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Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire

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ABSTRACT

The evolution of domino scenarios triggered by fire critically depends on the presence and the performance of safety barriers that may have the potential to prevent escalation, delaying or avoiding the heat-up of secondary targets. The aim of the present study is the quantitative assessment of safety barrier performance in preventing the escalation of fired domino scenarios. A LOPA (layer of protection analysis) based methodology, aimed at the definition and quantification of safety barrier performance in the prevention of escalation was developed. Data on the more common types of safety barriers were obtained in order to characterize the effectiveness and probability of failure on demand of relevant safety barriers. The methodology was exemplified with a case study. The results obtained define a procedure for the estimation of safety barrier performance in the prevention of fire escalation in domino scenarios.

1. Introduction

Domino accident scenarios triggered by the escalation of fires were responsible of severe accidents that affected the chemical and process industry [1–5]. Past accident data analysis confirmed that in more than half of the industrial accidents involving a domino effect occurred in the past fifty years escalation was triggered by a primary fire. Secondary targets more frequently affected by escalation were pressurized tanks, atmospheric tanks, process vessels and pipelines [4,6,7].

The awareness of the hazards posed by domino effect led to important efforts aimed at the prevention of such scenarios. In the European Union, the legislation on the control of major accident hazard (the so-called "Seveso-III" Directive, 2012/18/EU [8]) includes measures to assess, control and prevent domino effect [3,9,10]. Moreover, several technical standards introduce the use of protective systems or barriers to reduce the likelihood or possibility of domino events. In industrial facilities where such hazard is present, protections from escalation is usually obtained adopting multiple safety layers [11] that can include: the basic process control system, safety instrumented systems, passive and active devices, safety shutdown systems, protective systems (post-release actions) and emergency response plans.

The specific feature of escalation due to fires is the time lapse present between the start of secondary events with respect to the start of the primary fire [4,12–14]. In other escalation scenarios, as those triggered by overpressure or fragments, the secondary scenarios start almost simultaneously to the primary event. The delay in the start of secondary events in escalation triggered by fire is due to the damage mechanism of secondary vessels when exposed to fire. Actually, time is needed before the temperatures of the shell and of the internal fluid are able to jeopardize the structural integrity of the target vessels [15]. This time lapse, occurring between the start of the primary fire and the failure of the secondary equipment is generally termed "time to failure" (*ttf*) [15–17]. The *ttf* represents a key parameter to describe the resistance of equipment to external fires. The *ttf* depends on both the characteristics of the primary fire scenarios and the features of the secondary equipment involved in the fire [3,9,18–20]. A key point in the assessment of escalation probability in fire scenarios is that in most cases both factors may be modified by the installation of mitigation barriers and by appropriate emergency measures.

Therefore, an accurate assessment of escalation probability needs to include the analysis of the available fire protection systems and safety barriers. However, an exhaustive approach to the quantitative assessment of protection layers relevant to the prevention or mitigation of fired domino effect is still lacking.

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Besides, a comprehensive approach to the quantitative evaluation of the performance of all categories of protection layers (passive, active, procedural) in reducing the probability of escalation still represents an open issue.

The present study aims at the integration of a systematic quantitative analysis of safety barrier performance with probabilistic models for the assessment of escalation developed in previous studies [12,15]. A methodology to assess the performance of safety barriers in the prevention of escalation was developed. The performance of active, passive and procedural safety barriers for escalation prevention was assessed considering both availability and effectiveness, introducing a LOPA (Layer of Protection Analysis) approach. A database of expected performance reference data was obtained for standard safety barriers adopted in escalation prevention in different types of facilities. Equipment vulnerability models based on probit functions were integrated with the LOPA results. Modified escalation probabilities, including the influence of safety barriers, were thus obtained. The approach allowed assessing the reduction in escalation probability provided by each protection layer as well as by the overall system of safeguards implemented. The application to a case-study allowed the exploration of the features and potentialities of the methodology.

2. Methodology

2.1. Type and action of standard safety barriers

In order to include the action of safety barriers in the assessment of escalation, a categorization of safety barriers needs to be introduced. Actually, different types of safety barriers are effective in delaying or preventing escalation, and the procedure to consider their action in a quantitative assessment of escalation probability is different. Three different categories of barriers were identified, adapting the classification of protection layers proposed by AIChE [21] and in the Aramis project [22]:

- Active protection systems;
- Passive protection systems;
- Procedural and emergency measures.

2.1.1. Active fire protection systems

This type of protection systems is typically composed of three subsystems in chain [4,14,23–25]: a fire and gas detection system, a treatment system (logic solver, releasing panel or alarm advising operator) and an actuation system (mechanical, instrumented, human etc.) that provides water distribution. The detection system has the primary function of alerting personnel of the existence of a fire condition, allowing rapid identification of the location of the fire. The detection system activates emergency alarms, and usually triggers the emergency shutdown system, isolates fuel sources, starts fire water pumps and activates fire extinguishing systems [4,14,23–26].

Active fire protection systems more relevant in escalation prevention can be divided into two different categories [4,14,23–26]:

- Systems for the delivery of fire-fighting agents (such as water or water-based foam) which can be further classified into fixed, semi-fixed, mobile and portable systems;
- Emergency Shutdown Systems (ESD) and Emergency Depressurization Systems (EDP).

Active fire protection systems are aimed and designed to [4,22,25]:

- Mitigate fire exposure protection of the target, keeping a water film on exposed surfaces to absorb radiant heat and to cool the steelwork, thus preventing loss of strength (water delivery systems);
- Isolate and empty the target vessel, reducing the potential loss and consequent damage connected to the large inventory (ESD and EDP systems);
- Provide effective control of the primary fire and prevention of fire spread in nearby units (fire-fighting agents delivery systems).

2.1.2. Passive fire protection systems

A generic passive protection device is a system or a barrier which does not require either power or external activation to trigger the protection action [4,11,22]. In the framework of escalation prevention, the application of fireproofing material (cementitious or vermiculite sprays, intumescent, mineral or ceramic fibers, etc.) is a relevant and effective safety barrier. Pressure Safety Valves (PSVs) are a further widely applied passive safety barrier. Fireproofing and PSVs are aimed at combining two possible effects of mitigation [4,27–32]:

- reduction of the vessel wall temperature (heat resistant coating/shielding effect);
- limitation of the vessel internal pressure by the control of the vapor pressure increase due to the raise of the liquid temperature (PSV effect).

2.1.3. Procedural and emergency measures

Procedural measures include the company operating procedures which are relevant with respect to escalation prevention [4,11,22]. Emergency measures represent the coordinated response to a major accident scenario, in which different roles and functions are to be performed by different actors. They typically involve the mobilization of resources and follow specific procedures since all actions are to be carried out in agreement with local authorities, fire brigade, emergency teams, etc. [4,33,34].

2.2. Assessment of safety barrier performance in the prevention of escalation

Each type of safety barrier has a different action and a different availability. The quantitative assessment of safety barrier performance is routinely carried out by standard assessment techniques as the Layer of Protection Analysis (LOPA) approach. However, the specific framework of escalation prevention requires a tailorized approach to be developed, in particular for passive barriers and procedural measures.

A first issue is that the safety barriers considered may be classified as Protection Layers (PLs), and not Independent Protection Layers (IPLs), since most do not fulfill the criterion of independence [23,35], as they may fail by a common cause (the fire itself). Moreover, safety barriers may reduce the probability of escalation and/or mitigate the consequences (thus limiting the severity of the impact), but may not completely prevent escalation [35]. The evaluation of safety barriers performance in the specific framework of escalation prevention was thus aimed at quantifying:

- *availability*, defined as the probability of failure on demand (PFD) of the safety barriers;