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The Link between Fire Research and Process Safety: An Evolution from Specific Needs to General Concern

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Fire Safety Engineering generates key research that allows improving the knowledge and models of fire dynamics, therefore such research should constitute an input for Performance-based Risk Analysis of fire events. This Risk Analysis process for complex industrial facilities and operations are usually carried out within a Process Safety framework, in which is traditional to rely on the prescriptive approach given by standards such as NFPA. Nevertheless, with fire prescriptive codes integrating Performance-based Design and being this a traditional approach for other events such as explosions, Fire Safety Engineering research becomes a needed input for Process Safety. This link between the two engineering areas already exists but needs more structure and application in order to make it a usual practice for the design of facilities and their fire protection systems. This document seeks to throw light into this link and discuss its importance for the Risk Analysis of fire scenarios in complex industrial facilities, integrating the prescriptive and Performance-based approaches.

1. Introduction

Fire events are one of the categories of Process Safety (PS) for events that may occur at an industrial facility that can have undesired consequences. But fire events are a global problem as shown in Figure 1 in which fire events in all types of buildings are reported. In Figure 1 fire fatalities rates tend to be stable for most of the developed countries even when the global trend of fire protection costs of building is to rise.

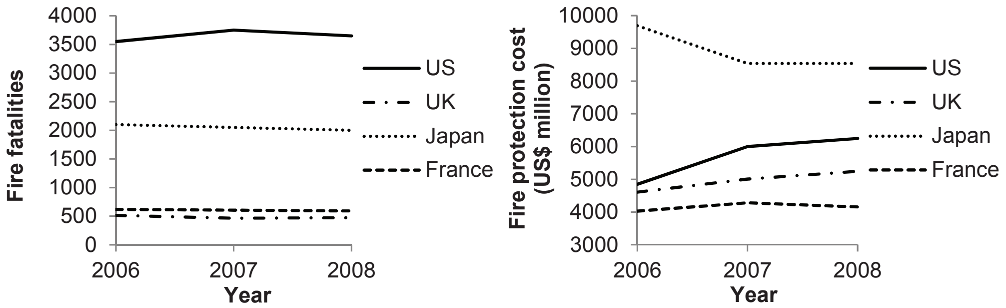

Figure 1: Fire fatalities (left) and fire protection costs statistics (US costs are scaled down by a factor of 10; right) (WFSC, 2011)

Off course, the tendency to rise of the fire protection costs carry a positive effect which is the reduction of fire events frequency of occurrence, as shown for the United States in Figure 2. But this reduction in

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frequency does not imply a reduction in fire costs, all the contrary, statistics show that the less frequent fire events are the loss increases for the US case. That means less but more severe fires, leading Fire Safety Engineering (FSE) to develop knowledge and tools to reduce the rates presented. The objective of FSE is to have a positive impact on systems performance under fire (Usmani et al., 2001, Fletcher et al., 2007) and the understanding of the behaviour of structures in past catastrophic events (Torero, 2011).

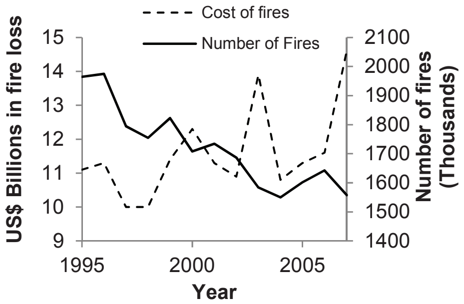

Figure 2: United States loss-frequency statistics (USFA-NFDC, 2009)

The issue can be translated to the non-residential sector, in which the number of fires are only around 7% of the total, but with direct loss of 150% compared to the average cost of all structures fires for the United States case. Within non-residential fires, fires might be grouped in three groups concerning the application of PS: industrial, storage, and manufacturing. These groups contribute to around 44% of all non-residential fires, with a higher percentage of property loss and fatalities for storage and injuries for manufacturing (USFA-NFDC, 2004). Other concerning element are major fire events and their consequences such as the presented in Table 1.

Table 1: Major fire events in the process industry and their consequences

Incident	Date	Location	Consequences
Caribbean Petroleum Company fire (Romo and Brice, 2009) (Currently under investigation)	26/10/2009	Bayamon, PR, USA	– 1 injured – Costs around US$6.4 M – Around 5.6 M of product loss – Around 600 people evacuated – Damage to buildings in a radius over 1 mi (1.6 km)
Valero-McKee refinery propane release and fire (Holmstrom et al., 2010)	16/02/2007	Sunray, TX, USA	– Over 10 injured – Costs over US$50 M – 2 months shut down
Silver Eagle refinery flash fire due to light naphtha release (CSB, 2009)	12/01/2009	Wood Cross, UT, USA	– 4 injured – Damage to shed and lab facilities

The wide panorama shown makes fires a real and present problem for all type of structures, but particular concern rises from industrial fires in which PS is the leading tool for loss prevention (Crowl and Louvar, 2011). This means that current prescriptive PS approach can be aided by FSE's in order to "defy solution(s) by the old 'prescriptive' approach to fire safety" and to "permit and promote engineered solutions to fire safety problems" (Drysdale, 1999). In order to identify the link that supports PS with FSE, a review of both is needed to identify and understand the linking element. Afterwards examples of PS supported by FSE are presented and finally conclusions are presented along with some perspectives.

2. Process Safety framework

A PS framework consists of management and technical structures, tools and guidelines for an organization to apply in order to manage the risks involved in its facilities and operations. These risks are directly related to events (fire, explosions and dispersions) and the consequences that these might have on the facility and surroundings. Such a framework is object of extensive work and research such as (Santos-Reyes and Beard, 2001). To understand where FSE and PS are linked, the framework might be presented as in Figure 3, dividing it in sources of risks, Risk Analysis and higher structures such as Risk Assessment and Risk Management. These sources of risk can result in events (fire, explosions and dispersions) with undesired consequences; therefore an understanding of such events is needed. This is achieved through the process of Risk Analysis (RA), for which several methodologies exist (Tixier et al., 2002). After this process is carried out, and understanding of the risks involved is established and higher structures allow determining additional safety measures (Perrin et al., 2012).

2.1 Risk Analysis

The RA process has gained great importance due to its contribution to a more accurate understanding of risks (Pasman et al., 2009). The process is better understood when doing a description of its pillars, and this was gracefully done by the global process safety academia in a consolidated document known as Process Safety Research Agenda for the 21st Century (MKOPSC, 2011). The global academia defined three pillars: a *design* necessity, the use of (safety) *engineering* concepts and tools, and the information generated by pure *science* regarding materials properties and behaviour as shown in Figure 3.

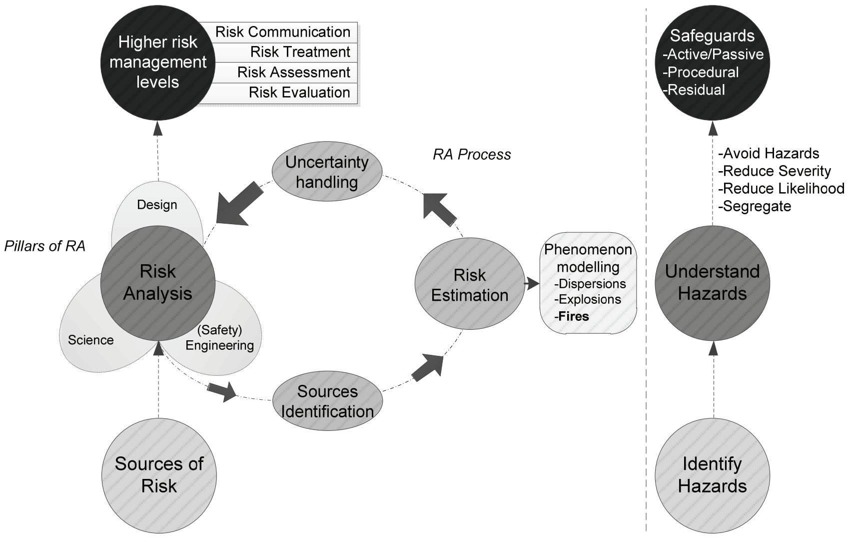

Figure 3: General Risk Management structure. Risk Analysis pillars (left) (MKOPSC, 2011) and process (middle). Risk Management framework for dust explosions (right) (Abuswer et al., 2011)

Figure 3 shows how RA fits into a general Risk Management structure, establishing a bridge between the identified Sources of Risk and the higher structures that deal with managing risk such as (Santos-Reyes and Beard, 2001). RA is defined as the systematic use of information to identify sources and to estimate the risk (ISO/IEC, 2002), which is interpreted as the understanding of risks as presented by (Abuswer et al., 2011) in a particular Risk Management framework for dusts explosions (shown in parallel to the general structure in Figure 3). This understanding of the risk leads to its estimation, which implies three basic steps: Sources identification, Risk estimation and Uncertainty handling; these are described as follows:

1. *Sources identification* requires as many details of the facility and operation as possible. This information is used to determine the (most) likely and worst scenarios involved, which at the same time are the input for the next step (Tixier et al., 2002).
2. *Risk estimation* refers to the estimation of the risk by describing (physically or stochastically) the events (e.g. fire) in the scenarios of interest. By describing such events, the intensities or variables of interest are estimated, e.g. thermal flux and duration of a flash fire. This estimation allows

calculating the consequences associated to a frequency or probability of occurrence (Mannan et al., 2005). This step gives a risk level result which is the input for the next step.

3. *Uncertainty handling* is gaining importance as presented by (Hurley, 2011). Uncertainty is classified in general as aleatory and epistemic. The first one concerns input parameters and their variability which is beyond the control of the analyst, e.g. wind speed and direction. It is uncontrollable and inherent to nature but it is compensated by using large amounts of empirical data such as historical records. The second one concerns the gap between the models used to describe certain phenomena and the real behaviour. It is implicit in all the models available to model fire and other phenomena, e.g. Fire Dynamics Simulator (FDS) (McGrattan, 2005). These models still lack important amounts of validation and their application is limited to two key elements: the physical restrictions of the model and the expertise of the user (Beard, 1997).

Steps 2 and 3 are the key for the link between FSE and PS, but a brief description of FSE's approaches to Fire Safety is needed in order to identify the inputs for PS.

3. Fire Safety Engineering approaches

As mentioned, the aim of FSE is to "permit and promote engineered solutions to fire safety problems" (Drysdale, 1999), and this has been done in two manners: Classical prescriptive approach and Performance-based approach. The first one concerns prescriptive codes which are in simple terms, the standardization of several decades of knowledge regarding fire behaviour in structures. This allows categorizing buildings according to several parameters such as type of structure, type of use and capacity, i.e. giving thumb rules for certain types of buildings. But with innovation in structures and architecture, resulting buildings no longer fall into these standard categories and improvement opportunities emerge such as those reported by (Morrison et al., 2012). These improvement opportunities take into account the particularities of each complex building is needed; this is the Performance-based approach, and many prescriptive codes are migrating towards or taking into account this approach. The latter is the reason for this document, since it is the work beyond the standardization of prescriptive codes that allows establishing the link between FSE and PS due to a simple reason: it allows having a better understanding of the phenomena, therefore of the risks.

4. Link between PS and FSE

After reviewing the PS framework, the details of RA process and the approach to fire safety problems of FSE, all elements are in place to describe in detail the link. Going back to the **Risk Analysis** section it was presented that steps 2 and 3 are the key to the link. In step 2, *Risk estimation*, models and knowledge are required to describe the fire phenomena. Such models and knowledge in the form of fire dynamics concepts and theories are best provided by FSE. Some relevant examples are the extensive and detailed literature such as (Drysdale, 1999) and the experience of applying models as complex as Computational Fluid Dynamics, e.g. FDS (McGrattan, 2005), or as "simple" as two control-volumes, e.g. Consolidated Model of Fire and Smoke Transport or CFAST (Jones et al., 2005). This knowledge along with the application of models experience provides technical input to carry out Performance-based analysis of the behavior of a facility under fire scenarios, allowing a detailed understanding of these, hence of the risk. Nevertheless, knowledge and models are susceptible of uncertainty, and this is especially true for fire when one takes into account the complexity of the phenomena. This complexity is given by the combustion reaction type (usually incomplete), spatial and time scales ranging from less than 1 mm to over 100 mm and from 1 µs to several minutes. The modeling of the previous is already highly complex, but when momentum, energy and mass balances, radiation heat transport and structural behavior are added, uncertainty grows significantly. This is presented by (Rein et al., 2009) in which a Round-Robin study of the a-priori use of FDS and CFAST for simulating a full scale test resulted in uncertainty ranging from -95% to 100% for a key variable of the fire –Heat Release Rate (HRR)-. Therefore the other key input from FSE is the analysis of uncertainty, which even if it is not removed or reduced, can help understand and manage it.

All fire dynamics knowledge, fire models and uncertainty analysis are the needed input to aid the RA process and therefore improving the decision making process for the design, operation or retrofitting of complex process facilities. In general terms, a risk analyst needs these inputs in order to make an informed decision in which the best tools available are applied and the uncertainty is taken into account. And this is precisely the link between FSE and PS: the key to informed decision making for fire safety problems. Some recent examples exist in which the mentioned link is noticeable and build the path to many more projects. Among others, some relevant examples are presented here:

- Use of a fire modelling tool (FDS) in a PS framework in order to approach fire risk scenarios in academic Chemical Engineering R&D facilities (Cadena et al., 2010)
- Literature in which Performance-based consequence analysis are carried out and explained within a PS framework (Casal, 2001)
- “The utilisation of the new (Performance-based) approach requires the existence of fire engineering tools to perform consequence analysis, which is the core of the risk analysis technique” and is applied to typical ship layouts (Salem, 2009)

5. Conclusions

FSE and PS should be considered intersecting areas of engineering; therefore its joint application should be encouraged in order to have a detailed view of fire safety problems such as those handled in RA for process facilities. This is particularly important for complex systems such as petrochemical facilities in which both the fire dynamics and the behaviour of the facility are not represented by prescriptive approaches.

Fire models application for consequences analysis and uncertainty handling are key elements which should not be omitted for scenarios of such a high complexity as fires. This presents a Performance-based approach, therefore aligning to the common approach for other events such as explosions and dispersions. This represents a higher degree of complexity, but a better understanding of the phenomena, hence of the risks.

The link between FSE and PS is still not a common practice in the process industry; therefore more efforts such as those mentioned should be developed in order to strengthen the link and making visible the potential for better RA, hence better application of PS.

6. Perspectives

Further work is needed in order to identify all improvement opportunities in analysing fire scenarios in a RA process and study how FSE input might offer solutions to these opportunities. Currently, the Safety Group at Universidad de los Andes is working on a-priori and a-posteriori study of the uncertainty for FDS simulations of compartment fires, reinforcing one of FSE inputs in order to apply them to further PS problems.

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