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Identification of fireproofing zones in Oil&Gas facilities by a risk-based procedure

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ABSTRACT

Fire is among the more dangerous accident scenarios that may affect the process and chemical industry. Beside the immediate and direct harm to workers and population, fire may also cause damages to structures, which may trigger escalation resulting in severe secondary scenarios. Fireproofing is usually applied to improve the capacity of structures to maintain their integrity during a fire. Past accidents evidenced that the available standards for fireproofing application in onshore chemical and process plants do not consider all the fire scenarios that may cause structural damage. In the present study a methodology was developed for the identification of the zones where fireproofing should be applied. The effect of both pool fires and jet fires was accounted. Simplified criteria, based on radiative heat intensity, were provided for the identification of the fire protection zones. A risk-based procedure was proposed for the selection of significant reference release scenarios to be used in the evaluation of worst credible fire consequences.

1. Introduction

Fire scenarios in the process and chemical industry have the potential to harm people, pollute the environment and cause severe damages to the assets. In particular, accidents involving fire may cause direct damages (e.g., injuries, fatalities, asset loss, etc.), as well as accident escalation to secondary and more severe scenarios (domino effect) [1–5]. Structural elements exposed to high temperatures during a fire event may undergo a significant loss of mechanical properties that may cause failures and loss of containment. In particular, the collapse of the support structures of equipment and piping is a well known critical issue [6], as well as the failure of pressurized vessels exposed to fire [7–10]. Reducing the risk of structural collapse due to the exposure to fire requires the adoption of specific mitigation systems.

Fireproofing is a passive fire protection based on the application of a protective coating that delays the temperature raise of structural elements exposed to fire [1,3,11,12]. All active mitigation systems require a start-up phase to be fully effective. When properly implemented, fireproofing delays the effects of fire exposure providing additional time for the implementation of active protection measures. Thus, fireproofing plays a fundamental role in the reduction of losses, in the protection of personnel and equipment, and in the effectiveness of firefighting operations [13].

Cost and maintenance issues require to identify fire protection zones where the risk reduction justifies the application of fireproofing materials. Technical standards provide criteria for the application of fireproofing in onshore chemical and process plants [13,14]. However, most of these standards do not consider the effect of jet-fires and are based on deterministic approaches for the assessment of damage distances of the reference fire scenarios considered. As an example, protection from jet-fires falls out of the scope of American Petroleum Institute (API) 2218 standard. Prevention of potential escalation from jet-fire scenarios falls out of the scope of the standard, even if several past accidents pointed out the potential severity of domino effects triggered by jet fires (e.g., see the Valero accident, occurred in Texas in 2007 [15]).

In the present study a risk-based methodology was developed for the identification of fireproofing zones, aimed at extending and improving the criteria for fireproofing application provided by the current standards. A risk-based approach was introduced to allow a more detailed approach to the identification of the reference accident scenarios considered for the identification of fire protection zones, taking into account also the credibility of the different scenarios, not considered in consequence-based approaches.

The method developed considers the consequences of both jet-fire and pool-fire scenarios in the evaluation of fire damage and uses a risk-based approach for the selection of the relevant reference scenarios. Simplified criteria are proposed for fire damage estimation, based on fire impingement and on thresholds for radiative heat flux. An application to the analysis of two case-studies of industrial interest is also discussed, in order to understand the potentialities of the technique and to compare the results

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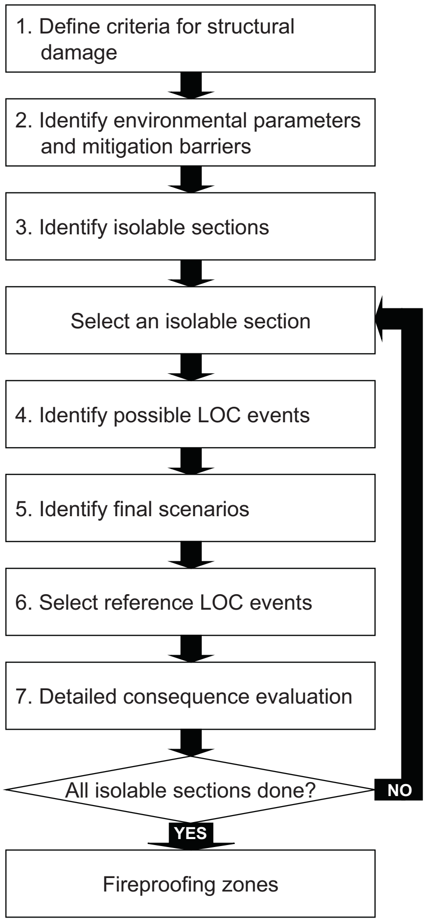


Fig. 1. Flow diagram of the developed methodology.

obtained with those deriving from the application of the API 2218 standard.

2. Methodology

Fig. 1 reports a flow chart of the methodology, that may be divided in seven sequential steps. The first three stages of the methodology are applied to the entire plant, while the remaining steps are applied recursively to each isolable section of the plant, as defined in Step 3.

2.1. Step1 – definition of the criteria for structural damage

In this step simplified threshold criteria are defined for the classification of fireproofing zones. Two fireproofing zones should be defined, according to the different requirements for fireproofing materials and/or strategies: (i) the zone interested by far-field heat radiation form non-impinging flame; (ii) the zone of possible fire impingement or engulfment.

The detailed assessment of the potential for structural damage during a fire scenario would require the complex modelling of wall temperature and induced stress transients [8,9,16–18]. However, the aim of the present methodology is only the identification of zones where damage due to fire should be considered likely. Thus, simplified but conservative damage criteria may be adopted. Several technical sources suggest values between 10 and 15 kW/m^2 as damage thresholds for steel structures exposed to fire heat radiation [19]. In the case-studies discussed below a threshold of 12.5 kW/m^2 was adopted [13].

In the case of flame engulfment or impingement, the exposed materials are loaded by heat fluxes having the order of magnitude of the surface emissive power (SEP) of the flame. Sensitive targets should not be present within these areas or, if present, should be specifically protected from flame impingement (e.g., fire resistant coating, fire resistant walls, bunds, etc.).

The duration of the scenario should also be accounted. Structural damage due to fire is also related to fire duration, being negligible for scenarios having a limited time duration [3,20]. In the case-studies discussed below, a minimum reference time of 10 min was adopted for the radiative heat flux zone, while a minimum reference time of 3 min was considered in the zone where flame impingement or engulfment is possible [1,13].

2.2. Step 2 – identification of the relevant environmental parameters and of mitigation barriers

In this step, a set of representative meteorological conditions, each defined by an atmospheric stability class and an average wind velocity, is identified from the meteorological data available for the site [3,21]. Further data that should be collected are the relevant mitigation barriers present or considered in plant design (containment basins, fire walls, etc.).

2.3. Step 3 – identification of isolable sections

In this step, the plant should be divided in “isolable sections”, defined herein as a section which, in the event of emergency, can be isolated completely from the other parts of the plant (e.g., by emergency shut-down valves (ESDVs), by check valves, etc.). Examples of the features of an isolable section are provided in Section 4. Only isolable sections where flammable substances are present should be further considered in steps 4–7.

2.4. Step 4 – identification of possible loss of containment (LOC) events

For each isolable section, the possible LOC events involving flammable substances should be identified. Potential release modes can be identified by standard hazard identification techniques [22] as well as by pre-defined sets of release categories available for specific equipment types [23,24]. The release categories suggested by API 581 standard [23] are widely used in the Oil&Gas sector and may be easily applied, as well as those provided by the MIMAH procedure [25] or by the “Purple Book” [24]. Clearly enough, any other alternative method for the identification of release categories may be applied within the present methodology.

Starting from the analysis of the general release categories identified by the above procedures, the actual LOC events need to be identified. A single LOC event is considered for any release that, independently of the actual position of the leak point, has the same:

- substance or mixture released
- phase (or multiphase mixture) released
- pressure and temperature at the release
- equivalent release diameter or release mode and duration of release
- total quantity of substance available for release

One or more than one “reference stream” (RS) should then be defined for the section. A RS identifies the phase, the composition and the operating conditions (temperature and pressure) of any release stream due to a LOC that may take place from a given set of components (pipes, flanges, equipment items). The case-studies discussed in Section 4 report examples of LOC and RS definition.

Finally, for each RS, the total amount of flammable substances that may be released from the isolable section of concern should be estimated. The time of activation of automatic systems should be accounted in the appraisal of the total releasable mass. 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. In the present approach, the total inventory available for release is conventionally estimated as the amount of hazardous substances contained in the isolated section plus the amount fed by the input streams, at nominal rate, during the time lapse needed for the activation of isolation valves.

2.5. Step 5 – identification of final scenarios

Several alternative final scenarios may follow a LOC event, mainly depending on release features and on the presence of ignition sources and on ignition delay. In this step, standard unmitigated event trees should be defined for each LOC event, on the basis of the characteristics of the RS associated to the LOC. Standard events trees may be obtained from several sources [3,21,23–25]. In the case-studies developed in the following, the structure of the event trees presented in the Purple Book [24] were used. An example is reported in Fig. 2-a.

Clearly enough, in the further steps only RS having associated event trees that include jet fires or pool fires as final scenarios should be considered.

2.6. Step 6 – selection of reference LOC events

The procedure at Step 4 will usually lead to the identification of a quite high number of relevant LOC events, independently of their actual probability and severity. In the present step, reference LOC events are selected by a simplified assessment of the expected frequency and of the severity of the final fire scenarios that may follow the LOC. Three activities are needed to carry out this step.

2.7. Step 6a – definition of the frequencies of final scenarios

The frequency of the possible final scenarios of concern for the definition of fireproofing zones should be evaluated. A two phase procedure is suggested for this step. The quantified analysis of the generic event tree obtained in Step 5 allows the calculation of the expected frequency of the final scenarios of concern without considering mitigation systems. Several sources of data can be used to estimate the base frequencies of the initial releases and the probabilities of immediate and delayed ignition. The base leak frequencies are generally defined according to the data source used in the definition of the associate LOC category [23,24] or by specific statistical correlations [26]. The probability of ignition and the conditional probability of a scenario given the ignition can be as well defined depending on type of release [3,24,27]. If available, specific data for the installation of concern should be used.

If effective mitigation of the final scenarios is possible, the conditional probability of mitigation success should be accounted. Since the framework of the present analysis is limited to a simplified frequency assessment, only fire & gas alarm systems, emergency shut-down systems and depressuring systems, if present, should be considered in the analysis. In order to obtain conservative results, other mitigation systems (e.g., drainage, water deluge system, etc.) may be neglected, in particular if the effectiveness of the mitigation is difficult to assess. Fig. 2-b reports a specific simplified event tree developed to assess the probability of successful mitigation response. As shown in the figure, in the absence of specific data, upper bound values defined in the classification of safety instrumented systems may be used to assess the probability of success of mitigation. In the case-studies discussed below, the following values were used: 10^{-2} events/demand (safety integrity level, SIL, 2) for fire & gas system; 10^{-1} events/demand (SIL 1) for emergency shut-down system and depressuring system) [28,29].

Frequencies of non-mitigated scenarios are calculated multiplying the expected frequency of the final scenario by the conditional probability of failure of mitigation systems. Clearly enough, such correction should be applied only if effective mitigation is possible.

2.8. Step 6b – definition of scenario severity

The severity classification is based on a preliminary analysis of the consequences of the final non-mitigated scenarios present in the event tree. Worst-case assumptions should be introduced to rank each relevant non-mitigated final scenario. Radiation intensity maps may be obtained from conventional consequence assessment models [3,30] or, in alternative, from generic safety distances for escalation [4,31].

The worst-case damage distance is used to identify the potential damage area, 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. The severity of the scenario is ranked considering the potential consequences deriving from the catastrophic failure of these target items. Five severity classes were adopted for severity ranking, as shown in Table 1. The damage severity level can be directly related to the value of the damaged assets in the area or to the plant downtime necessary for restoring regular operations. Beside asset loss, other categories of damage can be assessed, if relevant to the plant (Table 1). These may refer both to the direct damage from the fire scenario or to the cascading consequences. The latter can be either ranked by indexing methods [32–34] or assessed by a swift worst-case simulation by conventional consequence models. The worst possible consequence among the target categories from the worst-case non-mitigated scenario should be considered in order to rank the overall severity of the LOC event. If the initial event may cause both pool-fire and jet-fire scenarios, the severity class is based on the worst consequences among the two.

2.9. Step 6c – identification of reference LOC events

The reference LOC events may be selected using the criteria given by a risk matrix as the one reported in Fig. 3. The risk matrix approach is well known [3,29,35,36] and widely used for risk-based decisions, both by public authorities [37,38] and by company standards [39]. The risk matrix in Fig. 3 was adapted from the risk decision matrix proposed in ISO 17776 [35].

For each possible LOC event involving a relevant reference stream, the expected frequency as defined in Step 6a and the severity class as defined in Step 6b are entered in the risk matrix. The LOC events belonging to the zones where “risk reducing measures are needed” or where the risk is “not acceptable” zone should be considered credible events and are retained for detailed analysis (Step 7). The LOC events that fall in the “acceptable” zone are not further considered in the procedure. If more than one LOC falls into the same frequency class, only the one having the higher severity class should be retained for further assessment.

2.10. Step 7 – detailed consequence evaluation and identification of fireproofing zones

A detailed consequence evaluation is carried out in this step for each of the reference LOC events identified in Step 6. The assessment can be performed by the application of validated consequence analysis models (e.g., [3,30]). The maximum damage distances in the horizontal and vertical direction (worst case scenarios), based on damage criteria defined in Step 1, are considered to build the

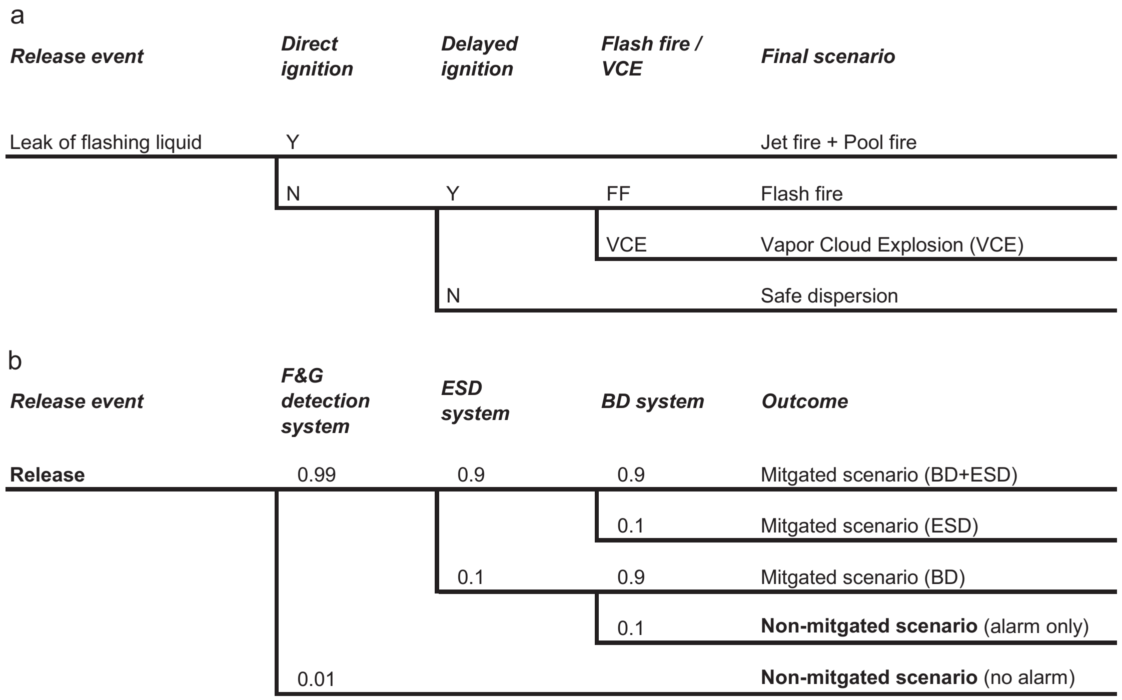


Fig. 2. Examples of event trees used in the assessment of case-studies: (a) event tree for the continuous release of liquefied n-butane (case-study 1), adapted from Purple Book [24]; (b) event tree developed for the success of mitigation response (case-study 2). The numbers represents the probability of success of mitigation gates. F&G, fire & gas; ESD, emergency shut down; BD, depressuring (blow-down).

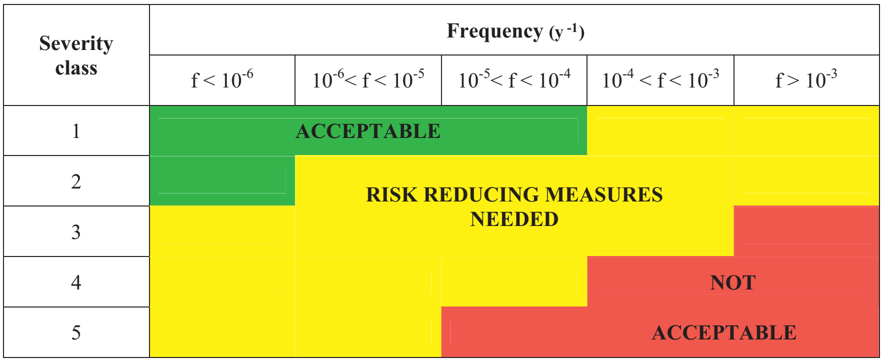
envelopes that define the fireproofing zones for each isolable section. Fig. 4 provides an example of the fireproofing zones identified by the application of the methodology.

3. Case-studies

Two case-studies were defined to assess the performance of the developed methodology and to allow a comparison with the results provided by API standard 2218. Case-study 1 concerned the pump section of an LPG storage unit of an oil refinery. The layout of the plant section considered is reported in Fig. 4. The pump section is an auxiliary unit, connected to 12 off-ground storage tanks and consists of 2 centrifugal pumps. Near the unit there are some pipe racks, a power station, a tanker loading/unloading facility, a diesel fuel storage tank, two diesel pumps and several other atmospheric tanks containing flammable liquids. A secondary containment is present around the pumps. An emergency shut-down system (ESD) and a fire & gas detection system is also present. The closing time of

Table 1
Severity classes (S) defined for the qualitative evaluation of consequence severity.

S	People	Environment	Asset	Reputation
1	Offsite medical treatment. Reversible effects on health.	Concern of some local stakeholders. Temporary impact on the area. Impact on a small number of species. Impact on localized ground.	Production downtime < 1 day.	Some loss of reputation in the area, which might be recovered.
2	Hospitalization. Serious and potentially irreversible effects on health.	1–2 year for natural recovery. 1 week for clean-up. Threatening of some species. Impact on protected natural area.	The unit must be repaired/replaced to resume operations. Production downtime < 1 week.	Significant potential damage to the regional reputation.
3	Permanent disability or death of a limited number of people working inside the plant.	Concern of national stakeholders. Impact on licenses. 2–5 years for natural recovery. Up to 5 months for clean-up. Threatening to biodiversity. Impact on interesting areas for science.	Long time/major change required to resume operations/business. Production downtime < 3 months. Major inquiry for the damage cost.	Serious/permanent damage to the ability of the Company to sustain business position in the location, some broader implication to the Company.
4	Permanent disability or death of people working inside the plant.	Concern of international stakeholders. Impact on licenses. > 5 years for natural recovery. >5 months for clean-up. Reduction of biodiversity. Impact on special conservation areas.	Total loss of operations/business. Revamping necessary to resume the process. Production downtime > 3 months. Extensive inquiry for the damage cost.	Potential loss of future position in the location/region and/or lasting significant damage to broader Company image.
5	Permanent disability or death of people outside the plant.	Higher impact than the levels above.	Permanent loss of the operation/business at site.	Loss of the future business in the region and/or lasting significant damage to broader Company image.



Severity class	Frequency (y^{-1})				
	$f < 10^{-6}$	$10^{-6} < f < 10^{-5}$	$10^{-5} < f < 10^{-4}$	$10^{-4} < f < 10^{-3}$	$f > 10^{-3}$
1	🟩	🟩 ACCEPTABLE	🟩	🟨	🟨
2	🟩	🟨	🟨 RISK REDUCING MEASURES NEEDED	🟨	🟨
3	🟨	🟨	🟨	🟨	🟥
4	🟨	🟨	🟨	🟥	🟥 NOT
5	🟨	🟨	🟥	🟥 ACCEPTABLE	🟥

Fig. 3. Risk matrix used for the assessment of the case-studies. Definition of severity classes is reported in Table 1.

the ESD valves was assumed equal to 10 min on the basis of available data [24]. For the sake of simplicity, n-butane was considered as the only component of LPG in the case-study.

The second case-study concerned the analysis of an on-shore oil degassing plant (Central Degassing Station or CDS). The production potentiality of the plant was assumed of 72,000 bbl/d of crude oil (about 1.32×10^{-1} m^3/s). Fig. 5 shows the lay-out of the plant and the main units handling hazardous materials. The preliminary plant layout (Fig. 5) evidences the presence of catch basins underneath separators and the mounding of the drain treatment unit. A fire & gas detection system is present, triggering both an emergency shut-down system (ESD) and a depressuring system (blow-down system). The closing time of the ESD valves was assumed equal to 2 min [24].

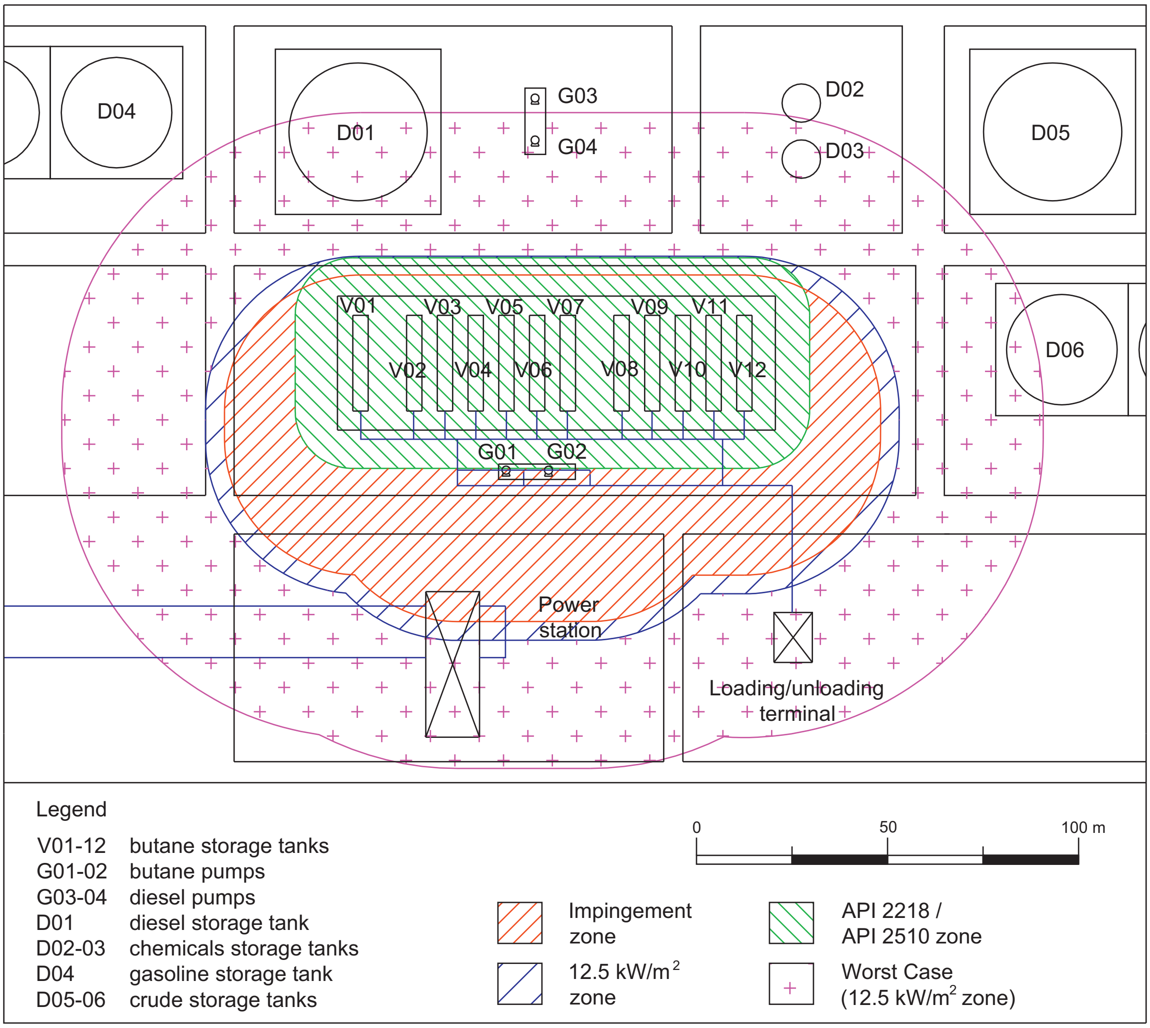


Fig. 4. Layout considered in case study-1 and footprint of the fireproofing zones proposed for IS-01. Fireproofing zones suggested by API 2218 and API 2510 for the LPG storage vessels are also shown.

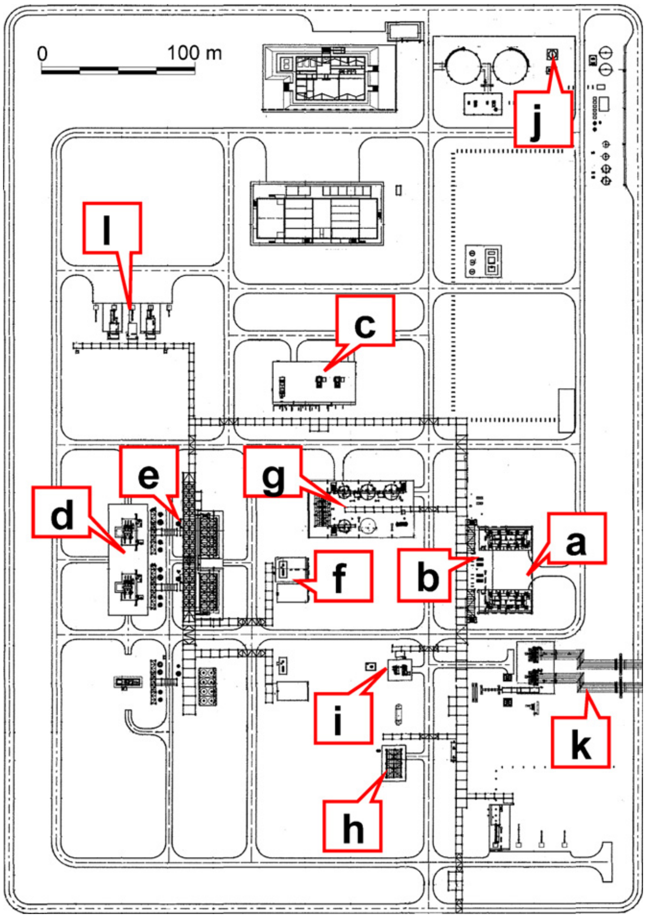


Fig. 5. Lay-out of CDS: (a) three-phase separators; (b) mol booster pumps; (c) mol pumps; (d) compressors; (e) dehydration; (f) TEG regenerator; (g) water separators; (h) vapor recovery; (i) drain treatment; (j) diesel tank; (k) inlet; (l) outlet.

4. Results and discussion

4.1. *Results of case-study 1*

The criteria and threshold for structural damage selected in Step 1 (Section 2) were adopted in this case-study. For the sake of simplicity, only 1.5/*F* (indicating wind velocity in m/s and atmospheric stability class) meteorological conditions were considered (Step 2). The pump section of the LPG storage may be divided in two isolable sections by the criteria provided in Step 3 (see Fig. 6), each consisting of a pump and of about 80 m of 4″ pipework. The results obtained for section IS-01 (pump G01 and related pipework, see Fig. 6) will be analyzed in detail. The same results were obtained for the spare pump.

The release categories and baseline frequencies proposed in API Standard 581 [23] were considered to identify the LOC events in the case study. Relevant LOC categories considered by this approach are: 1/4″, 1″, and 4″ (full bore) equivalent release diameters. The application of criteria defined in Step 4 of the methodology to unit IS-01 lead to the identification of the possible LOCs events reported in Table 2. The pump section delivers LPG to plant utilities at a maximum nominal flow rate of 4.5 kg/s. Thus, a single reference stream, RS-01-L may be identified. Saturated liquid n-butane at 25 °C may be assumed as the model compound for the release stream involved in all LOC events. Section hold-up is 370 kg. Assuming 600 s (10 min) as the time required for ESD action, the maximum amount of n-butane that may be released is of 3070 kg. The RS-01-L stream undergoes flash during release, yielding a continuous two phase release. The event tree in Fig. 2-a was used to identify the final scenarios associated to each LOC event by the procedure defined in Step 5.

Table 2 reports the results of Step 6a, concerning the estimation of the expected frequencies of non-mitigated scenarios. Total expected frequencies were assessed for final scenarios caused by the same LOC and the same reference stream. The values of release frequencies were derived from API 581 [23], according to the LOC classification used in current case study. The conditional probabilities of direct ignition were derived from Purple Book [24], while the relevant section of the event tree provided in Fig. 2-b was used to assess the conditional probability of successful mitigation (no depressuring system is present in IS-01).

Table 2 reports the results of the simplified consequence assessment carried out for each relevant final scenario (Step 6b of the methodology). As stated above, only pool fire and jet fire scenarios were considered in the framework of the present methodology. Conventional assumptions, widely used in consequence analysis, were introduced to simplify the assessment. In the case of jet-fires, conservative results were obtained considering only horizontal direction and ignoring obstacles. The data reported in Table 2 were used to define the contours of an impact area, enveloping all the possible release positions. The severity class of the consequences was identified considering the downtime of vulnerable targets present within the impact area. As an example, in the case of a LOC from a 1″ equivalent diameter the items involved by the potential jet-fires are several LPG storage vessels, piperacks, a pump and the power station. A 2 month time-to-repair is estimated, so the severity class of the LOC is 3.

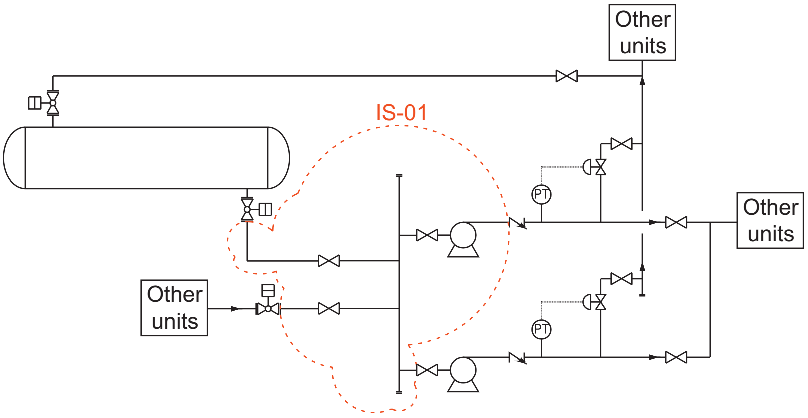


Fig. 6. Process flow diagram of isolable section IS-01 in case study-1. Dashed line identifies the boundaries of the isolable section.

Table 2
Case-study 1: results of the reference LOC identification procedure (Step 4-6) for IS-01.

	LOC size (equivalent hole diameter)		
	1/4″ (6.4 mm)	1″ (25.4 mm)	4″ (101.6 mm)
Reference stream	RS-01-L	RS-01-L	RS-01-L
Pressure (kPa)	242	242	242
Temperature (°C)	25	25	25
Hold-up (kg)	370	370	370
Nominal flowrate (kg/s)	4.5	4.5	4.5
Total amount available for release (kg)	3070	3070	3070
Final scenario of concern	Jet fire Pool fire	Jet fire Pool fire	Jet fire Pool fire
Leak frequency (y^{-1})			
Centrifugal pump, double seal	6.0×10^{-03}	5.0×10^{-04}	1.0×10^{-04}
Piping – 4″	2.4×10^{-04}	1.6×10^{-04}	1.9×10^{-05}
Total of the section	6.2×10^{-03}	6.6×10^{-04}	1.2×10^{-04}
Probability of direct ignition	2.0×10^{-01}	2.0×10^{-01}	2.0×10^{-01}
Probability of non-mitigated scenario	1.0×10^{00}	2.0×10^{-02}	2.0×10^{-02}
Frequency of final non-mitigated scenario (y^{-1})	1.2×10^{-03}	1.4×10^{-05}	2.6×10^{-06}
Simplified consequence analysis			
Duration of the release (s)	>7200	780	600
$L_{\text{jet-fire}}$ (m)	18	56	180
$D_{\text{pool-fire}}$ (m)	3	6	14
Severity class (Table 1)	2	3	3
Classification in the risk-matrix	Risk reduction measures needed	Risk reduction measures needed	Risk reduction measures needed
Selected as reference LOC	Yes	Yes	Yes

Table 2 reports the results of the semi-quantitative risk analysis performed in Step 6c of the methodology. All the potential LOCs fall into the yellow region of the matrix in Fig. 3 (“risk reduction measures needed”) and should be taken into account for detailed assessment. However, LOC events associated to small release diameters (1/4″) may not be further considered, since 1″ releases lead to worst case consequences (Table 3). The 4″ release is relevant only for the impinging fire scenarios, since the fire duration is lower than the minimum reference time threshold defined in the criteria for structural damage (Step 1). Table 3 summarizes the results of the consequence assessment carried out in Step 7 of the methodology. Fig. 4 shows the footprint of the fireproofing zone required by fire scenarios in section IS-01.

The simplified criteria proposed in the method allowed a risk-based identification of the fireproofing zones, limiting the complexity of the approach. Jet-fire scenarios were determinant to define the extension of fireproofing areas identified in Fig. 4. The damage caused by jet-fires is not accounted by some of the more widely used technical standards. In particular, API 2218 standard only considers protection from pool fires. Thus the LPG pump and the pipework in case-study 1 are not considered a “fire potential equipment” and the application of the standard will yield no fire-

Table 3
Worst-case results of the detailed consequence evaluation of selected sections in the case-studies and identified fireproofing zones (Step 7). Values in bold are the maximum distances satisfying time criteria and were use for fireproofing zone definition. X: horizontal distance from the release point; Z: vertical distance from the ground; T.C.: satisfaction of the minimum reference time criteria; n.a. not applicable.

Reference stream	Release category	Pool fire			Jet fire		
		X (m)	Z (m)	T.C.	X (m)	Z (m)	T.C.
Case study 1 – IS-01		Flame impingement or engulfment					
RS-01-L	1/4″	1	3	Yes	3	2	Yes
	1″	4	17	Yes	11	7	Yes
	4″	10	**35**	Yes	**35**	23	Yes
Case study 1 – IS-01		Radiative heat flux					
RS-01-L	1/4″	4	6	Yes	11	11	Yes
	1″	31	**38**	Yes	**40**	28	Yes
	4″	60	51	No	135	97	No
Case study 2 – CDS-03		Flame impingement or engulfment					
RS-03-RO	4″	7.5	19	Yes	20	18	Yes
	FB	7.5	19	Yes	27	24	No
RS-03-G	4″	n.a.	n.a.	n.a.	25	23	Yes
	FB	n.a.	n.a.	n.a.	44	43	No
RS-03-L	1″	5.0	13	Yes	8	7	Yes
	4″	7.5	19	Yes	**25**	**23**	Yes
	FB	7.5	19	Yes	44	39	No
	Cat.	7.5	19	Yes	n.a.	n.a.	n.a.
Case study 2 – CDS-03		Radiative heat flux					
RS-03-RO	4″	18	25	No	35	33	No
	FB	18	26	No	47	44	No
RS-03-G	4″	n.a.	n.a.	n.a.	40	38	No
	FB	n.a.	n.a.	n.a.	83	80	No
RS-03-L	1″	15	26	Yes	13	12	Yes
	4″	18	26	Yes	**45**	**42**	Yes
	FB	18	26	Yes	82	77	No
	Cat.	18	26	Yes	n.a.	n.a.	n.a.

proofing zone for SI-01. Even if the API 2218 standard, in accordance with the relevant API standard for design of LPG installations (API 2510), actually considers the LPG vessels near IS-01 as a potential fire scenario source, the corresponding fire scenario envelope (50 ft, about 15 m) is not sufficient to encompass all the possible targets identified by the proposed method for IS-01 (see Fig. 4). Thus, the application of the proposed methodology to this case-study seems to complete and extend the protection criteria provided by API 2218.

For the sake of comparison, Fig. 4 also reports the footprint of the fireproofing zones obtained using a deterministic worst-case criterion. Only the worst case scenario for the material stream was considered (the more severe jet fire having a duration of 10 min, corresponding to a 54 mm release diameter), ignoring the expected frequency of such scenario. As shown in the figure, the zone suggested for fireproofing application is much more extended. Thus, as expected, the results obtained applying a worst-case criterion are extremely conservative with respect to those obtained by the risk-based approach proposed in the present study.

Fig. 4 evidences that the risk-based method proposed, allowing a sound assessment of both credible and severe LOCs for the definition of fireproofing zones, avoids over-conservative estimates, also resulting in a cost-effective approach to the definition of fireproofing zones.

4.2. Results of case-study 2

In case-study 2 the methodology was applied to a more complex installation in order to understand its potentialities and to allow a more detailed comparison of alternative criteria for fireproofing.

The same thresholds for structural damage adopted for case-study 1 were used (Step 1). The representative meteorological conditions for the site are identified as 1.5/*F* and 5/*D* and the passive barriers considered for fire scenario mitigation are catch basins and mounding (Step 2). The installation could be divided in 63 isolable sections (Step 3, see Table 4). Isolable section CDS-03 was

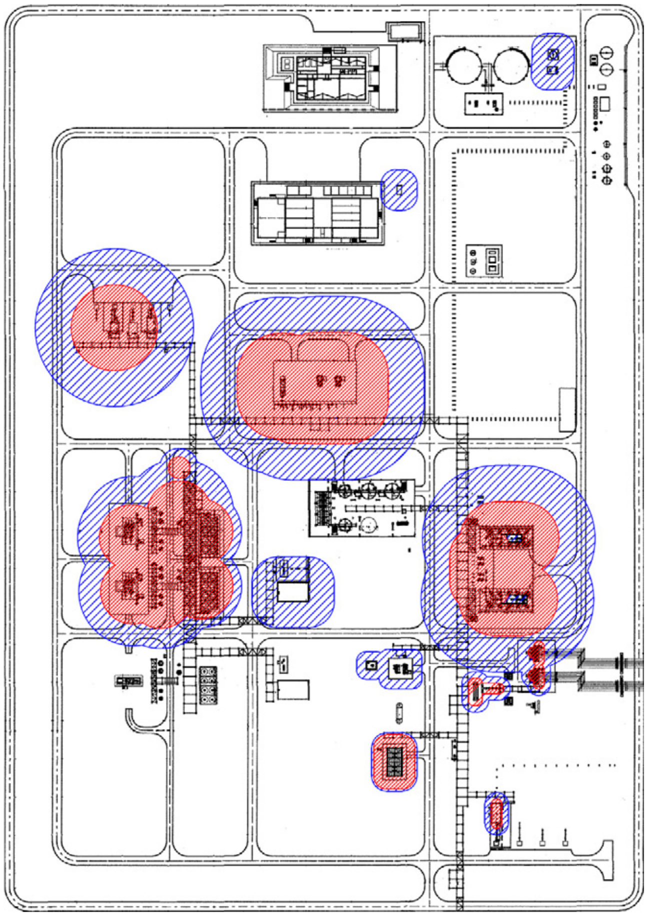


Fig. 7. Layout considered in the case-study and footprint of the fireproofing zones according to the proposed methodology. Red (internal) area: impingement zone; Blue (outer) area: radiative heat zone (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

Table 4
Accident scenarios considered in the application of the developed methodology and of API 2218 [13] for the isolable sections of the CDS plant.

Isolable section	Units	Proposed method		API 2218
		Pool Fire	Jet Fire	
CDS-01	Manifolds		√	
CDS-02	Separators Headers		√	
CDS-03,04	Separator	√	√	√
CDS-05	Pipework			
CDS-06,07	Mol booster pumps	√	√	√
CDS-08	Pipework	√	√	√
CDS-09,10	Mol pump	√	√	√
CDS-11	Pig launcher (oil)	√	√	√
CDS-12	Pipework		√	
CDS-13,20	Compressor (1st & 2nd stage)	√	√	√
CDS-14,21	Glycol contactor	√	√	√
CDS-15,36	Pipework		√	
CDS-16,17,26,27	TEG Regenerator	√		√
CDS-18,22	Compressor (3rd stage)	√	√	√
CDS-19,23	Compressor (4th stage)			
CDS-24	Pig launcher (gas)			
CDS-25	Pipework			
CDS-28	Glycol closed drain drum			
CDS-29.31	Production water system (separation and storage)			
CDS-32,63	Vapour recovery package		√	
CDS-33,60	Closed drain drum	√		√
CDS-34	Tundish drain sump	√		√
CDS-35	Process drain drum	√		√
CDS-37.42	Utilities (compressed air, nitrogen)			
CDS-43.48	Utilities (chemicals)			
CDS-49,50	Diesel fuel system (tank & generator engine)	√		√
CDS-51,52	Utilities (fresh water)			
CDS-53,54	Utilities (freighting water)			
CDS-55.59,61.62	Flare system (pipework, flares, KO drums)			

Table 5
Items in isolable section CDS-03 of case-study 2 (Step 3); pressure 450 kPa; temperature in the inlet stream (60 °C); temperature in the separator and other lines 59 °C. G, gas phase; L, liquid oil phase; W, liquid water phase; RO, raw oil mixture (gas + liquid).

Item	Diameter (m)	Volume (m^3)	Phase	Hold-up (kg)	Nominal flowrate (kg/s)
Separator		243.16			
			G	600	–
			L	65,700	–
			W	43,800	–
Pipework and connections					
To fuel gas	0.05	0.08	G	0.41	0.04
To flare	0.10	0.15	G	0.74	0.00
Recycle	0.10	0.47	L	380	0.81
Water outlet	0.15	0.16	W	133	0.60
Oil outlet	0.20	0.12	L	94	28.67
To PSV	0.20	1.49	G	7.6	0.00
Gas outlet	0.30	1.28	G	6.5	2.98
Bi-phase inlet	0.41	2.29	RO	1146	31.45
Instruments gas phase	0.05	0.07	G	0.34	0.00
Instruments liquid phase	0.05	0.03	L	25	0.00

Table 6
Reference streams and possible LOC events for isolable section CDS-03 of case-study 2 (Step 4). FB, full bore rupture; Cat., catastrophic rupture of a vessel; n.a., not applicable; n.c., not considered (RS-03-W was not considered in further steps since not flammable).

	Reference streams			
	RS-03-RO	RS-03-L	RS-03-G	RS-03-W
Properties of the stream				
Reference substance	n-Octane	n-Octane	Methane	Water
Pressure (kPa)	450	450	450	450
Temperature (°C)	60	59	59	59
Amount available for release (kg)	4920	69,700	1030	44,000
Section item of concern				
Separator	n.a.	1/4″, 1″, 4″, Cat.	1/4″, 1″, 4″, Cat.	n.c.
To fuel gas	n.a.	n.a.	1/4″, 1″	n.a.
To flare	n.a.	n.a.	1/4″, 1″, 4″	n.a.
Recycle	n.a.	1/4″, 1″, 4″	n.a.	n.c.
Water outlet	n.a.	1/4″, 1″, 4″, FB	n.a.	n.c.
Oil outlet	n.a.	1/4″, 1″, 4″, FB	n.a.	n.c.
To PSV	n.a.	n.a.	1/4″, 1″, 4″, FB	n.a.
Gas outlet	n.a.	n.a.	1/4″, 1″, 4″, FB	n.a.
Bi-phase inlet	1/4″, 1″, 4″, FB	n.a.	n.a.	n.a.
Instrumentation gas phase	n.a.	n.a.	1/4″, 1″	n.a.
Instrumentation liquid phase	n.a.	1/4″, 1″	n.a.	n.c.

selected as a leading example for the application of steps 4–7 of the procedure.

Section CDS-03 consists of a three-phase separator and of the connected pipework (see Table 5). Four different reference streams were identified by the criteria provided in Step 4, as shown in Table 6. The table reports the main material properties of each relevant reference stream, as well as the estimation of the maximum quantities that may be released. Table 6 shows the LOC events identified for the unit. Fig. 2-a shows the event tree used to identify the final scenarios for each LOC event by the procedure defined in Step 5. The final scenarios of concern (FSOC) are reported in Table 7. The table shows the results of Step 6a, concerning the estimation of the expected frequencies of leaks and non-mitigated scenarios of concern. Table 7 also reports the results of the simplified conse-

Table 7
Results of simplified risk analysis for CDS-03 (Step 6). The length of flame and the duration of jet fire scenarios were calculated on the basis of initial release conditions. FB, full bore; Cat., catastrophic release; ACC., Acceptable risk; RRMN, Risk Reduction Measures Needed.

Reference stream	Release category	Final scenario of concern (FSOC)	Total leak frequency (y^{-1})	Frequency of the FSOC (y^{-1})	Pool fire diameter (m)	Pool fire duration (s)	Jet fire flame length (m)	Jet fire duration (s)	Severity class	Rank in the risk-matrix	Selected as reference LOC
RS-03-RO	1/4″	Pool fire Jet fire	3.5×10^{-06}	7.1×10^{-08}	3	>7200	2	>7200	1	ACC.	No
	1″	Pool fire Jet fire	1.2×10^{-05}	4.7×10^{-09}	10	750	6	750	2	ACC.	No
	4″	Pool fire Jet fire	1.2×10^{-06}	4.7×10^{-10}	15	400	20	280	3	RRMN	Yes
	FB	Pool fire Jet fire	5.9×10^{-07}	4.7×10^{-10}	15	400	27	120	3	RRMN	Yes
RS-03-G	1/4″	Jet fire	2.6×10^{-03}	5.3×10^{-05}	n.a.	n.a.	2	>7200	1	ACC.	No
	1″	Jet fire	6.5×10^{-04}	2.6×10^{-07}	n.a.	n.a.	8	3300	2	ACC.	No
	4″	Jet fire	1.5×10^{-05}	6.1×10^{-09}	n.a.	n.a.	25	210	3	RRMN	Yes
	FB	Jet fire	5.4×10^{-06}	4.3×10^{-09}	n.a.	n.a.	44	120	3	RRMN	Yes
	Cat.	None	2.6×10^{-06}	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	No
RS-03-L	1/4″	Pool fire Jet fire	7.2×10^{-04}	4.7×10^{-05}	3	>7200	2	>7200	1	ACC.	No
	1″	Pool fire Jet fire	6.2×10^{-04}	8.0×10^{-07}	11	>7200	8	>7200	3	RRMN	Yes
	4″	Pool fire Jet fire	2.6×10^{-05}	3.4×10^{-08}	15	6450	25	660	3	RRMN	Yes
	FB	Pool fire Jet fire	1.4×10^{-06}	1.8×10^{-09}	15	6450	44	165	3	RRMN	Yes
	Cat.	Pool fire	3.4×10^{-06}	2.2×10^{-07}	15	6450	n.a.	n.a.	3	RRMN	Yes

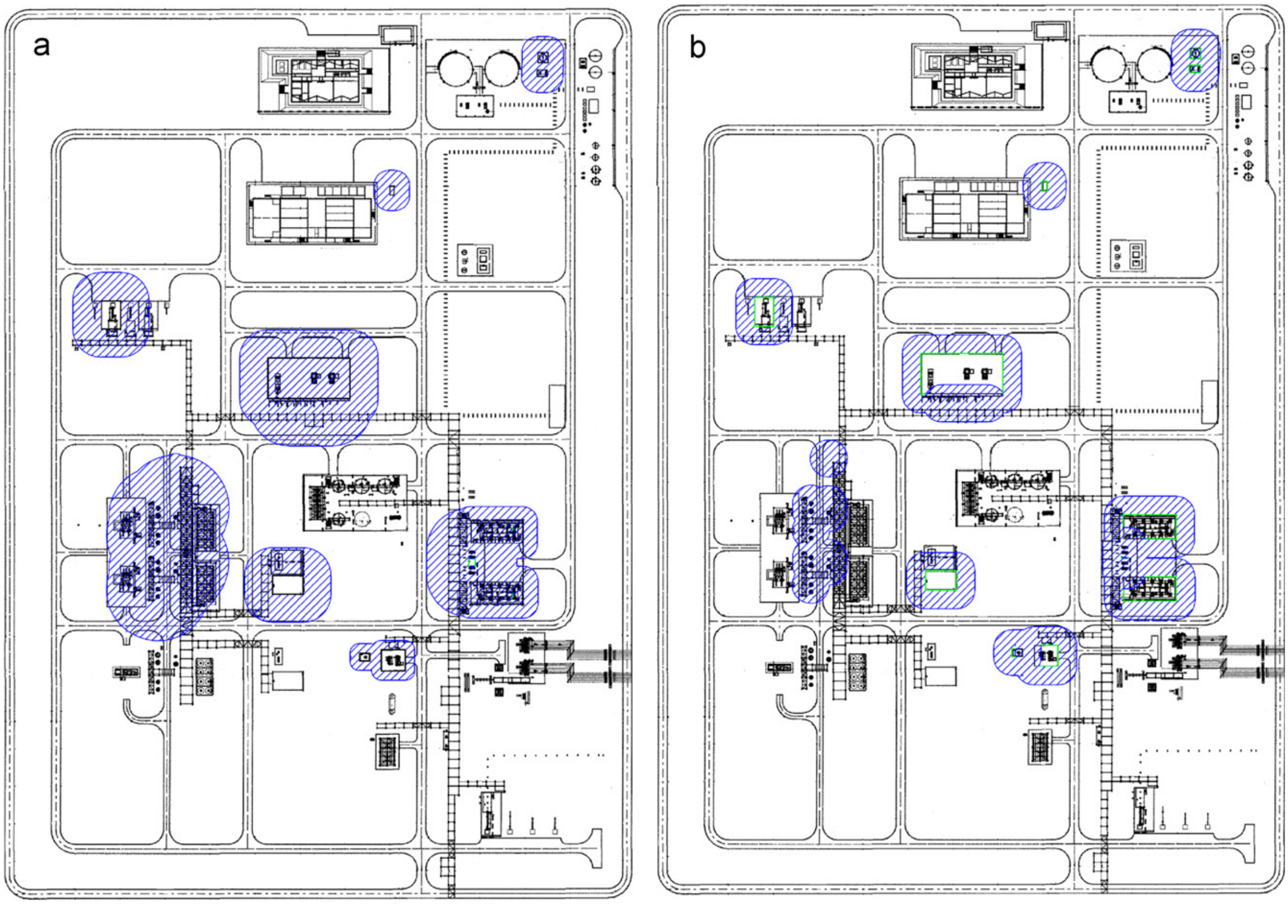


Fig. 8. Layout considered in the case-study and footprint of the fireproofing zones: (a) according to the proposed methodology only for the pool-fire scenario; (b) according to API 2218 [13].

quence assessment carried out for each relevant final scenario (Step 6b). The severity class of the consequences was identified considering the downtime of the vulnerable targets present within the impact area (Table 1). The application of the risk matrix reported in Fig. 3 yielded the semi-quantitative ranking of final scenarios (Step 6c). Table 7 shows that small diameter leaks (1/4″ and 1″) are all in the acceptable region, with the exception of 1″ flammable liquid release. The larger diameter releases, instead, fall in the zone requiring risk reduction measures and should be considered in the detailed consequence assessment.

Table 3 summarizes horizontal and vertical the maximum distances obtained for the reference LOC events identified (Step 7 of the methodology). The envelope of the relevant maximum distances defines the fireproofing zones for flame impingement and radiative heat for section CDS-03 (Table 3). Fig. 7 shows the footprint of the fireproofing zones for the entire installation considered in the case-study, obtained repeating the procedure described above for all the 63 isolable sections identified in Step 3.

4.3. Comparison with API 2218 standard

The results of case-study 2 were compared to those obtained applying the API 2218 standard. It is important to recall that the API 2218 standard was developed considering only the hazard due to pool fires. Thus, in API 2218 the analysis is limited to equipment items which contain flammable liquids and jet-fire scenarios are not considered.

Table 4 shows the “potential fire equipment” identified by the API 2218 methodology. Fig. 8-b reports the footprint of the zones identified for the CDS plant based on deterministic values for the extension of the flame envelope suggested by the standard (the higher bound value, 12 m, was applied). Fig. 8-a shows the extension of the fireproofing zones estimated considering exclusively pool fire scenarios in the methodology developed in the present study. As shown by the comparison among the two figures, the extension of fireproofing zones is comparable. These results show that the developed methodology is able to soundly capture all the outcomes expected by the application of the API 2218 (both in the identification of the potential source items, as shown in Table 4, and in determining the extension of the zones for fireproofing application, as shown by the comparison of Figs. 8-a and b). The proposed methodology, however, has the potentiality to include in the assessment also the possible damage from jet-fires, explicitly excluded from the scope of the API standard. The comparison among Figs. 7 and 8-b evidences significant differences in the extension of the fireproofing zones. The potential damage areas of pool-fires in several cases are smaller than those estimated considering also jet-fires. This is coherent with evidence from past accidents, since in several industrial accidents structural damage was caused by jet-fire scenarios having a sufficient duration.

5. Conclusions

A new methodology for the evaluation of fireproofing zones in onshore chemical and process plants was developed. The methodology allows the inclusion of jet-fires in the assessment, not considered for the definition of fireproofing zones in several standards currently applied to on-shore facilities. The adoption of risk ranking criteria for the selection of relevant LOCs makes the application of the procedure straightforward, if associated to the current availability of user-friendly software for consequence simulation. The developed methodology thus allows a step ahead in fireproofing practice, allowing a simple, but model-based and case-customized, analysis of fire damage zones due to pool fires or jet fires, overcoming the use of generic pre-defined characteristic distances for the fire envelope.

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