

Using Hazards Assessment to Prevent Loss of Containment¹

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Abstract

Preventing loss of containment of materials and/or energy is a primary goal of industrial Process Safety Management (PSM) programs. A thorough understanding of the hazards, identification of a complete range of failure events, detailed analysis of the consequences of failure events, and the analysis of process risks accounting for all the safeguards can help significantly in preventing and mitigating loss of containment incidents. In this paper, additional details are provided on hazard assessment approaches, consequence analysis of potential events, and risk analysis for minimizing risks.

1. Introduction

Loss of containment (LOC) of toxic chemicals, flammable chemicals, and/or energy from vessels, pipes, or other equipment can potentially lead to consequences that can range from minor to catastrophic. A fundamental understanding and detailed assessment of process hazards is an important activity of industrial PSM programs [1], which must be much more involved than just reviewing or communicating material safety data sheets (MSDS). A complete range of failure scenarios must be analyzed in a systematic manner, including qualitative and quantitative methods, to develop information on potential consequences. With an understanding of hazards and the consequences of LOC events, a process hazards analysis (PHA) team, using semi-quantitative or quantitative risk analysis, can evaluate the adequacy of systems and the layers of protection necessary for preventing and mitigating loss of containment events. A summary of the paper on assessing hazards, consequences, and risks published elsewhere [2], is provided here.

2. Loss of Containment Incidents

LOC incidents are generally the largest category of process incidents, ranging from small releases of relatively non-hazardous materials to catastrophic events involving large releases of materials and/or energy. The consequences of LOC obviously relate to the intrinsic hazardous properties of the materials released as well as the processing conditions, such as concentration, temperature, or pressure. A small release of a highly toxic material can have more serious consequences than a much larger release of a non-hazardous material. A small release of a

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flammable material above its flash point may be more serious than a larger release below the flash point. Therefore, a careful evaluation of the range of failure scenarios is needed in order to determine the potential consequences and process risks associated with loss of containment.

Many significant chemical industry events involve LOC, but are not generally thought of directly as LOC events. The Bhopal incident in 1984, for example, is considered a toxic event [2] that killed or injured thousands of people. It was the inadvertent mixing of water and methyl isocyanate (MIC) in a storage tank leading to an uncontrolled reaction that resulted in a pressure increase and thus a LOC of toxic MIC. Similarly, the Flixborough incident in 1974 involved LOC of hot cyclohexane vapors followed by a vapor cloud explosion, the Seveso incident in 1976 resulted from LOC of toxic dioxin from a burst reactor rupture disk, and more recently, the BP Texas City explosion in 2005 occurred after LOC of hydrocarbons from a stack [3]. LOC, therefore, is present in many significant chemical incidents, either directly from equipment failure or from operating problems resulting in severe consequences, such as toxic exposures or fires/explosions, or indirectly, resulting from process events such as pressure build-up, runaway reactions, or dust deflagration that lead to emergency venting or loss of vessel integrity and release of contents.

Many LOC incidents relate to equipment failures caused by Mechanical Integrity system problems. This includes inadequate equipment installation, poor or lack of preventive maintenance, absence of reliability engineering, and ultimately inadequate analysis of the life cycle of equipment components. Many loss of containment incidents also result from operating and design problems, such as poor procedures, not following procedures (operational discipline), poor training, poor equipment design, etc. Any approach to preventing and mitigating the consequences of LOC must therefore consider a wide range of possible system failures encompassing all aspects of PSM. A systematic understanding and assessment of the hazards, analysis of consequences, and evaluation of risk in detailed PHA reviews can anticipate potential LOC failures and scenarios and provide appropriate process controls and safeguards to help prevent them.

3. Hazards Assessment

A hazard can be defined as a physical or chemical condition that has the potential for causing harm to people property or the environment [4]. A hazard assessment is different from consequence analysis, where the impacts of failure events are determined. It is also different from hazards identification and hazards evaluation in PHAs, where the focus is on identifying hazards, conducting a risk analysis and ensuring that sufficient layers of protection exist to minimize process risk. A systematic assessment of hazards and hazards level is one of the first steps necessary before conducting any consequence and/or risk analyses. A thorough understanding of process hazards is necessary for identification of potential loss of containment scenarios, which provide a pathway for exposure to the hazardous effects of the materials and of the processing conditions involved.

To systematically assess the hazards, it is necessary first to define process boundaries within a chemical plant. These process boundaries may correspond to those used in PHAs or to other appropriate parts of the facility. Within a process boundary, a complete list of all the raw

materials, intermediates, products, utilities, and other materials used should be compiled. Lists should also track amounts, rates, state (vapor/liquid/solid), compositions, etc. as appropriate. The level and nature of hazard will vary in different process boundaries depending on the quantities of chemicals handled, the intrinsic material properties, and how they are being used or processed. A tank farm that contains a variety of chemicals stored as liquids, for example, will have significantly different hazards than a manufacturing building that has some of the same chemicals being processed at high temperature or pressure. Consideration should also be given to the potential for chemicals and materials from one process boundary inadvertently entering another process boundary, possibly introducing new hazards that must be evaluated.

An MSDS or an International Chemical Safety Card (ICSC) prepared by a manufacturer of a specific chemical has often been used to provide data for hazard assessment. The quality of information in MSDSs and ICSCs is quite variable, and their use to compile and document information on hazards is generally inadequate, requiring additional sources of data.

3.1 Toxicity

Toxicity is the degree to which a chemical upon exposure can cause harm to any living organism [5], with toxicity effects determined by concentration and exposure time. The main concern from a process risk perspective is the acute toxicity effect resulting from a short-term exposure to an accidental release of a chemical. Chronic/subchronic toxicity effects are of greater concern for long-term environmental impact or worker exposure, resulting from longer exposures. In assessing the toxicity hazards, acute toxicity effects on people are evaluated, while the potential impact on plants and animals is also considered, where appropriate.

A good source of acute toxicity concentration and effects data has been developed by the American Industrial Hygienists Association and are called the Emergency Response Planning and Guideline (ERPG) concentrations [6]. Acute Exposure Guideline Level (AEGL) concentrations, developed by the U.S. EPA [7], are similar to ERPGs and can also be used. The ERPG/AEGL concentrations are developed by toxicologists using a wide range of available toxicological data to conservatively determine the concentration levels that might affect both general and susceptible populations. An AEGL-x concentration (like ERPG-x concentration), is defined as the airborne concentration (in ppmv or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience:

- 1 mild, short-term reversible adverse health effects
- 2 irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape
- 3 life threatening effects or death

The concentration values that are most appropriate in terms of assessing toxicity hazards are the AEGL-2/ERPG-2 for injury effects and AEGL-3/ERPG-3 for life threatening effects. Where the ERPG and AEGL values are not available, then equivalent values should be determined by industrial toxicologists.

The National Fire Protection Agency (NFPA) also publishes the Fire Protection Guide [8] which includes a Health Score that is on a 0 to 4 scale for a variety of chemicals. This score has been very useful from an emergency response perspective and is categorized based on health effects as follows: 0 (None); 1 (Slight); 2 (Moderate); 3 (Severe); and 4 (Extreme). This NFPA Health Score, where available, should be noted for chemicals and mixtures within a process boundary.

When assessing toxicity hazards, information about concentration levels of concern (ERPG, AEGL, or equivalent), NFPA Health Score, and other factors can all be used to determine the overall level of acute toxicity hazard within a process boundary. The hazard level score should be on a scale similar to the scale used for the NFPA Health Scoring and can be categorized as follows: 0 (None); 1 (Low); 2 (Medium); 3 (High); and 4 (Very High) using defined criteria.

3.2 Flammability and Thermal Radiation

Flammability is a property of chemicals that provides an indication of the potential for ignition and burning [9], with the degree of flammability determined by testing per standard protocols. For chemicals that are flammable, there are a variety of parameters that are useful in assessment of hazards, with the primary focus on harm to people from severe burn injuries upon exposure. An MSDS or ICSC may contain much of the pertinent data such as flash points, flammable limits, auto-ignition temperature, and products of combustion. However, it is important to verify and confirm the data from multiple sources.

For chemicals in a process boundary, based on the operating temperature and pressure, it is important to determine whether the chemicals or mixtures are in the flammable range. Upon ignition, a flame propagates from the ignition source to the release point resulting in a flash fire, pool fire, or a jet fire.

The NFPA has also published a Flammability Score that is on a 0 to 4 scale for a variety of chemicals [8]. This score is useful from an emergency response perspective and is categorized based on impacts as follows: 0 (None); 1 (Slight); 2 (Moderate); 3 (Severe); and 4 (Extreme). This NFPA Flammability Score, where available, should be noted for chemicals and mixtures within a process boundary. If a fire occurs, then in addition to burn injuries from direct contact, injuries and equipment damage can also occur from thermal radiation. Similar to toxicity impacts for lethal effects, the thermal radiation impacts are dependent on exposure time.

For a process boundary, once the list of flammable chemicals has been identified, a combination of the levels of concern, the NFPA Flammability Score, and any other available information should be used to determine the overall hazard level. The hazard level score should be on a scale similar to the scale used for the NFPA Flammability Scoring and can be categorized as follows: 0 (None); 1 (Low); 2 (Medium); 3 (High); and 4 (Very High).

3.3 Chemical Reactivity

Chemical reactivity is a hazard that results from uncontrolled chemical reactions in any equipment within a process boundary [10].

Exothermic reactions are usually of greater concern than endothermic reactions. Therefore, the first step in chemical reactivity hazard assessment is to identify the possible uncontrolled chemical reactions that can occur. These are usually side reactions that may not be normal within the process boundary and that could occur because of even small changes in operating conditions (i.e. pressures, temperature, composition, etc.), incorrect addition of materials, or inadvertent mixing of materials. Each reaction of concern within a process vessel should be evaluated to determine the potential level of hazard. Based on the reaction type, the exothermic nature can be used to determine the level of hazard.

The NFPA has also published a Reactivity/Instability Score that is on a 0 to 4 scale for a variety of chemicals [8]. This score is categorized based on impacts as follows: 0 (None); 1 (Slight); 2 (Moderate); 3 (Severe); and 4 (Extreme). For each specific reaction, the NFPA Instability Score, where available, should be reviewed for all the reactants and products. Where an NFPA score is not available, an equivalent score can be determined based on the structure of the chemical molecule.

For any reaction, the heat of reaction is a key measure of the hazard level, and in many cases, it can be estimated using the heats of formation of reactants and products. If the exothermic heat of reaction, usually expressed as calories per gram of reaction mass, is greater than 300 cal/g, then the hazard level is regarded as high; if it is less than 20 cal/g the hazard level is very low. The adiabatic temperature rise can be calculated using the overall heat generated in a reaction, the reaction mass, and the heat capacity of the mixture. The self-heat rate can be measured or often estimated based on the type of reaction, and the onset temperature where reaction occurs can be measured using calorimetric methods. Information on all of these parameters can be used to determine the level of chemical reactivity hazard within a process boundary. The hazard level score should be on a scale identical to the scale used for the NFPA Instability Score and can be categorized as follows: 0 (None); 1 (Low); 2 (Medium); 3 (High); and 4 (Very High).

3.4 Explosivity or Explosibility

Explosivity or explosibility can be viewed as the measure to which a material is explosive or explosible. Explosion hazards can result from loss of containment of flammable chemicals and/or fine combustible dusts into a confined and/or congested environment [9].

In addition to vapor cloud explosion (VCE) and dust explosions, explosions can also result from bursting of a vessel caused by a rapid increase in pressure. Such a build-up of pressure could be the result of an uncontrolled chemical reaction, from failure of pressure regulators upstream of equipment, or from deflagration of combustible dusts within pipes/equipment, and it is one of the primary causes of LOC. If the pressure inside the vessel exceeds the maximum working pressure, then a vessel burst occurs which can result in propagation of a blast wave. A rapid increase in temperature and pressure from a fire under a container can also lead to a boiling liquid expanding vapor cloud explosion (BLEVE), if the material in the container is a liquid under pressure at a temperature greater than its boiling point. If a BLEVE occurs, in addition to a blast wave, a fireball can form leading to thermal radiation impacts.

The maximum deflagration pressure and the rate of pressure rise are important parameters that can be measured for a variety of fuels. Once a fuel ignites, the rate of flame acceleration

determines the maximum pressure generated in a confined and congested environment. The fundamental burning velocity of a material [11] is a measure of the rate of flame propagation that can occur and indicates how reactive a material might be in terms of generating of high deflagration pressures and increased rate of pressure rise.

For assessing explosivity hazards, it is important to know the flammable mass/volume, particle size in the case of combustible dust releases, laminar burning velocity of chemical/mixtures, levels of confinement and congestion, and deflagration indices. Such information can then be utilized to determine the level of explosivity hazard within a process boundary. The hazard level score should be on a scale similar to the scale used for the NFPA Flammability Scoring and can be categorized as follows: 0 (None); 1(Low); 2 (Medium); 3 (High); and 4 (Very High).

4. Consequence Assessment

Consequence analysis consists of evaluating the direct, undesirable impact of potentially hazardous events, resulting from loss of engineering and administrative controls for the process [4]. The purpose of consequence analysis is to help a PHA team understand the type, severity, and number of potential injuries, property damage, and environmental harm that result from the incidents. The systematic hazards assessment discussed in Section 3 provides the basic input information necessary for consequence analysis. For events that result in loss of containment, the data might include the nature of discharge, rate of discharge, composition, temperature, pressure, and toxicity or flammability of chemicals or mixture. For events inside vessels that could lead to loss of containment, such as an unexpected chemical reaction, deflagration of gases, or deflagration of combustible dusts, the useful data would be the change in temperature and pressure with time, the material of construction, emergency vent design, and pressure rating of a vessel.

In conducting the consequence analysis, the team evaluates the impact of possible hazardous events in terms of potential release quantities, affected areas, and injuries or property damage. In determining the events for consequence analysis, especially for loss of containment, a complete range of small to catastrophic failure events should be considered. A small event could be caused by a small-diameter hole in a vessel or pipe or possibly a procedural error such as leaving a valve open or in the wrong position. Catastrophic failure events are those where there is a complete and sudden failure of any equipment, structure, or system resulting in major loss of containment of chemicals or energy. Even though catastrophic failure events are rare, the consequences of such an event could be significant and should be well understood.

Many models are available to calculate the areas impacted by loss of containment releases for events such as spills, holes in pipes, pump leaks, stack releases, etc. [12]. Typically, these models require inputs on physical properties, release conditions, meteorology, and levels of concern for various consequence thresholds. The primary result from modeling is the area impacted by the release for the defined input conditions and levels of concern. This model result must then be interpreted by the PHA team to evaluate the type, severity, and number of injuries or property damage in order to understand the consequences of the event. This will require the PHA team to also consider how many people may be exposed to the release, how long they may be exposed, the warning properties of the material, ventilation, exits, and the effects the material

may have on people. For toxic materials, for example, it will be necessary to consider the acute toxicity of the material, how it affects the body, and whether or not it will affect a person's ability to evacuate. Consequence modeling can also be used to consider possible secondary effects resulting from the event, such as broken lines or damaged vessels in other parts of the facility, which can lead to additional injuries or property damage. In addition, the effectiveness of certain preventive or mitigating safeguards can be evaluated for reducing possible injuries or property damage.

5. Risk Assessment

The primary purpose of a PHA is to assess the overall process risk and determine if a process is safe to operate. To evaluate risk, PHA teams use the information available on the nature and level of hazards from the PT/PSI compilation discussed in Section 3, and the consequence analysis results discussed in Section 4 for complete range of failure events. The frequencies of the primary failure events of interest can be determined qualitatively or quantitatively based on site data or industrial data sources. Risk resulting from any event is then determined as:

$$\text{Risk} = \text{Consequence} \times \text{Frequency}$$

Often, a qualitative to semi-quantitative risk assessment is adequate, using a risk matrix or similar approach [4]. Company risk guidelines are used to determine when new or improved safeguards are required to achieve an acceptable level of risk for the process. In some cases, layer of protection analysis [13] or more comprehensive quantitative risk analysis [14] may be required to properly evaluate risk within certain process boundaries.

Use of risk analysis helps to better balance the PHA team understanding of low frequency, high consequence events against higher frequency, lower consequence events. Small releases may occur relatively frequently with relatively lower consequences depending on the materials and processing conditions, but can represent overall higher risk because of the high frequency of occurrence vs. larger, more catastrophic release events. Knowledge of the frequency, consequences, and failure mechanisms helps the PHA team make informed recommendations to ensure process design and operation is appropriate to minimize process risk.

Risk analysis, both before and after the consideration of PHA Team recommendations, therefore, provides sufficient information to minimize the risk resulting from all possible failure events. In most cases, a qualitative to semi-quantitative assessment is adequate. However, sometimes a more comprehensive risk assessment [13, 14] may be needed to ensure that the risk within a process boundary is as low as reasonably practicable or achievable.

6. Summary

A thorough understanding of the process hazards, detailed consequence analyses for a complete range of failure events, and process risk analysis accounting for all the safeguards can help significantly in preventing and mitigating LOC incidents. By evaluating the potential causes of LOC through use of these methodologies, PHA teams can ensure process design is appropriate to minimize the potential for loss of containment events, can provide appropriate containment or

mitigation systems, can establish appropriate preventive maintenance schedules and procedures, and can provide safe operating practices. Developing and communicating knowledge of all the hazards, consequences, and risks is extremely important for a PHA team and a PSM program to ensure that a process is safe to operate.

Additional information on this topic is available in other PSP articles [15-17].

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