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Occupational Health Risk Assessment and Control of Fugitive Emissions in Chemical Processes

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Fugitive emissions are unavoidable and unanticipated releases can occur throughout a process plant wherever there are discontinuities or seals between the process fluids and the external environment. Despite being small in comparison to stack emissions, fugitive emissions can pose a significant hazard as it involves thousands of sources in a chemical plant (mostly from piping equipment and fittings) and the emissions occur continuously. Efforts to address the problem of fugitive emissions have mostly been driven by environmental concerns since emissions such as volatile organic compounds are an important source of greenhouse gases (GHGs). Besides the environmental impact, fugitive emissions are also considered as the main source of background exposure of workers to harmful chemical substances in chemical plants. Continuous, daily exposure to such emissions may pose a serious threat to the health of the workers. This study focuses on dealing with fugitive emissions from the occupational health risk perspective. The main aim of this study is to develop a hybrid framework for assessing fugitive emissions health risk by integrating the concepts of Layers of Protection, Source-Path-Receptor and Hierarchy of Control. To achieve this purpose, this project proposes a new approach of adopting the Layer of Protection (LoP) technique together with the concept of Source-Pathway-Receptor (SPR) for assessing and controlling the occupational health risk due to emissions in chemical plants. This paper presents the concept of the proposed approach that has been developed during the initial stage of this study.

1. Introduction

Fugitive emissions are broadly defined as “any chemical, or a mixture of chemicals, in any physical form, which represents an unanticipated or spurious leak in an industrial site” (Onat, 2006). These leaks are called fugitive because they are unanticipated, unavoidable and uncontrollable. They are released from discontinuities or seals which are designed throughout process plant to isolate the process fluids from external environment (Hassim, 2010). Fugitive emissions are minute when considering a single valve or any other piping component. However, since a huge number of these piping components i.e. valves, pipe connections, seals in pumps and compressors, pressure relief valves, and flanged joints as well as storage tanks, are distributed throughout the process plant, fugitive emissions are the largest source of volatile organic compounds (VOCs) in process industries (Speight, 2011). Fugitive emissions are a great concern since they are continuous and often remain unnoticed (Hassim et al., 2010). It is important to quantify the amount of fugitive emissions whether the process is still in the design stage or in operation. It provides companies with important information that is necessary to either perform technical modifications on the process to reduce the emissions or to design more effective leak repair programs (Speight, 2011).
Fugitive emissions are the main sources of the continuous exposure of workers to toxics in chemical plant industries (Lipton and Lynch, 1994). Workers are at risk since a wide range of toxic substances are directly released as fugitive emissions to the workers’ breathing zone in the plant on a daily basis. The routine exposure, even at low concentrations, to these toxic substances could impact their health.
The harmful nature of chemical plants has resulted in efforts by academia and industry to reduce the associated risks to a tolerable level. Various concepts targeted to achieve accident-free process plants have

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been basically driven by the desire to enhance process safety in the chemical industry. These concepts, however, have never been applied to deal with the issues of fugitive emissions and its associated health impacts.

2. Hazards Control in Process Industries

Generally, process hazards can be dealt with using two main approaches: (1) extrinsically and (2) intrinsically. Extrinsic safety is the conventional means practiced by all industries which basically relies on add-on and procedural (administrative) controls to keep processes in a safe state or prevent any deviation from occurring. In contrast to that, inherently safer design concept suggests a more fundamental means to handle hazards; that is to permanently eliminate or reduce the hazards in the process rather than to control them. This can be achieved through the use of more benign materials and operating conditions, smaller inventory and the design of user-friendly plants and process equipment (Mannan et al., 2015). More detailed description on inherent safety and other relevant concepts for hazards and risk management are provided in subsequent sections.

2.1 Concept of Layers of Protection (LOPs)

Layers of Protection (LOPs) are the control measures installed in a hierarchical manner to reduce the probability of accidents, not only in the chemical industry, but also in any industry dealing with hazards. There are two main types of protection layers, namely; (1) prevention layers and (2) mitigation layers (Macdonald, 2004). A preventive layer serves to prevent any deviation in the process (such as loss of cooling or overcharging of chemicals) from developing into an incident (such a release of hazardous materials). Once an accident occurs, mitigation layers serve to minimise the consequences (Frank, 2004). Protection layers can also be described as active safeguards (e.g. relief valves, safety instrumentation system (SIS), etc.) and passive safeguards (e.g. dyke, containment, etc.) (Ouazraoui et al., 2013). For better performance of the protection layers, each layer must be designed to be independent of the other layers (Macdonald, 2004).

An independent protection layer (IPL) is defined by The American Institute of Chemical Engineers, Center for Chemical Process Safety (CCPS) as “a device or system that is capable of preventing an accident scenario from proceeding to its undesired consequence independent of the initiating event or the action of any other layer of protection associated with the scenario” (Dowell and Hendershot, 2002). For a layer of protection to be considered independent, it must be effective in detecting and preventing an accident or mitigating its consequences. Also, an IPL must be independent of the initiating event and any other IPLs associated with the same hazardous scenario. The IPL must allow a regular validation of its protective function (Summers, 2003).

Practically, no layer of protection is designed to perform perfectly without any possibility of failure (Khalil et al., 2012). There is a time at which an IPL will probably fail, when demanded, to perform its function as required. This situation is referred to as the probability of failure on demand (PFD). A risk assessment is needed to assess the adequacy of an IPL and its ability to respond, when challenged, and quickly shift a deviation of a process operation to a safe state. In Layer of Protection Analysis (LOPA), a widely-used risk assessment technique, the PFD is used to quantify the effectiveness of a certain IPL in reducing the frequency of a consequence (CCPS, 2011). LOPA is also used to determine the Safety Integrity Level (SIL) required for the Safety Instrumented System (SIS) in a process (Dowell, 1999).

Hazards in chemical process plants cannot be eliminated even by the presence of highly effective add-on and administrative control systems. Add-on controls have the probability to fail and human behaviour cannot be totally controlled to avoid errors (Hassim, 2010). According to the hierarchy of controls concept, inherently safer design remains the most effective strategy, not in controlling the existing hazards, but in eliminating or reducing them starting from the source itself.

2.2 Concept of Hierarchy of Controls

Hazards and their ensuing risk in chemical plants are basically dealt with by designing a set of control measures that are prioritised, in terms of effectiveness, from the most effective to the least. This approach is referred to as the “Hierarchy of Controls”. This hierarchy starts with the elimination (achieved by inherently safer design) through to controlling by passive and active engineered add-ons, administrative (procedural) controls and personal protective equipment (PPE) (Amyotte et al., 2009). Describing these control measures with the term “hierarchy” “indicates that inherently safer design is not a stand-alone concept” (Amyotte et al., 2009). In other words, “inherently safer design works through a hierarchical arrangement in concert with engineered add-on and administrative controls to reduce risk” (Amyotte et al., 2009). At the same time, the hierarchy of controls does not deny the effectiveness of engineered and procedural control measures, but it recognises the importance of careful examination and assessment of these measures to insure their reliability when demanded (Amyotte et al., 2009). It is actually a system that compliments each other but the primary efforts should be put on inherent safety so as to reduce the burden of the subsequent less effective layers.

2.3 Concept of Inherently Safer Design

Following the tragic events of the Flixborough explosion in 1974 in the UK, a profusion of papers has been published discussing ways of preventing similar accident from occurring. Suggestions for more reliable protective equipment (e.g. gas detectors, emergency isolation valves and trips and alarms) were the most common outcomes of most of the papers (Kletz and Amyotte, 2010). In a different way of thinking, Trevor Kletz introduced the concept of inherently safer design. The essence of the inherently safer design is to avoid hazards in chemical plants rather than controlling them by add-on and procedural control measures (Kletz and Amyotte, 2010). An inherently safer design of a plant can be achieved through four strategies, namely; minimisation, substitution, moderation or attenuation or through simplification (Kletz and Amyotte, 2010). These strategies represent the main principles of inherently safer design concept.

The principles of inherently safer design can be implemented at any stage of the process lifecycle, but the best results will only be attained if it is implemented during the earliest stages of process development. That is because at the earliest stages, most of the basic decisions on the process are made and the process is still conceptual, giving the process engineers and designers the maximum freedom for making changes with lowest costs. In fact, the possibility of implementing inherent safety decreases as the design phase proceeds. Thus, the principles of inherent safety should be considered as early as possible.

It is clear that the concept of inherently safer design was developed to deal with safety-related issues in chemical process industries (CPIs). Unlike safety, health aspect in CPIs has received much less attention despite of the fact that every year more people die due to occupational-related diseases than those by safety-related accidents (Hassim and Edwards, 2006).

3. Occupational Health

The term “occupational health” indicates a two-way relationship between work and health. An occupational health hazard has the potential to cause harm to workers’ health (Hassim and Edwards, 2006). Work that is associated with health hazards, e.g. in chemical plants, may cause occupational diseases to workers. Although, chemical plants and their products have become an indispensable part of human life, they are a certain cause of adverse effects on human health (workers and community). Millions of workers worldwide are working in workplaces that are not safe to their health.

It is surprising that there is not enough attention paid to health issues which in reality, are as serious as safety issues. Lack of attention to health is somewhat understandable, especially when considering the way it differs from safety aspects. In terms of time, safety deals with events that occur within short time (acute) caused by deviations in the process and resulting in massive impacts to human and properties through fires or explosions (Hassim and Edwards, 2006). In contrast, health-related issues are a matter of long term (chronic) and accumulative workers exposure to hazardous chemical substances. Basically, workers’ exposure to chemicals substances within the process area takes place continuously on a daily basis during normal operations due to fugitive emissions.

3.1 Source-Pathway-Receptor Concept (SPR)

Assessment of health risk due to fugitive emissions requires attention on the three main elements of hazard - (1) source, (2) pathway and (3) receptor. ‘Source’ refers to the generation or origin of the presence of hazards in the process. This includes the chemical substances used in the process, the operating conditions employed as well as the work procedures involved. But from the context of fugitive emissions, the source can be represented by the properties of the chemicals to be emitted. This involves both physical properties which can determine the distribution of the materials and toxicological properties. Pathway, in this case, represents the potential leak. Basically, chemical plants with higher number of potential leak points (e.g. valves, flanges, pumps) have greater possibility for and quantity of emissions. Meanwhile ‘receptor’ means the potential exposure among workers to harmful materials escaped from the process (Hassim, 2010).

3.2 Motivation of the Study

As aforementioned, process safety has been and is still the main concern of chemical process industries unlike health. The nature of safety-related events i.e. their occurrence within a short time and causing massive impacts to human and property by explosions and fires, is the main reason behind its high priority. Many well accepted safety concepts and strategies (e.g. inherently safer design, hierarchy of controls, layers of protection, safety culture, and safety climate) were introduced to mainly deal with safety-related issues. For health-related risks, there is little effort made to understand, evaluate and reduce them especially in the early stage of process development. Application of the above-discussed concepts to deal with FEs issue has never been attempted before. In this study, the combination of both concepts is found to be very interesting in proposing a hybrid framework that can inherently and effectively assess emission-related inherent hazards to workers. The proposed tool will cover all elements of the hazard – source, pathway and receptor. Development of such a hybrid technique would be a great step towards eliminating or reducing the emissions of financially valuable, environmentally unfriendly or toxic chemicals.

4. Proposed Tool

In this study, a hybrid SPR-LOP tool is proposed. This tool will adopt current safety approaches (e.g. layers of protection) and apply them to assess health risk. In this study, the concept of LOPs and hierarchy of controls together with the SPR concept are integrated to produce a hybrid tool that can be used to assess the occupational health risk due to fugitive emissions in chemical plants. Subsequent sections will provide a more detailed description of the proposed tool.

4.1 Structure of the Proposed Tool

As illustrated in Figure 2, the SPR-LOP hybrid tool is composed of three essential parts, namely hazard, control and assessment. As previously described in Figure 1, hazard is represented by the SPR model which comprises (1) the inherent health hazard, (2) the inherent leak potential and (3) the inherent exposure potential. Next, control includes all possible and applicable protection layers (PLs) which are designed for each hazard to be controlled. In practical terms PLs can be in the form of technical, organisational (procedural) or behavioural (human factor) control measures. In Figure 2, these protection layers are illustrated by safer chemicals/conditions/design, maintenance, management system and safety culture. Finally, assessment involves the use of relevant health and safety indices and performance indicators to assess the PLs installed as control measures.

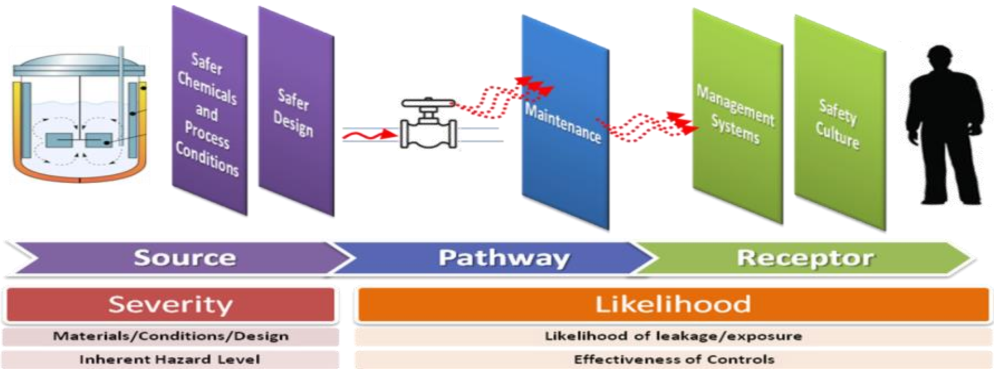

Figure 2: The structure of the SPR-LOP hybrid tool

In general, the hybrid SPR-LOP model illustrates how a person exposed to a particular hazard is protected. The protection layers in this case represent measures in the Hierarchy of Control ranging from engineering to administrative controls. The effectiveness of these PLs has a direct effect on the severity and likelihood of the hazard (i.e. risk) faced by the receptor. Each protective measure in the PL can be subsequently characterised and measured using suitable metrics.

4.2 Usage of the Proposed Tool

The process flow for the usage of the proposed SPR-LOP tool is shown in Figure 3. Firstly, the three hazard elements (SPR) are identified. Then, the relevant PLs are listed for each hazard component.

The assessment of the hazard element represented as source (health hazard potential) indicates the severity (consequence) of the overall health risk posed by fugitive emissions in the process. The assessment of the hazards at the pathway element (leak potential) and receptor (exposure potential) indicate the likelihood of that health risk. Each PL is assessed using suitable metrics as shown in Table 1.

Ultimately, the safety and health performance of a company, sector or industry can be assessed by the intrinsic level of hazard and the effectiveness of the PLs that have been implemented. This is therefore a hazards and risk-based approach to assessing occupational health risk. The results obtained from the metrics can be subsequently presented in a twin-axis format with the horizontal axis representing the inherent hazard level (severity) whilst the vertical axis represents the aggregated effectiveness of the various PLs (inverse of likelihood). The risk matrix formed from this assessment is illustrated in Figure 4.

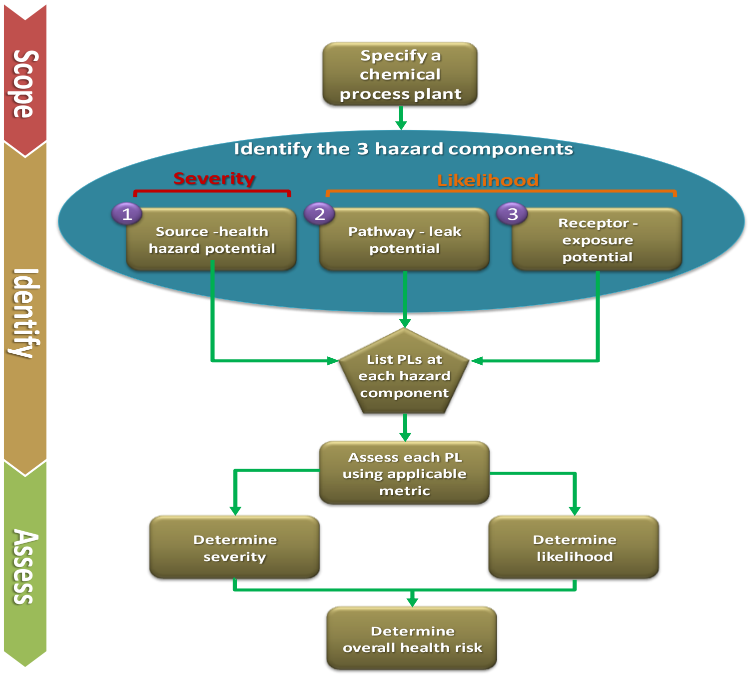

Figure 3: Conceptual framework of SPR-LOP hybrid tool

Table 1: Assessment of health hazard using currently available metrics

Stage	Hazard	Variable	Layer of protection	Possible metrics	Result
Source	Inherent health hazard potential	Material properties, operating conditions	Safer chemicals, processes, equipment	IOH Index, Inherent Safety Index	Overall Scoring for Health hazard
Pathway	Inherent leak hazard potential	Plant design	Inherently safer design	Plant size & complexity	Overall Scoring for Effectiveness of Controls
		Maintenance level	Plant maintenance	Plant audit	
Receptor	Inherent exposure potential	Work practices Management system	Good SOP OHSAS 18001	Plant audit	
		Worker behaviour Work practices	Good safety culture, behaviour-based safety	Audit	
		Management system	OHSAS 18001	Plant audit	

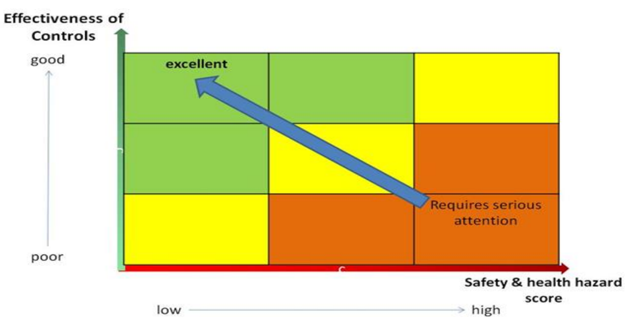

Figure 4: Risk matrix

5. Conclusions

Fugitive emissions are a significant source of workers' exposure to harmful chemical substances in chemical plants. Continuous exposure to fugitive emissions in chemical processes i.e. from piping components and fittings, even though very small, may pose a serious health threat to workers. This study seeks to develop a tool that can comprehensively assess and subsequently control occupational health hazards associated with fugitive emissions. The proposed method is called the SPR-LOP hybrid tool, which integrates the concepts of Layers of Protection, Source-Pathway-Receptor and Hierarchy of Control.

The tool is designed to deal with three elements that describe the fate of fugitive emissions' health hazards (1) the inherent health hazard at the source, (2) the inherent leak potential along the pathway and (3) the inherent exposure potential of the receptor. The hybrid SPR-LOP model traces how a person exposed to a particular hazard is protected. The tool is able to capture the different control measures (i.e. technical, organisational and behavioural) that can be implemented. The PLs represent measures in the Hierarchy of Control ranging from engineering to administrative controls. Each protective measure in the various PLs can be characterised and measured using suitable metrics. The effectiveness of these PLs has a direct effect on the severity and likelihood of the hazard (i.e. risk) faced by the receptor. This should allow us to comprehensively assess the overall risk of worker exposure to fugitive emissions in chemical processes before recommending the suitable measures to control the risks within the company's available resources.

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