AIDIC CONFERENCE SERIES

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/acos

VOL. 11, 2013
Chief Editor: Sauro Pierucci

ISBN 978-88-95608-55-6; **ISSN** 2036-5969

DOI: 10.3303/ACOS1311041

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

Alessandro Tugnoli[*,a], Valerio Cozzani[a], Annamaria Di Padova[b], Tiziana Barbaresi[b], Fabrizio Tallone[b]

[a] Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna, via Terracini 28, 40131 Bologna, Italy
[b]Saipem, Business Unit Engineering & Construction, FANO Plant Engineering & Process, via Toniolo 1, 61032 Fano, Italy
a.tugnoli@unibo.it

Accidental fires in Oil&Gas facilities have a significant potential for severe adverse consequences: personnel, environment, assets, production continuity and company reputation are all at risk from direct fire damage. The possibility of in-plant domino effects further increases the negative outcomes of fires. Fireproofing is crucial in preventing this kind of accident propagation. Maintenance and cost considerations require the application of such safety barrier only where an actual risk of fire scenarios is present. Moreover, current practice for the identification of fireproofing zones in on-shore installations is 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 in fireproofing design (e.g. Valero accident in 2007).
In the present study, a risk-based methodology for the identification of fireproofing zones was developed. The method is mainly oriented to early design application, allowing the identification of fireproofing zones in the initial lay-out definition. It constitutes an advancement in the framework of fireproofing design of oil&gas on-shore facilities. 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 application. 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 potential outcomes of the methodology are investigated by the application to a case-study 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 has been reported to 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). This resulted in domino propagation phenomena with severe losses in terms of human life, asset value and company reputation. Active and passive protections are usually provided to prevent or mitigate such events. All active mitigation systems require a start-up phase to be fully effective, making them inefficient in the early stages of a fire accident. On the other hand, fireproofing delays the temperature rise of structural elements exposed to fire without need of activation procedures (CCPS, 2003), providing additional time for the implementation of effective mitigation measures (firefighting, depressurization, etc.). As such, fireproofing is widely applied as passive protection barrier.
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

Please cite this article as: Tugnoli A., Cozzani V., Di Padova A., Barbaresi T., Tallone F., 2013, Reducing the consequences of accidental fires in oil&gas facilities: a risk-based procedure for identification of the fireproofing zones, AIDIC Conference Series, 11, 401-410
DOI: 10.3303/ACOS1311041

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, 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). However the non prescriptive nature of the standards make them too generic to effectively guide a systematic evaluation of fireproofing needs. As a consequence, usual practice is strongly bases on expert judgement and case-by-case analysis, which may lead to inconsistent results among different studies. For example, the possible damage due to jet-fires is usually neglected in on-shore fireproofing studies, and deterministic approaches based on generic fire envelope dimensions are used for the assessment of fire damage potential for pool fires. Moreover, existing standards do not specifically 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, 2013), 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 (process flow diagram, piping and instrumentation diagram, preliminary sizing of process equipment), as well as on lay-out and safety barriers (catch basins, emergency shut-down systems, etc.). The methodology provides as an output the list of items in the plant that may be damaged by pool fire and jet-fire scenarios, and are suggested for fireproofing application. The graphic outputs of the methodology are maps plotting the zones around a unit where potentially affected targets should be protected ("fireproofing zone"); these zones are different depending on the target type and fire hazard (impingement, distant radiation). 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), Lien et al. (2010)). The non-linearity of the response of structures exposed to fire further complicates the analysis (e.g. see CCPS (2000), Cozzani et al. (2006), Landucci et al. (2009), Mannan (2005) and references cited therein).

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. The different resistance of the structural elements suggests to adopt different damage criteria for the three categories of potential targets four zones identified. Moreover different levels of fire exposure are possible (impingement, distant radiation) and require very different considerations for fireproofing application (e.g. temperatures reached in case of fire are different). Table 1 proposes criteria for the identification of four main damage zones. The values provided in the table were derived both from available standards and from detailed studies, also based on finite elements simulations, aiming at the assessment of the time to failure of equipment items and structural elements (CCPS, 2000, 2003; Landucci et al., 2009; UKOOA, 2007). 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. SETs are items that, if damaged by the primary fire, may cause an escalation of the event. This means that the severity of the consequences from the cascading scenario exceeds the one of the initial fire (Cozzani et al., 2006).
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. For each IS, the inventory and conditions (pressure, temperature, physical state) of the flammable materials is defined from the data available in the process documentation.

	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)**	**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.

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. Only RS of flammable substances should be further considered. 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. For each LOC and each RS, the total amount of flammable substances that may be released from the IS of concern should be assessed. The time of activation of automatic systems should be accounted in the appraisal of the total inventory that may be released. Reference values for the closure time of valves are provided in the technical literature, but specific values for the plant of concern should be preferred if available. 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. Standard event tree trees reported by the "Purple Book" (Uijt de Haag and Ale, 2005) were applied in the case-study discussed in the following, but alternative sources may be considered (Mannan, 2005; API, 2000; Delvosalle, 2006). In the present framework, only pool fires and jet fires are considered relevant FOs. Thus, in the further steps only LOC events and RS that include jet fires or pool fires as FOs should be considered.

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)), also taking advantage of the current availability of swift simulation software. 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. The time duration of the scenario should also be assessed.

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. The base leak frequencies and the conditional probabilities of ignition can be easily defined according to generic reference data available in the literature (Delvosalle, 2006; Uijt de Haag and Ale, 2005; Ronza et al. 2007). If available, specific data for the installation of concern should be used. If effective mitigation of the FO is possible (fire&gas alarm systems, emergency shut-down systems, depressuring systems), the conditional probability of success in mitigation should be considered. If specific data are not available for the installation, upper bound values defined in the classification of safety instrumented systems may be used. 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. When considering escalation damage due to a SET damage, assessment may be carried out applying to SET units the procedure used in steps 4 and 5 considering only intense or catastrophic LOCs.

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

The reference LOC events are screened for severity and frequency using a risk matrix as the one reported in Figure 1. Risk ranking based on a matrix approach is widely used and is applied to risk-based decisions both by public authorities and private companies (HSE, 2009). The risk matrix of Figure 1 was adapted to the current work from the risk decision matrix proposed in ISO 17776. 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. The proposed methodology aims at providing risk-based criteria for identification of these zones. Clearly enough, the assessment of risk due to fire damage and escalation is only one of the factors that should be considered in decision-making concerning actual fireproofing application. Besides cost issues, maintenance and integrity assurance, difficulties in inspections of the protected steel structures, and possible enhancement of local corrosion phenomena should be carefully considered. A more detailed analysis of fireproofing pros and cons is available in the literature (e.g. see CCPS (2003), Mannan (2005), UKOOA (2007)).

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). Reference damage distances were calculated for each vessel containing a relevant quantity of hazardous materials, according to a methodology earlier proposed for the Inherent Safety KPIs (Tugnoli et al., 2011) (Table 2). The consequence analysis models provided in the Phast software package were used to calculate the worst-case damage distances. Consequence severity was ranked according to the classification in Figure 1. Table 2 also reports the 13 isolable sections identified by an analysis of the process flow diagram (step 3). Each isolable sections consists of several items and is delimited by ESD valves and check valves. Table 3 reports and example of the definition of the isolable section IS-12.
For each isolable section the LOC categories and equivalent release diameters were identified (see e.g. Table 3). The classification was derived from API Standard 581 (API, 2000). Reference streams were identified for each LOC: some units where liquid and gas phases were present at different levels of pressure required the definition of several RS: an example is shown in Table 3 for the low pressure compression train.

Table 2: Isolable sections considered in the case study. Severity scores: see Figure 1 for score definition.

Code	Units	Damage distance (m)	Severity score from failure		
			P	E	A
IS-09a/b	Delivery pumps	34	3	1	3
IS-10a/b	Pig launcher	63	5	1	4
IS-11	Pipe-rack (gas)	71	3	1	3
IS-12	LP compression train	65	3	1	4
IS-13a/b	Gas dehydration	103	3	1	4
IS-14a/b	Stabilizer	98	3	1	4
IS-15a/b/c	Glycol Regenerator	13	2	1	2
IS-16	HP compression train	78	3	1	4
IS-19a/b/c	Utilities (technical gases)	0	1	1	1
IS-20	Fuel gas system	9	2	1	2
IS-21a/b/c/d	Utilities (chemicals)	27	3	2	2
IS-23a/b	Utilities (freighting water)	0	1	1	1
IS-25	Oil storage tank	96	3	2	3

Table 3: Items, reference streams, and possible LOC in isolable section IS-12 of the case-study (step 3 & 4). G: gas phase; L: liquid oil phase, Press.: pressure; Temp.: temperature.

Item	Phase	Press. (bar g)	Temp (°C)	Volume (m3)	Reference Stream	¼”	1”	4”	Full Bore	Cat.
1° Stage suction drum	G-L	2.5	55	5.4	RS-12-G1	√	√	√		√
				2.3	RS-12-L1	√	√	√		√
2° Stage suction drum	G-L	9.6	65	4.5	RS-12-G2	√	√	√		√
				1.1	RS-12-L2	√	√	√		√
Discharge drum	G-L	35.2	65	0.7	RS-12-G3	√	√	√		√
				0.4	RS-12-L3	√	√	√		√
1° Stage cooler	G	9.6	65	1.1	RS-12-G2	√	√	√	√	
2° Stage cooler	G	35.2	65	1.2	RS-12-G3	√	√	√	√	
1° Stage compressor	G	9.6	350	1.1	RS-12-G2	√	√	√	√	
2° Stage compressor	G	35.2	350	0.9	RS-12-G3	√	√	√	√	
Pipework 3”, liquid service	L	2.5	55.3	0.01	RS-12-L1	√	√			
Pipework 3”, gas service	G	2.5	55.3	0.09	RS-12-G1	√	√			
Pipework 3”, liquid service	L	9.8	54	0.01	RS-12-L2	√	√			
Pipework 3”, gas service	G	9.6	65	0.09	RS-12-G2	√	√			
Pipework 3”, liquid service	L	35.2	65	0.01	RS-12-L3	√	√			
Pipework 8”, gas service	G	9.6	65	0.32	RS-12-G2	√	√	√	√	
Pipework 8”, gas service	G	35.2	65	6.7	RS-12-G3	√	√	√	√	
Pipework 10”, gas service	G	9.6	65	0.51	RS-12-G2	√	√	√	√	
Pipework 12”, gas service	G	9.6	65	16.9	RS-12-G2	√	√	√	√	
Pipework 16”, gas service	G	2.5	55.3	5.8	RS-12-G1	√	√	√	√	

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 (step 5). 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 release duration. As shown in Table 4, the criteria concerning the fire minimum duration (Table 1) played a relevant role in the identification of the relevant FOs. In the examples of Table 4, most of the greater diameter releases (4” and full bore) produce scenarios to short to qualify for fireproofing zones S2, AV, and PV and a few meet only the S1 criterion.
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. Results for selected IS are reported in Table 5.
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 (Table 5). If a SET falls inside the damage area of the FO considered, the higher score between primary fire and secondary escalation was considered. Table 5 shows the results obtained for the frequency, severity and risk ranking of some of the relevant FO identified. As evident in the table some leaks (small diameter and low pressure leak from compression train; spills into the catch basin in storage tank) are in the acceptable region and can be neglected for further consideration. The larger diameter releases, instead, and in particular jet-fire scenarios, fall in the zone requiring risk reduction measures and should be considered in the definition of fireproofing zones.
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

Table 4: Results of consequence evaluation for IS-03 (step 5). FB: full bore; Cat.: catastrophic release; n.a.: not applicable.

Isolable section	Reference stream	LOC category	Relevant FO	Scenario duration (s)	Time criteria check				Affected damage distance (m)			
					S1	S2	AV	PV	S1	S2	AV	PV
IS-08	RS-08-L	¼”	Pool fire	>7200	Y	Y	Y	Y	2	7	7	-
			Jet fire	>7200	Y	Y	Y	Y	3	3	-	-
		1”	Pool fire	1780	Y	Y	Y	Y	6	21	18	-
			Jet fire	1280	Y	Y	Y	Y	14	13	-	-
		4”	Pool fire	127	N	N	N	N	25	26	25	-
			Jet fire	127	N	N	N	N	27	34	33	-
		FB	Pool fire	106	N	N	N	N	32	33	33	-
IS-11	RS-11-G	¼”	Jet fire	>7200	Y	Y	Y	Y	3	3	-	-
		1”	Jet fire	875	Y	Y	Y	Y	9	9	-	-
		4”	Jet fire	111	N	N	N	N	25	42	41	35
		FB	Jet fire	< 30	N	N	N	N	-	-	-	-
IS-12	RS-12-L1	¼”	Pool fire	>7200	Y	Y	Y	Y	1	5	5	2
			Jet fire	6410	Y	N	N	N	-	-	-	-
		1”	Pool fire	730	Y	Y	Y	Y	5	18	16	6
			Jet fire	455	Y	N	N	N	7	7	-	-
		4”	Pool fire	85	N	N	N	N	23	21	19	-
			Jet fire	85	N	N	N	N	21	21	-	-
		FB	Pool fire	110	N	N	N	N	13	20	16	-
	RS-12-L2	¼”	Pool fire	4600	Y	Y	Y	Y	2	7	6	3
			Jet fire	1224	Y	Y	Y	Y	8	8	-	-
		1”	Pool fire	164	N	N	N	N	6	21	18	-
			Jet fire	133	N	N	N	N	24	31	31	-
		4”	Pool fire	65	N	N	N	N	24	27	25	-
			Jet fire	65	N	N	N	N	70	106	105	99
		FB	Pool fire	118	N	N	N	N	8	21	17	-
	RS-12-L3	¼”	Pool fire	706	Y	Y	Y	Y	2	8	7	3
			Jet fire	252	Y	N	N	N	11	15	3	-
		1”	Pool fire	76	N	N	N	N	7	22	18	-
			Jet fire	72	N	N	N	N	34	53	53	50
		4”	Pool fire	60	N	N	N	N	28	30	29	-
			Jet fire	60	N	N	N	N	103	174	171	156
		FB	Pool fire	150	N	N	N	N	4	15	14	5
	RS-12-G1	¼”	Jet fire	1800	Y	Y	Y	Y	3	3	-	-
		1”	Jet fire	170	N	N	N	N	3	10	10	-
		4”	Jet fire	67	N	N	N	N	25	34	33	14
		FB (16”)	Jet fire	< 30	N	N	N	N	-	-	-	-
	RS-12-G2	¼”	Jet fire	3824	Y	Y	Y	Y	5	5	-	-
		1”	Jet fire	295	Y	N	N	N	14	19	18	-
		4”	Jet fire	75	N	N	N	N	42	57	53	32
		FB (≥8”)	Jet fire	< 30	N	N	N	N	-	-	-	-
	RS-12-G3	¼”	Jet fire	1410	Y	Y	Y	Y	8	10	-	-
		1”	Jet fire	184	Y	N	N	N	23	31	30	28
		4”	Jet fire	75	N	N	N	N	74	107	104	93
		FB (8”)	Jet fire	< 30	N	N	N	N	-	-	-	-
IS-25	RS-25-L	¼”	Pool fire	>7200	Y	Y	Y	Y	1	8	8	6
		1”	Pool fire	>7200	Y	Y	Y	Y	4	22	21	11
		4”	Pool fire	>7200	Y	Y	Y	Y	15	28	24	-
		Cat.	Pool fire	>7200	Y	Y	Y	Y	50	79	78	-

Table 5: Results of risk-based selection of reference LOC for isolable section IS-03 (step 7). Values in bold were considered for definition of fireproofing zones. JF: jet fire; PF: pool fire. See Figure 1 and Tables 2 and 7 for other acronym definition.

Isolable section	Reference stream	LOC category	Total leak frequency (y-1)	Frequency of the final scenario (y-1)	Severity class	Rank in the risk-matrix	Selected as reference LOC	Affected damage distance (m)			
								S1	S2	AV	PV
IS-08	RS-08-L	¼”	2.38e-4	1.54E-5	2	RR	Y	3	7	7	-
		1”	3.09e-4	4.00E-7	3	RR	Y	**14**	**21**	**18**	-
IS-11	RS-11-G	¼”	1.33e-4	2.66E-6	2	RR	Y	3	3	-	-
		1”	3.63e-4	1.44E-7	3	RR	Y	**9**	**9**	-	-
IS-12	RS-12-L1	¼”	3.18E-05	2.06E-06	1	AC	N	1	5	5	2
		1”	3.34E-05	4.32E-08	3	RR	Y	7	**18**	**16**	**6**
	RS-12-L2	¼”	2.81E-05	1.82E-06	2	RR	Y	8	8	6	3
	RS-12-L3	¼”	3.44E-05	2.24E-06	3	RR	Y	11	8	7	3
	RS-12-G1	¼”	1.14E-03	2.29E-05	1	AC	N	3	3	-	-
	RS-12-G2	¼”	1.27E-03	2.53E-05	1	AC	N	5	5	-	-
		1”	1.57E-03	6.26E-07	3	RR	Y	14	-	-	-
	RS-12-G3	¼”	2.74E-04	5.47E-06	2	RR	Y	8	10	-	-
		1”	3.72E-04	1.48E-07	4	RR	Y	**23**	-	-	-
IS-25	RS-25-L	¼”	4e-5	2.6E-6	1	AC	N	1	8	8	6
		1”	1e-4	1.29E-7	2	AC	N	4	22	21	11
		4”	1e-5	1.29E-8	2	AC	N	15	28	24	-
		FB (8”)	6e-6	7.76E-9	3	RR	Y	**50**	**79**	**78**	-

Table 6: 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			√	

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 (Tugnoli et al., 2011). Table 6 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 6) 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 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.

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. Separate fireproofing zones are defined for different classes of vulnerable targets. In particular the possibility of domino escalation by failure of other process equipment is accounted by the method. 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.

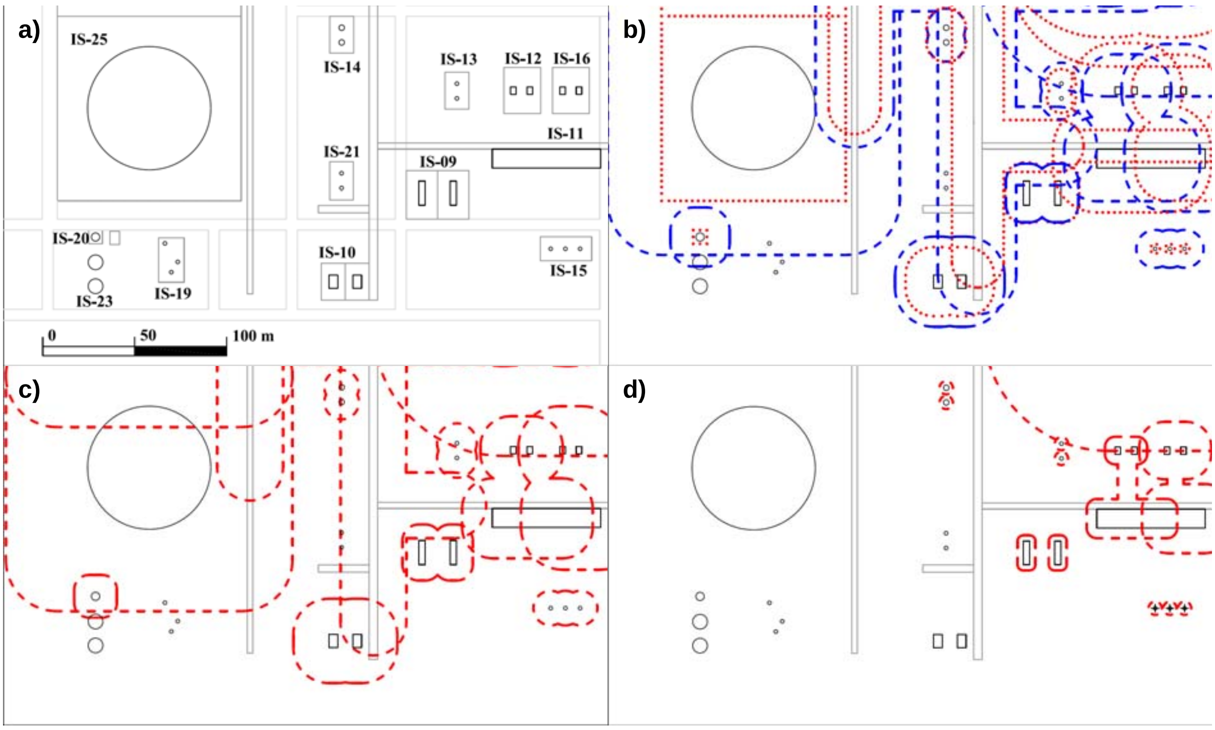

Figure 2: Layout considered in the case-study and footprint of the fireproofing zones according to the criteria of Table 1. Panel a) layout and location of isolable sections. Panel b) fireproofing zones for structural elements; red (internal) area: impingement zone (S1); blue (outer) area: radiative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

References

API (American Petroleum Institute), 1999, Fireproofing practices in petroleum and petrochemical processing plants, API publication 2218. 2nd ed. API, Washington, D.C., U.S.A.

API (American Petroleum Institute), 2000, Risk-based inspection base resource document, API publication 581. 1st ed. API, Washington, D.C., U.S.A.

API (American Petroleum Institute), 2001, Design and construction of LPG installations, API publication 2510. 8th ed. API, Washington, D. C., U.S.A.

CCPS (Center for Chemical Process Safety), 2003, Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities. CCPS/AIChE, New York, U.S.A.

Cozzani V., Gubinelli G., Antonioni G., Spadoni G., Zanelli S., 2005, The assessment of risk caused by domino effect in quantitative area risk analysis, J Hazard Mater. 127(1-3),14-30.

Cozzani V., Gubinelli G., Salzano E., 2006, Escalation thresholds in the assessment of domino accidental events, J Hazard Mater. 129, 1-21.

Cozzani V., Tugnoli A., Salzano E., 2009, The Development of an inherent safety approach to the prevention of domino accidents, Accid Anal Prev. 41, 1216-1227.

Delvosalle C., Fievez C., Pipart A., Debray B., 2006, ARAMIS project: A comprehensive methodology for the identification of reference accident scenarios in process industries, J Hazard Mater. 130, 200–219.

Di Padova A., Tugnoli A., Cozzani V., Barbaresi T., Tallone F., 2011, Identification of fireproofing zones in Oil&Gas facilities by a risk-based procedure, J Haz Mater. 191(1-3), 83-93.

Gomez-Mares M., Tugnoli A., Landucci G., Barontini F., Cozzani V., 2012a, Behavior of intumescent epoxy resins in fireproofing applications, J Anal Appl Pyrol. 97, 99-108.

Gomez-Mares M., Tugnoli A., Landucci G., Cozzani V., 2012b, Performance assessment of passive fire protection materials, Ind Eng Chem Res. 51 (22), 7679–7689.

Heidarpour A., Bradford M.A., 2009, Generic nonlinear modelling of restrained steel beams at elevated temperatures, Eng Struct. 31(11), 2787-2796.

HSE (Health and Safety Executive), 2009, PADHI – HSE’s land use planning methodology <http://www.hse.gov.uk/landuseplanning/methodology.htm> accessed 06.11.2013

Khan F.I., Amyotte P.R., 2003, How to make inherent safety practice a reality, Can J Chem Eng. 81, 2-16.

Landucci G., Molag M., Cozzani V., 2009, Modeling the performance of coated LPG tanks engulfed in fires, J Hazard Mater. 172(1), 447-456.

Lien K.H., Chiou Y.J., Wang R.Z., Hsiao P.A., 2010, Vector form intrinsic finite element analysis of nonlinear behavior of steel structures exposed to fire, Eng Struct. 32(1), 80-92.

Mannan S., Eds., 2005, Lees’ Loss Prevention in the Process Industries (3rd ed.). Elsevier, Oxford, U.K.

Ronza A., Vílchez J.A., Casal J., 2007, Using transportation accident databases to investigate ignition and explosion probabilities of flammable spills, J Hazard Mater. 146, 106-123.

Tugnoli A., Khan F., Amyotte P., Cozzani V., 2008, Safety Assessment in Plant Layout Design using Indexing Approach: Implementing Inherent Safety Perspective; Part 1 – Guideword applicability and method description, J Hazard Mater. 160(1), 100–109.

Tugnoli A., Santarelli F., Cozzani V., 2011, Implementation of Sustainability Drivers in the Design of Industrial Chemical Processes, AIChE J. 57 (11), 3063–3084.

Tugnoli A., Cozzani V., Di Padova A., Barbaresi T., Tallone F., 2012, Mitigation of fire damage and escalation by fireproofing: A risk-based strategy, Reliab Eng Sys Safe. 105, 25-35.

Tugnoli A., Cozzani V., Di Padova A., Barbaresi T., Tallone F., 2013, Reducing the consequences of accidental fires in oil&gas facilities: a risk-based procedure for identification of the fireproofing zones, Chemical Engineering Transactions, 32, 103-108, DOI: 10.3303/CET1332018

Uijt de Haag P.A.M., Ale B.J.M., 2005, Guidelines for quantitative risk assessment (Purple Book). The Hague (NL): Committee for the Prevention of Disasters, The Hague, Netherlands

UKOOA (UK Offshore Operators Association Limited) / HSE (Health and Safety Executive), 2007, Fire and explosion guidance - Part 2: Avoidance and mitigation of fires. HS025. UKOOA/HSE, Laurencekirk, Scotland.

US-CSB (U.S. Chemical Safety and Hazard Investigation Board), 2008, Investigation report: LPG fire at Valero – McKee refinery, Report NO. 2007-05-I-TX. Washington, D.C.: US CSB. <purl.access.gpo.gov/GPO/LPS100916> accessed 20.09.2012

Van Den Bosch C.J.H., Weterings R.A.P.M., 2005, Methods for the calculation of physical effects (Yellow Book). 3rd ed. The Hague (NL): Committee for the Prevention of Disasters, The Hague, Netherlands