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A methodology for the analysis of domino and cascading events in Oil & Gas facilities operating in harsh environments

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ABSTRACT

The present study is aimed at defining a structured approach to the quantitative assessment of cascading events triggered by fire, accounting for the influence of harsh environmental conditions on the emergency response and on the performance of hardware safety barriers. A specific metric was defined in order to consider the external factors related to harsh environments on the determination of hardware and emergency safety barriers availability, with a specific focus on operations in extremely cold climates. The metric allows evaluating the time scale of emergency and the related efficiency of barriers in contrasting accident escalation. The values obtained for availability and effectiveness of barriers were input to a specific event tree analysis in order to support the quantitative assessment of accident frequency associated to cascading events. The approach is tested by its application to a case study, aimed at the assessment of the influence of extremely cold environmental conditions on the risk due to cascading events in an industrial site.

1. Introduction

Fires and explosions are critical accidents which may occur among Oil & Gas (O&G) production facilities, causing severe consequences for human health, environment, structural safety and asset. In this latter case, accidents may propagate among different units processing or storing hydrocarbons, eventually leading to the amplification of consequences (Khakzad and Reniers, 2015; Necci et al., 2015). This type of events are indicated as cascading or domino events, and severely affected offshore O&G installations and, more in general, the process industry (Cozzani and Reniers, 2013). Safety barriers, such as interlocks, fireproofing, and firefighting systems, are critical elements aimed at preventing the propagation of accidents among units and to ensure the integrity of the facility. These may be considered as "hardware" barriers, since they require activation (active protections) or are permanently in place (passive protections) (CCPS - Center of Chemical Process Safety, 2001). However, procedural and emergency measures play also a key role in the interruption of accident chains potentially leading to escalation, e.g. providing a suppression or attenuation of the primary events which trigger the accidents cascade, as in the case of fire-triggered scenarios (Lees, 1996).

The performance of safety barriers or protective layers against the propagation of cascading events may be strongly affected by external factors, in particular if the facility of interest is located in harsh environments. Harsh environments refer to those climatic conditions which may lead to difficulties for people to work and for process plants to be operated, with possible reduction of operational performance and system availability (Bercha et al., 2003; Gao et al., 2010; Khan et al., 2015).

In recent years, the exploitation of natural resources in harsh, remote and sensitive areas (such as Arctic and sub-Arctic regions) increased (Barabadi et al., 2015; Naseri and Barabady, 2013). This raised concerns about safety and environmental issues, also considering the limited amount of data and methodologies able to support structured analyses in this type of environment, which are critical to define a risk-based design framework to enhance the safety of operations (Gao et al., 2010; Paik et al., 2011; Vinnem, 2014).

The present study is aimed at defining a structured approach to support the quantitative risk assessment of cascading events, accounting for the influence of harsh environmental conditions on the effectiveness and availability of safety barriers, with particular reference to installations located in Arctic and sub-Arctic regions, either offshore or onshore, with subsea connections with marine or offshore facilities.

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The approach is based on the adoption of consolidated and verified vulnerability models for the evaluation of process and storage equipment probability of failure given an initiating event (Cozzani et al., 2005). In particular, the study focused on the assessment of cascading events triggered by fire, adopting previously developed probit models (Landucci et al., 2009). Then, the prevention and mitigation effect associated with the safety barriers and their performance in harsh environments is implemented. Relevant phenomena associated with the degradation of hardware barriers due to extreme weather conditions are also considered in the method. The specific role of emergency teams, and the possible delayed intervention and increment of human error probability due to extremely cold environments were determined.

The influence of extremely cold environment conditions on operational performance and availability of safety barriers was inferred on the basis of the analysis and of the systematization of previous studies and literature data. In particular, the outcomes of studies related to harsh environmental conditions influence on human factors (Bercha et al., 2003; Musharraf et al., 2013; Song et al., 2016) and statistical studies devoted to emergency response time modelling (Matteson et al., 2011; Taylor, 2016) were adopted in order to determine emergency teams performance data. On the other side, specific approaches recently developed for reliability and maintainability studies in Arctic and sub-Arctic regions (Gao et al., 2010) were adapted in order to model the performance of hardware barriers.

A dedicated event tree analysis, based on a previously developed approach (Landucci et al., 2016; 2015), was applied to support the quantitative assessment of accident frequency associated to cascading events. The approach was tested by a case study aimed at determining the influence of harsh environment on the risk profile of industrial facilities.

2. Methodology

2.1. Overview

The aim of the present methodology is to account for the influence of harsh environmental conditions on the frequency of cascading events, through a specific analysis of the effects on the expected safety barrier performance. Fig. 1 shows the flowchart of the methodology.

The preliminary step of the methodology (step 0 in Fig. 1) is aimed at the characterization of the safety barriers performance, with particular reference to the prevention and mitigation of cascading events triggered by fire. Three categories of barriers are considered (CCPS - Center of Chemical Process Safety, 2001): (i) active protection systems, (ii) passive protection systems and (iii) procedural and emergency measures. This step is based on the application of a previously developed methodology (Landucci et al., 2016; 2015), in which the evaluation of safety barriers performance in the framework of escalation is aimed at quantifying:

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

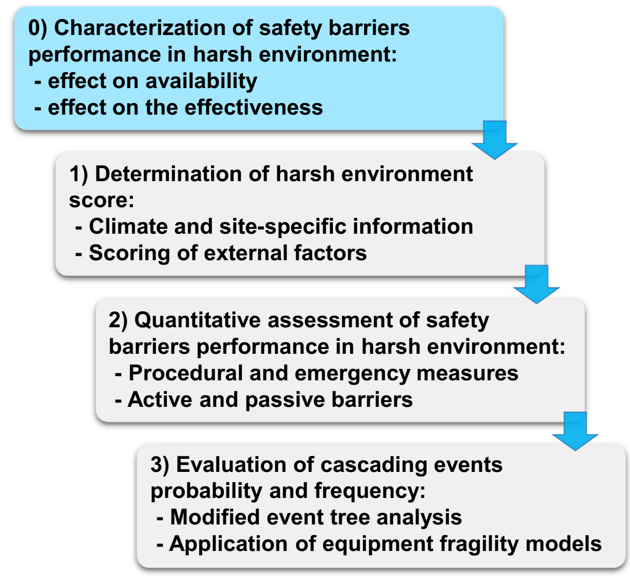

Fig. 1. Flowchart of the methodology adopted in the present study.

Once the parameters needed to support the quantitative evaluation of safety barriers are defined, the influence of harsh environmental conditions on their protection performance is addressed. In particular, for "hardware" barriers (both passive and active), it is assumed that extreme environmental conditions may seriously affect the availability characteristics of the components (Gao et al., 2010). No relevant effect is instead associated to the effectiveness, which was considered not affected by harsh environmental conditions.

In the case of procedural and emergency measures, both availability and effectiveness may decrease due to the influence of harsh environmental conditions. In fact, extreme weather and environments may have a relevant influence on human reliability (Musharraf et al., 2013), thus causing an increment of the probability of failure on demand (PFD) of emergency barriers when human factors are involved. Moreover, the emergency response time may be seriously affected by the environmental conditions, resulting in delayed deployment and operation, with a reduction of barrier efficiency. The latter issue was considered only with reference to extremely cold climates, since these are the conditions more likely to affect response time.

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

Starting from the estimated value of HES, the modification of availability and effectiveness of the barriers is carried out (Step 2 in Fig. 1), based on the tailoring of several models and approaches available in the literature. Finally, in Step 3 of the methodology (see Fig. 1) the escalation frequency and probability values are evaluated according to a modified event tree analysis (Landucci et al., 2016, 2015).

2.2. Definition of the harsh environment score (HES)

Cold environments impose serious stresses on operators and may adversely affect both their physical and cognitive performance (Bea, 2002). Furthermore, extreme temperatures, wind, waves or other external elements may seriously deteriorate the

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