severity score				
	1	2	3	4	5
People (P)	Minor injuries; reversible effects on health requiring offsite treatment	Serious / potentially irreversible health effects, hospitalization	Fatalities / permanent disability of few people in the plant	Fatalities or permanent disability of people inside the plant	Fatalities or permanent disability of people outside the plant
Environment (E)	Temporary local impact / few species affected. Concern of local stakeholders	Natural recovery: 1-2 years. Clean-up: 1 week. Some species threatened / protected natural areas affected	Natural recovery: 2-5 years. Clean-up:<5months Impact on areas of scientific interest. Concern of national stakeholders.	Natural recovery: > 5 years. Clean-up:>5months Impact on special conservation areas. Concern of international stakeholders.	Higher impact than the other levels.
Asset (A)	Production downtime < 1 day.	Downtime < 1 week. The unit must be repaired/replaced	Downtime < 3 months. Major change required / major inquiry for costs	Downtime>3months Total loss of operations / revamping necessary.	Permanent loss of the operation / business at site.
Frequency					
$f < 10^{-6}\ y^{-1}$	**ACCEPTABLE (AC)**				
$10^{-6} < f < 10^{-5}\ y^{-1}$			**RISK REDUCING MEASURES NEEDED (RR)**		
$10^{-5} < f < 10^{-4}\ y^{-1}$					
$10^{-4} < f < 10^{-3}\ y^{-1}$				**NOT**	
$f > 10^{-3}\ y^{-1}$				**ACCEPTABLE (NA)**	

Figure 1: Risk matrix used for the assessment of the case-studies and definition of severity scores.

Table 1: Threshold criteria for the identification of the zones for fireproofing application. Adapted from API (1999), CCPS (2003), Cozzani et al. (2009).

Fireproofing zone code	Target type	Scenario	Heat flux threshold (kW/m^2)	Minimum reference time (min)
S1	Structural element	Flame impingement or engulfment	Impingement/engulfment	3
S2	Structural element	Radiative heat flux	12.5	10
AV	Atmospheric vessel	Radiative heat flux	15	10
PV	Pressurized vessel	Radiative heat flux	60	10

3. Application to a case study

The proposed methodology is demonstrated by the application to a section of an on-shore oil treatment facility (Figure 2-a). The analyzed section includes process equipment (columns, compressors, etc.) as well as storage units (e.g. crude tanks).

Table 1 reports the classification of fireproofing zones adopted in the case-study (step 1). Sensitive escalation targets (SET) were identified in the plant (step 2). The analysis of the process flow diagram lead to the identification of 13 isolable sections, delimited by ESD valves and check valves (step 3).

For each isolable section the LOC categories and equivalent release diameters were identified. The classification was derived from API Standard 581 (API, 2000). Reference streams were identified for each LOC. The event tree analysis (step 4) evidenced that continuous release of flammable gases can lead to jet-fires, while the flashing stream from liquid or two-phase releases can yield both pool and jet fires. These final outcomes (FO) were evaluated in the consequence analysis. The Phast software package by DNV was used to calculate the duration of the release and the maximum direct damage distances of pool and jet fires based on the threshold values in Table 1. The presence of mitigative measures (fire & gas detection system, emergency shut-down system, etc.) was considered in the calculation of duration.

The expected frequencies of the relevant FOs were estimated by fault tree analysis (step 6). In the study, the baseline frequencies were derived from API 581 (API, 2000), the conditional probabilities of ignition from Purple Book (Uijt de Haag and Ale , 2005) and the probabilities of failure on demand for the mitigation barriers from SIL assessment considerations.

The risk matrix reported in Figure 1 was applied to rank the risk associated to each FO and to identify reference LOC events (Step 7). The severity class of the consequences was identified considering the targets present within the area affected by the worst fire scenario. If a SET falls inside the damage area of the FO considered, the higher score between primary fire and secondary escalation was considered.

The envelope of the relevant maximum distances defines the fireproofing zones for each target class. Figures from 2-b to 2-d show the footprint of the fireproofing zones for the section considered in the case-study. The damage distances reported in the figure are clearly dependent on the thresholds defined in Table 1. However, consequence analysis models (Van Den Bosch and Weterings, 2005) clearly evidence that the thermal radiating flux decreases quickly with distance for the considered fire scenarios. Thus, the uncertainty in damage distances may be limited if a reasonable range for the damage threshold values is considered. This is clearly evident if Figures 2-(b) and 2-(c) are compared: quite similar damage distances are obtained in these figures for S2 and AV damage categories (10 and 12.5 kW/m^2).

In regards to the potential for domino propagation, it was recognized that two elements are necessary in order to have a relevant accident escalation (Cozzani et al., 2005): (i) the primary accident should trigger a secondary accident scenario; (ii) the severity of the resulting scenario (primary + secondary) should exceed that of the primary fire. Clearly enough, not all the SETs may actually cause a relevant escalation. The Unit Potential Index (UPI) was used in previous studies to qualify the damage potential of a unit (Landucci et al., 2008). Table 2 shows a comparison among the UPIs calculated considering only the primary stationary fire scenarios from the selected reference LOCs (jet fires and pool fires), and the classical UPIs for all the worst-case secondary fire scenarios generated by target units. As shown in the table, differences up to a few orders of magnitude may exist. However, the UPI approach only considers the extension of the potential damage area due to primary or secondary scenarios alone. The simplified severity assessment based on Figure 1 also considers the vulnerability of the area affected, accounting for the actual presence of persons, relevant assets and vulnerable equipment items. A comparison with the UPI results (Table 2) shows that the potential for escalation is mostly recognized for the same targets. In fact, when the presence of SETs is roughly uniform in the plant, as in the case-study considered, accounting for actual damage does not lead to a shift in the results obtained by only considering the extension of the damage areas. Nevertheless, in a few cases, as for example the escalation from the oil storage tank (IS-25) to the diesel storage tank (IS-20), the two approaches may not be equivalent. In fact, UPI simply accounts for the different extensions of the pool fire scenarios, while the severity score recognizes that a significant part of the area affected by the fire falls inside the catch basin of the tank, where a very limited number of possible targets are located. The larger damage area in this case is not proportional to a higher severity. Therefore, even if the UPI approach still yields acceptable results in the current case-study, the risk-based criteria developed in the present contribution are more suitable to capture and control the actual escalation hazard due to stationary fires.

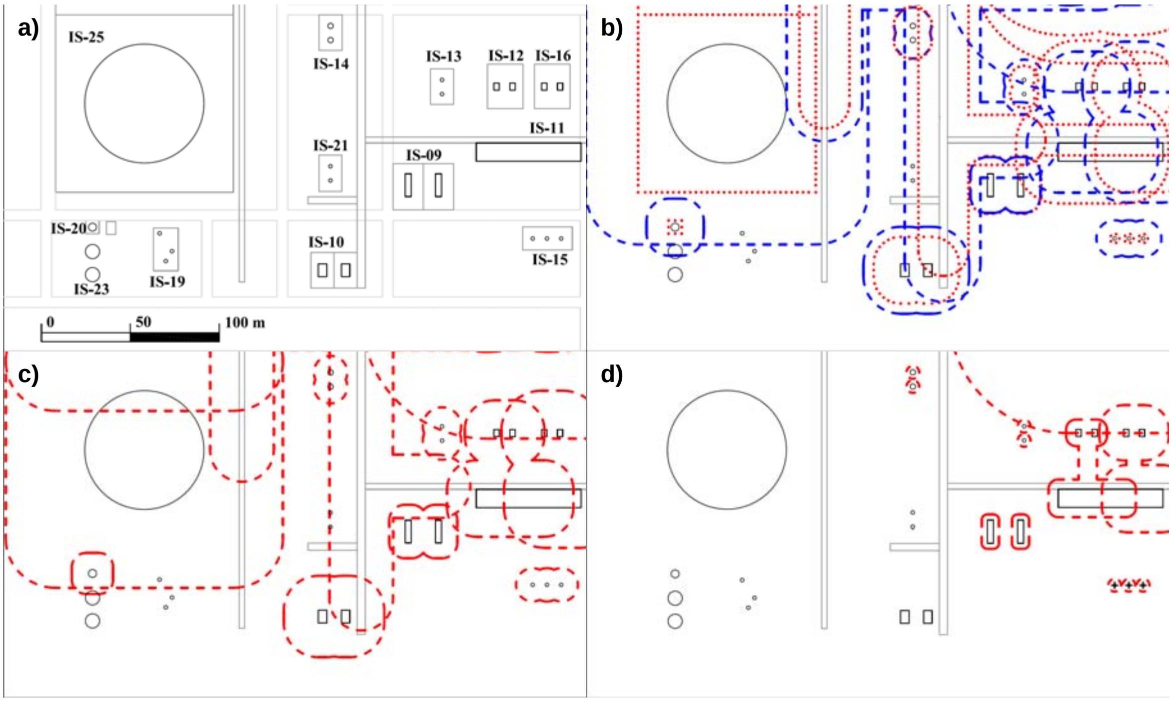

Figure 2: Layout considered in the case-study and footprint of the fireproofing zones according to the criteria of Table 1. Panel a) layout and location of isolable sections. Panel b) fireproofing zones for structural elements; red (internal) area: impingement zone (S1); blue (outer) area: radiative heat zone (S2). Panel c) fireproofing zone for atmospheric vessel targets (AV). Panel d) fireproofing zone for pressurized vessel targets (PV).

Table 2: Check of the potential for accident escalation (step 8) for selected isolable sections. Tick mark (√): consequences from target failure may have greater severity than primary scenario; S_I severity score of primary event; S_{II} severity score of secondary event; UPI_I potential hazard index of primary event; UPI_{II} potential hazard index of secondary event.

					Primary event		
				ID	IS-25	IS-12	IS-16
	Secondary event			UPI_I	9.1 E+3	3.4 E+2	5.2 E+2
ID		UPI_{II}	S_{II}	S_I	3	3	3
Atmospheric targets							
IS-21a/b	Chemicals storage tank	7.2E+2	3				
IS-20	Diesel fuel tank	3.5E+3	3		√		
IS-23a/b	Freighting water tank	0.0E+0	1				
IS-25	Oil storage tank	9.1E+3	3				
Pressurized targets							
IS-12	Compressor (LP stage)	4.2E+3	4				√
IS-13a/b	Gas dehydration column	1.1E+4	4				
IS-16	Compressor (HP stage)	6.1E+3	4			√	

4. Conclusions

The proposed methodology aims at providing risk-based criteria for fireproofing application in on-shore plants. It provides an extension of existing technical standards, including jet-fire scenarios and domino specific considerations in the assessment. Both heat radiation thresholds and minimum duration of fire are accounted for in the potential damage of fire scenarios. A risk matrix approach is applied to scenario prioritization. A case-study evidenced that the methodology may be easily applied to early stages of design and that it is able to provide robust results for the identification of areas where fireproofing application should be considered.

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