Maintaining Consistency in the Determination of Consequence Severity Rankings for Process Hazard Analyses

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Abstract

A Process Hazard Analysis (PHA) is an important tool for identifying and managing the hazards associated with a chemical process. One of the most critical aspects of the analysis is the risk ranking of scenarios, which is used to determine which events pose a high risk and may require further mitigation. The risk ranking of a scenario is built on two factors – severity and likelihood. The severity of a scenario is a measure of the potential worst-case impact on facility operation, facility personnel, the public, or the environment, while the likelihood is an estimate of the probability with which an event may occur, given the presence of the safeguards acting to prevent or limit the severity of the event.

Severity of a scenario is generally expressed in qualitative terms. While a typical approach to assigning consequence severity rankings involves categorizing events by impact (e.g., recordable injury, permanent disability, or fatality), this approach relies on the subjective judgment of the analysis team in determining the exact impact of a specific event. Experience has shown that, because of the subjective nature of this step, different PHA study teams have had varying opinions on the potential severity level of a given scenario. It is the aim of this study to provide guidelines to improve consistency of severity rankings both within a single analysis, and across multiple analyses with separate PHA study teams. It is possible to increase the consistency in consequence severity rankings through application of standardized guidelines. A method has been developed to aid PHA facilitators based on dispersion modelling of various conditions typically encountered in a PHA. The underlying data is based on groups of chemicals with similar properties and other conditions (e.g., break size, break location, etc.).

1. Introduction and Background

Process Hazard Analysis (PHA) is an important tool for identifying and managing the hazards associated with a chemical process. The goal of a PHA is to use a systematic methodology to identify each potential hazard source within the process. A typical PHA methodology is the guideword-style Hazard and Operability (HAZOP) study. To ensure completeness, the HAZOP methodology breaks down a complex system into individual nodes, making it easier to thoroughly analyze each section of the process. Further, within each node, hazards are postulated according to a standard combination of guidewords and process deviations. For example, when the guideword 'No' is paired with the deviation "Flow," all scenarios within the node which lead to a loss of flow are considered.

Once a scenario is identified, the risk posed to the facility must then be determined. This is normally achieved through the risk ranking process. To determine the risk ranking, each scenario is assigned a severity and a likelihood level. This pair is then used in a risk ranking matrix, which defines the risk targets developed by company management prior to the start of the PHA. Assigning a risk ranking is one of the most important facets of the PHA process, as it is used to determine which risks are acceptable given the safeguards currently in place, and which require further actions to ensure that the risk is maintained at a tolerable level.

Currently, there is a large potential for variance in risk ranking determination, specifically with regard to consequence severity. While severity determination is meant to be a qualitative ranking, there are a number of benefits to improving the consistency of severity rankings among similar release scenarios. Kazarians & Associates, Inc. has developed a method that has proven effective in reducing variance among consequence severity rankings through the use of pre-determined dispersion modeling results.

2. Current Methods for Consequence Severity Determination

It is common practice to estimate the worst case consequence severity for the identified potential release scenarios. For this, it is assumed that all existing active safeguards are unavailable. Typically, the severity ranking is a qualitative determination made by the PHA study team based on their understanding of the potential impact a given scenario may have on the safety of facility personnel and the public, as well as the environment or business operations. The text provided in defining each severity level is generally used to determine the consequence severity. Table 1 provides an example of severity level definitions available to the PHA study team.

Definitions such as those in Table 1 can provide a good starting point for consequence severity selection. However, use of these limited definitions can result in inconsistent severity rankings, both within an individual PHA, as well as among PHAs. This variation stems from the fact that the PHA study team generally carries the chain of events to the release condition (i.e., flange leak, pipe rupture, etc.) whereas the definitions of consequence severity level is often in terms of level of harm (i.e., first aid injury, fatality, etc.). This then requires the study team to envision how the release will ultimately result in harm, which means that they have to take into consideration factors such as source conditions, dispersion, and ignition, which are often complex phenomena by themselves. Therefore, this leads different PHA study teams to hold varying opinions of what the impact of a certain event may be. Typically, these opinions are based on the experience of the personnel present during the PHA.

Table 1. Typical Consequence Severity Guidance

Consequence Severity	Impact on Personnel	Impact on the Environment	Impact on business
1	Minor first aid injury	Slight spill onto soil, release to flare	< $10,000
2	Recordable injury	Small spill onto water, moderate spill onto soil	< $100,000
3	Permanent disability	Moderate spill onto water, large spill onto soil	< $500,000
4	Fatality	Moderate spill into an environmentally sensitive area	< $1,000,000
5	Multiple fatalities	Large spill into an environmentally sensitive area	< $5,000,000

The following example is taken from PHAs conducted for chlorination systems at two facilities operated by the same organization. The example demonstrates the difference operational experience can make in the severity ranking of a given scenario. During PHA sessions for the two systems, the PHA team encountered the same scenario in which a storage tank is exposed to an external fire, resulting in a pressure increase within the tank, ultimately resulting in tank rupture. In this scenario, the two teams have arrived at an identical endpoint (i.e., release scenario). While the release conditions (i.e., temperature and pressure) will be the same for both cases, the first team concludes that a single fatality may result, the second believes that multiple fatalities may result. The two teams may record the scenarios according to Figure 1.

In each case, the PHA study team has arrived at the same chain of events leading up to an integrity failure of the storage tank, and release of chlorine into the atmosphere. However, the final consequence statement and therefore risk rankings vary based on the estimated severity of the release.

Inconsistency in severity rankings can cause a number of problems following a PHA. Most importantly, they can lead to an over- or under-estimation of the risk a scenario poses. A consequence with the potential to cause severe injury that has only been identified as a first aid issue could result in insufficient safeguarding to protect against the event. This could ultimately lead to major safety incidents during the operating lifetime of the process. Safeguards are typically added when the risk ranking of a scenario does not meet the pre-determined corporate risk target. A lower severity ranking may indicate that the appropriate safeguards are in place, when in reality an additional protection may be necessary.

Team 1:

Causes	Consequences	Safeguards	S	L	RR	HAZOP Recommendations
Greater than 140°F in the Chlorination Room caused by a fire	▪ Pressure buildup in the Chlorine Storage Tanks. ▪ Potential for loss of containment of a Chlorine Storage Tank if the relief valve fails to lift. Release of chlorine into the Chlorination Room. Potential for personnel exposure.	▪ Relief Valves will lift to prevent overpressure. ▪ Detectors alarm locally and on SCADA. ▪ Scrubber activated by detectors at 3 ppm. ▪ Plant housekeeping practices prohibits storage of any combustible materials in the Chlorination Room.	4	D	M	

Team 2:

Causes	Consequences	Safeguards	S	L	RR	HAZOP Recommendations
Fire inside the Chlorine Building.	Potential for increased pressure in the storage tanks. Potential to rupture the storage tank. Potential for release of chlorine inside the building. Potential for personnel and public exposure.	1. PSVs on the storage tanks set at 225 psig. 2. Chlorine detectors alarm at 1 ppm. Scrubber system will start at 3ppm on any one detector. 3. Good housekeeping practices.	5	E	M	No recommendations necessary. Safeguards are considered adequate.

Figure 1. Identical PHA Scenarios with Differing Consequene Statements and Risk Ranking

A second and more subtle consequence of inconsistent severity ranking is the potential discrepancy between processes or facilities. If two PHA study teams assign different severity rankings to similar events on two similar systems, there is a potential for one system to require an extra safeguard to be installed which is not in place on the second system. This discrepancy between units could potentially lead to confusion later in the life of the plant. If a group of operators is responsible for both systems, there could be confusion as to which setup is correct, as well as the incorrect assumption that both systems are configured in the same manner. Additionally if an incident occurs in the system with fewer safeguards, there is a potential for increased regulatory scrutiny and fines due to the fact that the second system is not as well protected as the first.

3. Improving Consistency through Dispersion Modeling

To reduce variation among consequence severity rankings, it is possible to provide PHA teams with improved guidance on the potential impacts of a release. Dispersion modelling is a tool which is commonly used to determine the hazardous area resulting from a specific chemical release scenario. There are a number of sophisticated dispersion models and software packages currently on the market which can provide a picture of the hazard distance presented by various chemical release events. Many of the commercially available packages allow the user to input specific data such as the temperature, pressure, quantity, and release orifice size, and calculate the released quantity, pool size, vaporization rate, and resulting hazard distance. Depending on the model chosen, the user may be able to customize the scenarios to a greater degree, including such factors as terrain type, degree of confinement, explosive characteristics, etc.

Currently, some PHA teams already use dispersion modeling to assist in performing a more in-depth analysis for select scenarios with complex release characteristics. These studies are useful, but require a large amount of input data to be determined by the PHA team in order for them to generate accurate results. Therefore, it is much too time consuming to use such an analysis for every release scenario postulated during a PHA.

To combine the time and cost efficiency of PHA with the increased accuracy afforded by the use of dispersion modeling, the dispersion calculations can be performed generically prior to beginning the PHA discussions. To utilize this method, a database is developed for each hazardous chemical which may be released, and dispersion calculations are performed for the range of temperatures, pressures, phases (liquid or gas), and break sizes which may be encountered during the PHA. Every possible combination of parameters does not need to be considered, as the PHA team may quickly interpolate between results when needed. With a pre-developed matrix in front of them during the PHA sessions, participants can quickly relate a set of known release conditions to an approximate hazard zone, which will allow them to choose a more refined consequence severity. Some large chemical processing and manufacturing corporations have already begun to adopt such methods to improve the consistency of their PHAs.

The method developed by Kazarians utilizes PHAST modeling software by Det Norske Veritas [Reference 1] to create databases for both flammable and toxic chemicals. Specifically, the common alkanes (i.e., methane through hexane), hydrogen, hydrogen sulfide, anhydrous ammonia, and chlorine have been analyzed, in both liquid and gaseous form. In each case, a generic outdoor release event is postulated for varying temperatures, pressures, spill quantities, and release sizes. From this basic input data, PHAST is capable of generating information on the maximum dispersion distance, the flammable range, the range of explosive overpressure, and toxic effects. For each release event, the maximum distance of each hazard type is compared, and the greatest distance is selected. For example, for a specific set of release conditions, the maximum distance at which an injury may occur due to thermal radiation is 200 feet, while the maximum injury distance due to explosive overpressure is 250 feet. For these release conditions, 250 feet will be selected and recorded as the worst-case injury hazard distance. The final result is a set of eight tables for each chemical, with four liquid phase tables and four vapor phase tables. Tables 2 and 3 below show the four hazard distance tables for methane in the liquid phase.

Table 2A. Methane Liquid Injury Hazard Distance (ft)

	Source Temperature (F)			
Release (lbs)	**-250**	**-200**	**-150**	**-117**
10	110	100	140	160
100	350	230	320	350
1,000	610	510	710	780
10,000	1,520	1,130	1,570	750
100,000	4,060	2,480	3,350	3,350
500,000	7,690	4,260	5,360	5,360

Table 2B. Methane Liquid Injury Hazard Distance (ft)

	Source Pressure (psi)				
Break Diameter (in)	**50**	**150**	**300**	**400**	**450**
0.25	20	30	30	30	30
0.5	110	110	110	110	110
0.75	180	210	210	210	210
1.0	210	280	310	310	310
1.5	280	410	480	510	510
2.0	380	540	640	670	700
3.0	510	770	970	1,070	1,100
4.0	610	1,000	1,330	1,430	1,460
6.0	840	1,430	2,020	2,180	2,250

Table 3A. Methane Liquid Fatality Hazard Distance (ft)

	Temperature (F)			
Release (lbs)	**-250**	**-200**	**-150**	**-117**
10	40	40	60	70
100	240	90	130	150
1,000	530	210	310	340
10,000	1,390	470	690	1,690
100,000	2,990	1,070	1,500	1,500
500,000	5,290	1,860	2,400	2,400

Table 3B. Methane Liquid Fatality Hazard Distance (ft)

	Pressure (psi)				
Break Diameter (in)	**50**	**150**	**300**	**400**	**450**
0.25	20	20	20	20	20
0.5	40	50	50	50	50
0.75	110	140	140	140	140
1.0	140	210	240	240	240
1.5	210	340	400	440	440
2.0	300	470	570	600	630
3.0	440	700	890	990	1,030
4.0	530	930	1,260	1,350	1,390
6.0	760	1,350	1,940	2,110	2,170

Tables 2 and 3 present two sets of hazard distances. One represents the distance inside which an injury is expected to occur, and one inside which it is possible for fatalities to occur. Additionally, the sets have been subdivided into Tables A and B, which provide dispersion information for Release Quantity vs Temperature, or Break Diameter vs Pressure. The PHA team may elect to use either of the tables based on what information is available for a given scenario. For example, Break Diameter vs Pressure tables may be more useful for a pipe break scenario, while Release Quantity vs Temperature may be easier to use in the event of a seal failure or liquid overfill scenario.

There are a few notable trends which can be identified from Tables 2 and 3. Specifically, it can be seen that in the tables relating Break Diameter and Pressure, the maximum hazard distances reach a constant value as pressure increases. This is due to the release reaching what is known as "sonic velocity." [Reference 2] When a material under pressure is released through an orifice, the velocity of the release is initially dependent on the pressure within the vessel. Higher release pressure will typically result in a higher release velocity. However, once the release velocity has reached sonic velocity, further increases in pressure will no longer cause the velocity to increase. Put simply, no more material can fit through the release orifice, no matter how much force is behind it.

4. Defining Exposure Thresholds

The final dispersion distances reported in Tables 2 and 3 can vary greatly depending on what thresholds values are chosen for injuries and fatalities. This analysis used three potential sources of impact to the population: overpressure due to explosion, thermal radiation due to fire, and exposure to toxic vapors. Each threat has a unique hazard zone that is determined by its effects on both the human body and surrounding structures.

There is a great deal of research performed on the various effects on the human body caused by exposure to overpressure, thermal radiation, or toxic chemicals [References 3 through 10]. From this research, threshold values can be estimated to determine the exposure limits for injuries and fatalities. Table 4 presents the threshold values used in this article to differentiate between effects.

Table 4. Exposure Threshold Definitions

Explosion Overpressure	
Effect	**Threshold Value**
Injury	0.5 psi
Fatality	2 psi
Thermal Radiation	
Effect	**Threshold Value**
Injury	5 (kW/m^2)
Fatality	10 (kW/m^2)
Toxic Exposure	
Effect	**Threshold Value**
Injury	ERPG-2
Fatality	ERPG-3

It is important to note that these values represent conservative estimates of the potential impact an event may have on a person. For example, the threshold values for thermal radiation exposure are time dependent. Exposure to 10 kW/m^2 will not result in an immediate fatality, but prolonged exposure of approximately 60 seconds could result in death. This value is chosen as it represents the possibility of a fatality since it requires rapid evacuation from the hazard zone.

For each scenario modeled in PHAST, the distances to each threshold value described in Table 4 are compared, and that which results in the largest hazard distance is selected as the worst-case hazard zone. Toxic effects are only calculated for those chemicals which pose a significant risk when inhaled or contacted.

5. Using Hazard Distance Tables During PHA Sessions

Once developed, hazard distance tables can be used during PHA discussions to quickly determine an appropriate severity ranking based on the potential impact to facility personnel and the public. To convert the hazard distance tables into a form which may be more easily used during the PHA, the PHA facilitator may review the company risk matrix, as well as the facility layout prior to starting the PHA sessions. During this time, the facilitator should convert the dispersion distances in Tables 2 and 3 into charts providing guidance on the potential worst-case severity of different release events.

For example, a hypothetical company has developed a risk matrix with the consequence severity rankings described in Table 1. The system under analysis is an LNG storage tank and associated piping, which are located in an isolated part of the facility, but approximately 700 feet from the closest residences. Using this information, the PHA facilitator may translate the worst-case hazard zones in Tables 2 and 3 into a set of tables with suggested consequence severity rankings which are tailored to the system under review. Table 5 provides an example of these consequence severity tables for the specific LNG system described above.

Table 5A. Methane Liquid Consequence Severity Rankings

	Source Temperature (F)			
Release (lbs)	**-250**	**-200**	**-150**	**-117**
10	1	1	2	2
100	3	2	2	3
1,000	4	3	3	4
10,000	4	4	4	5
100,000	5	5	5	5
500,000	5	5	5	5

Table 5B. Methane Liquid Consequence Severity Rankings

	Source Pressure (psi)				
Break Diameter (in)	**50**	**150**	**300**	**400**	**450**
0.25	1	1	1	1	1
0.5	1	1	1	1	1
0.75	2	2	2	2	2
1.0	2	2	3	3	3
1.5	2	3	4	4	4
2.0	3	4	4	4	4
3.0	4	4	4	5	5
4.0	4	5	5	5	5
6.0	5	5	5	5	5

When translating the calculated hazard zone to consequence severity, it is important to note that the dispersion modeling calculations are performed generically, and their results may need to be adjusted based on the specifics of the system under review. The relationship between hazard distance and similar consequence categories (i.e., first aid injury, reportable injury, and permanent disability) should be developed with the primary decision maker for the facility (i.e., company management). To accomplish this, the facilitator should record the decision making process used to relate hazard distances to consequence severity levels, and present these decisions to company management prior to beginning the PHA sessions, and adjust the severity tables based on comments received. .

Additionally, the model calculations make a number of assumptions which may or may not apply to the system being analyzed. Most importantly, the calculations assume that releases occur outdoors, and outside of any secondary containment areas. Indoor releases can have a significantly reduced hazard zone outside of the building. This may depend on the ventilation capabilities of the building, or doors normally kept open. Toxic material may build to higher concentrations within the building than those reported in the hazard distance tables. Similarly, the presence of secondary containment limits the surface area of a liquid pool, which may result in a smaller vapor cloud than an uncontained liquid spill. To adequately assess the severity of a chain of events, these deviations from the assumed model must be accounted for. In cases such as these, the hazard distance tables should be used as a starting point, but adjust their consequence severity ranking according to the physical systems present in the field.

During the PHA discussions, once a scenario has been identified and the release conditions are established, the consequence severity tables can be consulted to assist in selecting the most appropriate consequence severity ranking. To use the tables, a process engineer or other person familiar with the design of the system under consideration should determine the physical parameters of the release. It must first be determined whether the released material is in the liquid or the vapor state. Subsequently, the release conditions must be specified in terms of temperature, pressure, quantity spilled, or breach diameter, depending on what information is most readily available to the team. This determination is not intended to be a rigorous calculation, but rather a quick estimation of the conditions of the release.

Once the release parameters have been agreed upon, the team may then use the consequence severity tables to determine the worst-case severity ranking. For example, in the LNG system described above, it is postulated that a full break occurs in a one inch diameter pipe containing LNG at 170 psig. Given the information at hand, the team consults Table 5B, and identifies 150 psig as the closest pressure rating found on the tables. From the Table, the team selects a severity ranking of 2, indicating that a recordable injury is the anticipated worst-case consequence.

6. Conclusion

Kazarians & Associates, Inc. has developed a method which uses pre-developed consequence severity tables to refine the judgement of PHA teams with regard to the impact that a scenario may have on personnel. This method has been applied, resulting in a more accurate determination of consequence severity. When applied across multiple teams and studies, this increase in accuracy will lead to consistency in severity ranking among similar PHA scenarios. In turn, this will lead to consistent application of safeguards across multiple systems, resulting improved plant operability and avoiding the potential for confusion among operating staff.

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