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Risk-Based Approach: Quantitative Risk Assessment

Foundation of Process Safety and Loss Prevention

An ioMosaic White Paper

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Abstract

Process Safety and Loss Prevention field was born out of the need to avoid personnel injury, i.e., workforce and public, property damage, environmental impact and operation interruption (i.e., economic impact, due to several relevant accidents during the last fifty (50) years, e.g., Bhopal, Seveso, Buncefield, Flixborough, etc.) A Quantitative Risk-Based Assessment (QRA) is considered to be the foundation of process safety and loss prevention. Generally, there are two (2) main approaches to conduct a risk assessment: consequence-based or risk-based. The issue that arises by using a consequence-based approach is that the likelihood of occurrence is not considered, and therefore, it does not account for the frequency of an undesired event. A complete QRA consists of six main steps:

1. Hazard Identification, which consists of the identification of all Loss Of Containment scenarios (LOCs) with the potential to lead to an explosion, fire, or toxic hazards in a process facility.
2. Frequency Analysis, which estimates the likelihood of occurrence of all LOCs via analysis of historical data, specific plant data (if available), worldwide references with generic process equipment failure rates, and/or dedicated fault and event trees; i.e., bow-tie analysis;.
3. Consequence Analysis, which quantifies the effects and impacts of all potential outcomes that could occur from a given LOC, based on damage criteria for fires, explosions, and toxic hazards for personnel, structures, and process equipment.
4. Risk Analysis, which quantifies the risk level as a function of the likelihood of occurrence (i.e., frequency analysis) of possible undesired events (LOCs) and the magnitude of their associated impacts (i.e., consequence analysis), and it can be divided into two (2) categories: individual risk and societal risk.
5. Risk Tolerability Criteria, which consists of comparing the estimated risks to a worldwide recognized risk tolerability criteria to determine if the risk levels are deemed to be tolerable or not.
6. Risk Reduction, which consists of implementing risk reduction measures such as inherent safer process design, prevention, and/or mitigation in order to decrease the individual and/or societal risks to at least a tolerable if ALARP (As Low as Reasonably Practicable) risk region. Some examples of applicable safeguards or Independent Protection Layers (IPLs) are Safety Instrumented Systems (SIS), Fire and Gas detectors Systems (FGS), etc.

The completeness of risk-based assessment is based on the development of four (4) critical tools:

1. Individual Risk Contours used to characterize individual risk.
2. FN Curves, a requirement used by authorities to estimate the societal risk for facility workforce and/or public located in the surroundings of the process hazardous facility.
3. Exceedance Curves, approach that helps decision-makers to decide which location of interest (i.e., process equipment, building) needs further analysis based on the target being affected by a cumulative frequency of interest by overpressure, thermal radiation, or toxicity hazards.
4. Risk Indices, which allow the user to conduct valuable statistical and sensitivity analyses. The combination of the QRA results with other engineering tools, such as Dynamic Thermal Stress Analysis (DTSA) approach, Equivalent Elasto-Plastic SDOF (Single Degree Of Freedom) analysis, etc., allow managers to reinforce the decision-making process. Furthermore, when a complete QRA study is conducted, it is possible to identify severe accidents due to domino effect and escalation as a result of primary explosions such as vessels bursting, projectile fragmentation, fires, etc.

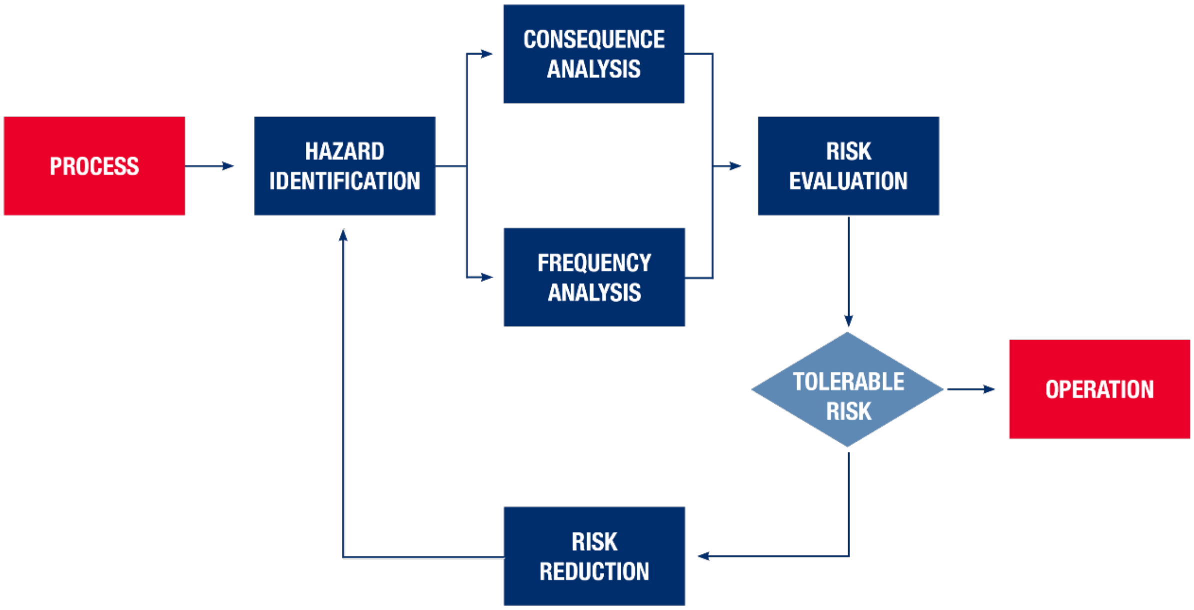
QRA applications are wide and very valuable to the decision makers, and some examples are the following:

- Facility Siting due to explosions, fires, and toxic and/or flammable dispersions.
- Land-Use Planning, applicable to existing and new housing developments near a hazardous facility.
- Emergency Planning, identifying escape routes in the event of an undesired release.
- Fire and Gas Mapping to properly locate fire and gas detectors onsite and reduce the risk.
- Cost and Business Analysis, used to protect the company investments in addition to workforce and public, as well as the environment.
- Environmental Analysis, to analyze the impacts to the environment in the event of an unwanted release.

Introduction – Risk Based Approach

Risk is defined in ISO 17776 **[1]** as the combination of the frequency of occurrence of an event and the consequences of that event. Accordingly, a risk-based approach considers both the frequency of occurrence and associated consequences of all outcomes that could lead to explosions, fires, and flammable and toxic dispersions in a chemical hazardous process facility. The main purpose of a risk-based assessment, known as Quantitative Risk Assessment (QRA), is to answer the following key questions: (1) *What can go wrong?* (2) *How likely is it?* (3) *What are the impacts?* (4) *What are the facility risk levels?* (5) *Is the risk tolerable?* and (6) *If not, which are the most appropriate safeguards for reducing risk to a tolerable level?* Figure 1 illustrates a simplified risk management program flowchart.

Figure 1: Risk Management Program Simplified Flowchart



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To be able to use risk in workable concepts, a general approach is to divide risk into two categories:

- Individual Risk: risk level associated to an individual based on an activity performed that poses some risk
- Societal Risk: function of the total population, workforce or public, present at a given location of interest

Both concepts are explained in the following sections.

Individual Risk Definition and Characterization

The individual risk concept can be defined as the risk which considers the acceptability of a particular level of risk to an exposed individual; i.e., it is not a function of the total number of individuals placed in a given location.

Individual risk can be presented as a probability *per period of exposure*. This may in some cases be a single figure for all individuals involved in an activity, for example the probability of fatality per hour while rock climbing. In many cases, the risk level an individual is subject to their location relative to the activity. The further away from an activity the individual is, the lower the risk is likely to be. It is therefore common in these cases to present the risks as contours of equal probability (Individual Risk Contours, IRC).

Furthermore, it can be expressed as a single number or index. When the goal is to determine the contribution level to overall individual risk by one or more process units or by a specific type of hazards, the index Total Individual Risk (IR_{TOT}) is sometimes used.

Additional risk indices (e.g., IR_{avg}) are also used to help the statistical analysis and the justification of specific recommendations when a QRA study is conducted. For a more detailed explanation on these additional indices, please refer to the following sections of this manuscript.

Societal Risk Definition and Characterization

The societal risk concept addresses the society's aversion to accidents which can result in multiple fatalities; i.e., the societal risk takes into account the actual population present in a given area.

Similar to the individual risk, a good tool to represent the societal risk is the F-N Curve (F-N Curve). The curve is a plot of the number of fatalities (N) versus the cumulative frequency at which that number of fatalities will occur (F). Thus, a point on the curve represents the frequency at which N or more fatalities will occur. F-N curves are particularly valuable for comparing multiple fatality risks and for assessing the difference in risk between two different proposals or cases. However, development of an F-N curve-based tolerability criterion is a complex issue.

Moreover, the societal risk can be expressed using a single number or index. When the goal is to determine the contribution level to the overall societal risk by one or more process units or by a specific type of hazard, the indices “Potential Loss of Life” (PLL) and “Average Rate of Death” (ROD) are sometimes used.

Additional risk indices (e.g., FAR) are also used when analyzing the societal risk. Please refer to the following sections of this manuscript for a more detailed explanation on the societal risk definition and characterization.

Risk-Based Approach versus Consequence-Based Approach

Before explaining the different steps that define a risk-based approach, it is important to mention that a risk assessment can be conducted following two (2) different approaches: (1) a consequence-based approach that only considers the worst credible event, or (2) a risk-based approach that considers both the consequence and the frequency values that characterize the associated risk level.

The consequence-based approach considers only the maximum credible event; e.g., a stoichiometric flammable cloud engulfing the whole congested area and ignited in the worst position, resulting in the worst credible case. However, as the frequency of occurrence is not considered, the consequence-based approach is not considered the best tool to represent the reality. For example, if there is a leak in a High-Pressure/Low-Pressure vessel, due to the mixture composition and based on the area congestion, wind speed, stability class, relative humidity, and the ignition sources present in the process area, the consequences can impact a given infrastructure and there may be a need to reinforce the building due to the results; however, the vessel may be subject to a specific mechanical integrity program, which could result in a low likelihood of rupturing the vessel completely. Another example would be to only consider a pool fire from a large storage tank containing flammable hydrocarbons; however, this specific tank may be double-walled, which could suggest that the frequency of occurrence of having flammable material released to the atmosphere with the possibility of resulting in a pool fire due to an external fire being very low. Based on criteria established in American Petroleum Institute (API) Recommended Practice (RP) 752 [2], a risk-based approach is considered a better and more precise methodology.

Risk-Based Approach Definition

Hazard Identification

A risk-based approach consists of six main steps as illustrated in Figure 1 above. The following contents summarize the main steps of a QRA. For a more detailed explanation on how to identify hazards and determine its associated frequency of occurrence, please refer to references [3] and [4]. For a more detailed description on how to calculate the consequences once that the hazardous scenarios are properly identified and characterized by its likelihood of occurrence, please refer to reference [5]. Reference [6] reviews the state-of-the-art damage criteria based on the different type of hazards, (i.e., explosions, fires, and toxic/flammable dispersions for people, buildings/structures, and process equipment). For the quantification of the risk based on the previous steps, and to answer if the risk is tolerable or not, please refer to references [7] and [8]. If the risk levels are not deemed acceptable or low enough, reference [9] consists of an overview of layers of protection capable of reducing the risk level of a given process facility; i.e., mitigation and/or prevention. Reference [10] and reference [11] address two types of specific safeguards respectively: Safety Instrumented Systems (SIS), and Fire and Gas Detectors (FGD), while reference [12] outlines a methodology to calculate risk reduction.

Hazard Identification is the first step in a risk-based assessment. During this section, the Loss of Containment scenarios (LOCs), which are the major hazards present in a facility that handles hazardous materials, can be identified using a systematic Process Hazard Analysis (PHA) technique. Normally, the basic input data required to properly identify the hazardous scenarios is taken from the chemical facility plot plans, Process Flow Diagrams (PFDs), Piping and Instrument Diagrams (P&IDs), equipment lists and Heat and Material Balances (H&MBs). The LOCs to be identified include process equipment failures, above ground and underground pipeline failures, mishaps in transport units and so on.

Loss of Containment scenarios (LOCs) are implicitly summarized in several guidelines such as API RP 581 [13], CPR18E [14], OREDA [15], HSE [16]. These guidelines are valid for characterizing the identification of potential LOCs and the associated frequency of occurrence.

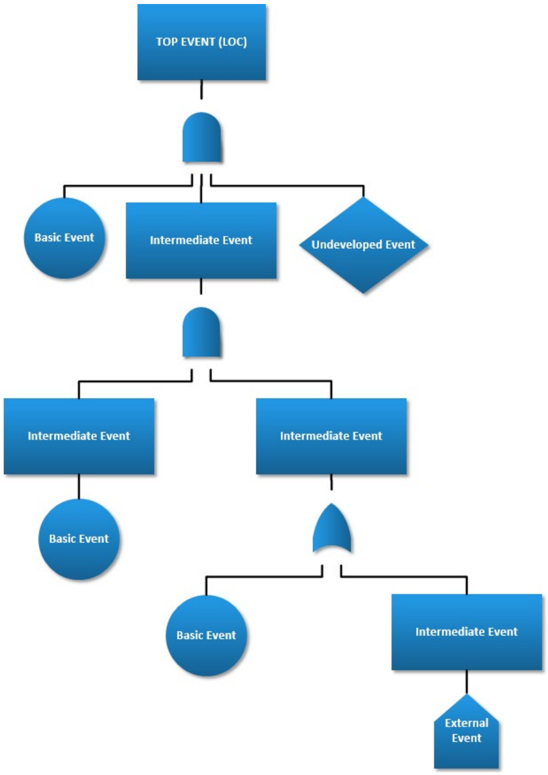
Normally, the first step of a risk-based assessment (i.e.; Hazard Identification) is conducted in conjunction with the second step of a risk-based assessment (i.e., Frequency Analysis). The following contents summarize the concept of frequency analysis, and explain the main differences between generic and specific LOCs. Note that the Hazard Identification step is the foundation for accurately evaluating the risk of a process facility. Thus, it is very important to thoroughly review all documentation associated to a chemical facility in order to be able to identify all possible LOCs. Refer to [3] for specific information on how to properly identify potential LOCs.

Frequency Analysis

The Frequency Analysis is the second step of a risk-based assessment, and it consists of accurately estimating the likelihood of occurrence of all LOCs identified in the previous step; i.e., Hazard Identification. Usually, when process equipment with a potential hazard is identified, several leak sizes with associated frequencies of occurrence are defined. These scenarios are called generic scenarios when a detailed frequency analysis is not needed (e.g., Fault Tree Analysis (FTA)). If the likelihood of occurrence is not calculated, worldwide recognized references such as API RP 581 [13], CPR18E [14], OREDA [15], and HSE [16] are used in order to associate pre-established frequencies of occurrence for each LOC identified. The data in the references mentioned are based on historical data from accidents and incidents occurred in the process industry. As a result, frequencies of occurrence due to a leak in any type of process equipment and any size of pipeline can be determined.

However, not all LOCs identified in the first step of a risk-based assessment can be considered “generic scenarios”. These “specific scenarios” are normally studied case-by-case, and the most used methodology to quantify the frequency of occurrence of these scenarios is the FTA. Figure 2 below illustrates a generic fault tree example.

Figure 2: Generic Fault Tree Example



Source: ioMosaic Corporation

Once the scenario is defined as “generic” or “specific” and the frequency of occurrence is defined by the associated method, the consequences of the LOCs are modeled through consequence analysis. The following contents provide an overview of the consequence analysis step.

For specific information on how to estimate the frequency of occurrence of generic or specific LOCs when conducting a QRA study, refer to [4].

Consequence Analysis

The Consequence Analysis is the third step of the risk-based assessment. The objective of this step is to estimate the source term and to accurately quantify the consequences of an explosion, a fire, and dispersion hazards.

Mathematical consequence modeling is defined as the use of mathematical representation of conservation and physical laws to analyze and quantify potential damaging effects of hazardous events, usually caused by LOCs. This mathematical consequence modeling is well-known in industry and is applied in a risk-based assessment, emergency response planning, loss prevention, safety design, facility siting, and environmental protection.

The consequence analysis consists of defining and thoroughly applying the following three sub-steps:

- Source term characterization from LOCs
- Identification using the Event Tree Analysis (ETA) technique of potential outcomes from LOCs
- Modeling of potential outcomes based on LOC source term results

After the consequence impacts are modeled based on the source term characteristics (see Figure 3 below) and the possible outcomes using the ETA technique (see Figure 4 below), meteorological conditions, and the damage criteria to an individual or given location of interest is based on the following hazard types: (1) explosions leading to overpressure exposure and exposure to flying fragments, (2) fires leading to exposure to thermal radiation, and (3) dispersions leading to exposure to toxic chemicals.

Figure 3: Source Term Characterization

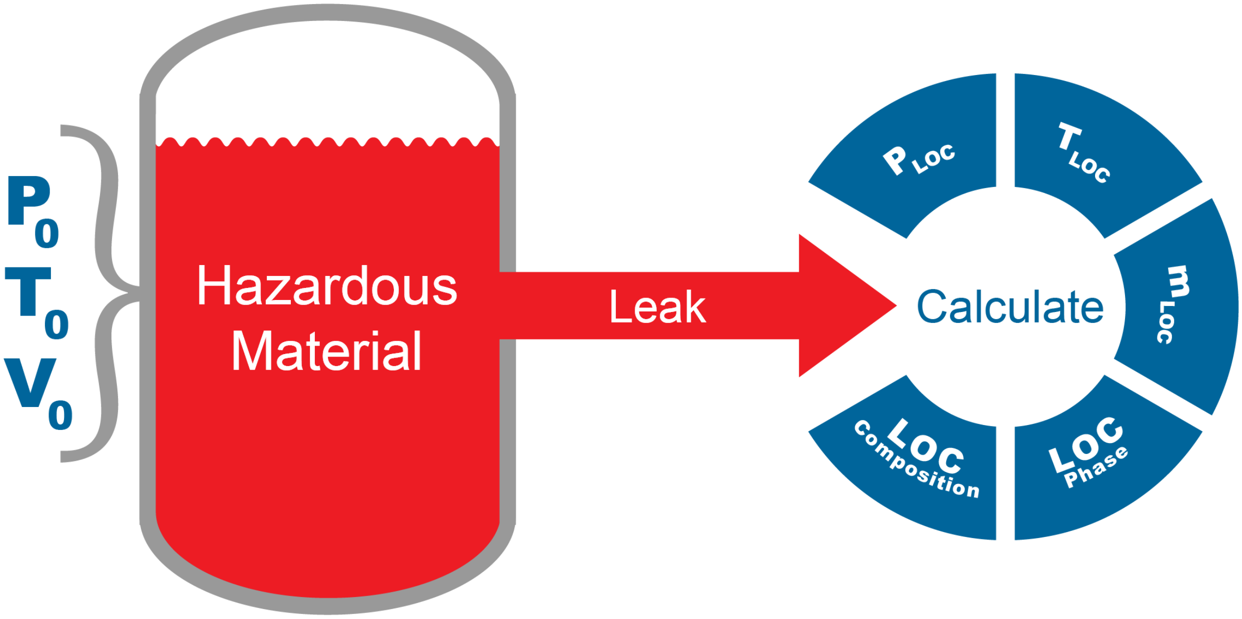


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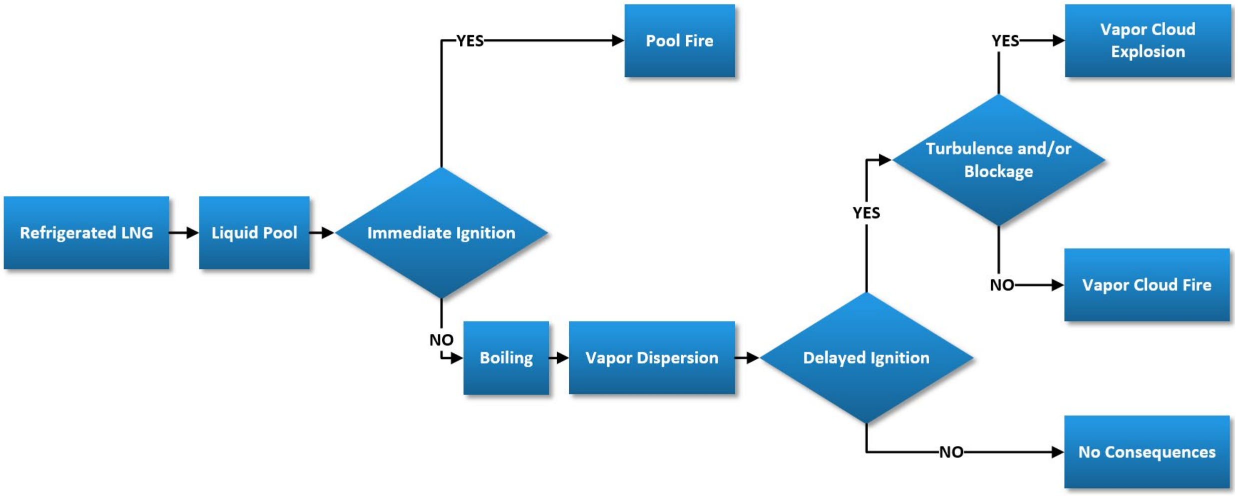
Figure 4: Refrigerated LNG Loss of Containment Event Tree



Source: ioMosaic Corporation

In order to calculate the damage, there are two important approaches: probit analysis and well-known thresholds or doses.

On one hand, when coupled with probits, consequence models can associate a probability of fatality (or receiving a dangerous dose) or building damage with a specific hazard zone or isopleth. A probit function (probability unit, Y) is a normally distributed random variable with a mean of 5 and a standard deviation of 1. On the other hand, recognized thresholds or doses can be applied to correlate fatality, major injury, or minor injury depending on the hazard type of interest and the exact location of the individual or location of interest. For further explanation on the probit and analysis and well-known doses or thresholds for toxicity, thermal radiation, and overpressure, please refer to [5]. Furthermore, note that when a LOC scenario contains more than one hazard (e.g., mixture containing flammable and toxic chemicals), the consequence models are going to consider all possible toxic and thermal radiation outcomes.

Figure 5 below illustrates the impact distances due to toxic dispersion at different thresholds using Process Safety Office® SuperChems™ [17].

Figure 5: Example of Toxic Dispersion Impact Distances

Source: Process Safety Office® SuperChems™ [17]

Risk Evaluation

The Risk Assessment (or Quantification of Risk) is the fourth step of the risk-based assessment, and is based on:

- The LOCs identified during the first QRA step, i.e., Hazard Identification
- The likelihood of occurrence of each LOC estimated on the second step, i.e., Frequency Analysis
- The impacts of each outcome from a LOC, calculated in the third step, i.e., Consequence Assessment

This phase consists of collecting all the results from the consequence assessment considering the frequency estimated per each outcome based on the parent frequency (i.e., Frequency Analysis) and the probability of each outcome via ETA methodology. As a result, the individual and societal risks for both workforce and public population are estimated by considering toxicity, thermal radiation, and overpressure risks.

The estimation of risk due to explosions, fires, and toxic dispersions is meaningless unless it is compared to a target risk of interest. Thus, the need for defining risk tolerability criteria exists. Reference [7] addresses the evaluation of risk and the tools and parameters that can be developed and extracted when conducting a QRA study.

Risk Tolerability Criteria

Comparing the individual and societal risks calculated in the fourth step of a risk-based assessment to worldwide recognized risk tolerability criteria is considered the fifth step of a QRA. As the analysis of risks derived from potentially hazardous facilities has advanced, so has the concept of what constitutes an acceptable risk. The sentence “acceptable risk” is generally used in quantitative risk assessment literature. However, what constitutes an “acceptable risk” can be misleading for a number of reasons. People may “accept” risk of an activity on a voluntary basis if they deem it low enough and if they derive a benefit from it. For example, flying in an airplane from point A to point B poses a small risk, but most people are willing to “accept” that risk. However, when a risk from an activity is conducted for the individual on an involuntary basis and there are no direct benefits that the individual gets from the activity, then no risk is truly “acceptable” no matter how small. Thus, when an individual experiences involuntary risk, the important concept from a risk tolerability criteria point of view is the following: “is the risk small enough to be tolerable?”.

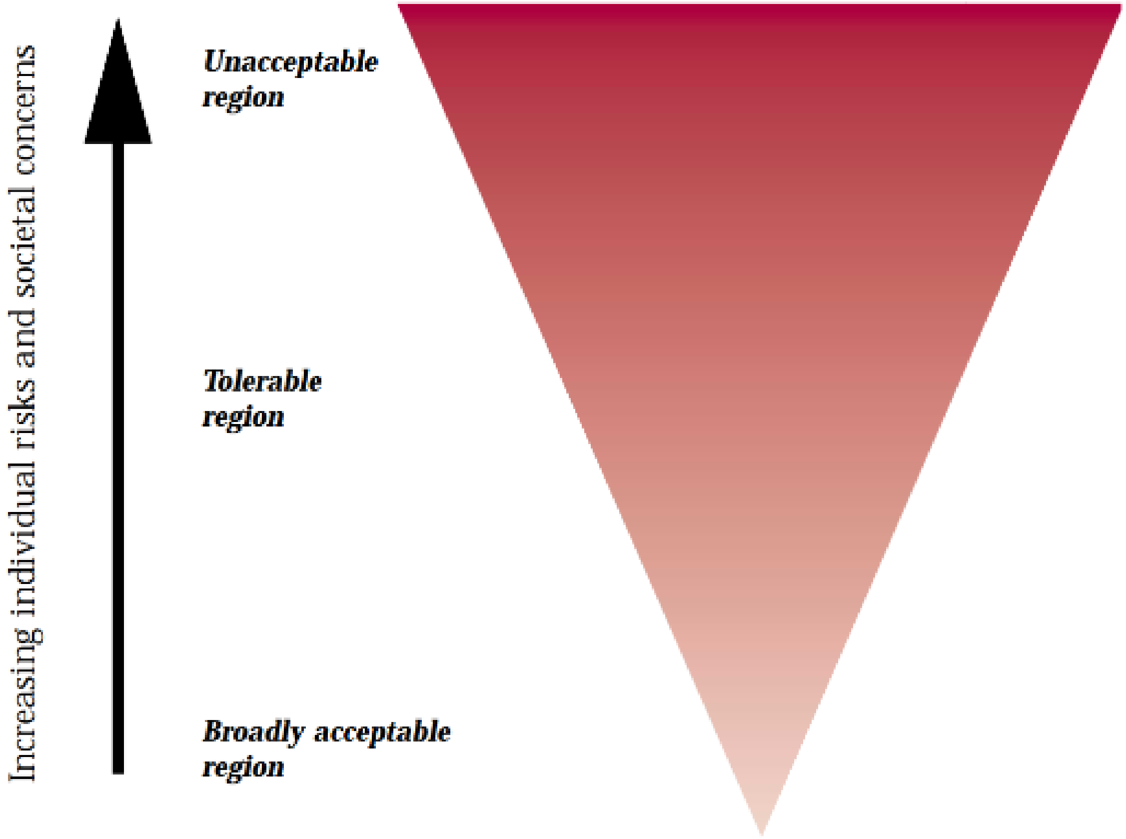
Based on the nature of the activity, the limits of negligible risk (i.e., broadly acceptable), risk in the ALARP region, and not tolerable risk depends on the nature of the individual (i.e., offsite public or workforce), and depends on the type of risk to be compared: individual risk or societal risk. While individual risk is function of the personnel present at a specific location of interest, societal risk is a function of the number of people present in that location at a given time. Risk tolerability criteria for individual and societal risks are compared between the actual risk estimated and the target risk to be achieved according to the ALARP principle, defined below. See Figure 6 for the differentiation of risk regions based on the Health and Safety Executive (HSE) [18].

The term ALARP arises from UK legislation, particularly the Health and Safety at Work etc. Act of 1974, which requires "*Provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health*". The phrase "So Far As is Reasonably Practicable" (SFARP) in this and similar clauses is interpreted as leading to a requirement that risks must be reduced to a level that is "As Low As is Reasonably Practicable" (ALARP). The key question in determining whether a risk is ALARP is the definition of "*reasonably practicable,*" which is interpreted to mean:

- Risk must be averted unless there is a gross disproportion between the costs and benefits of doing so.

It is important to mention that the risk tolerability criteria applicable to a present situation may not be suitable for a future development (i.e., land-use planning) [18]. Once the actual individual and societal risks for both workforce and public are compared to an applicable worldwide recognized risk tolerability criteria (considering present and future housing developments) and the hazardous facility risk regions are known, it is time for the decision makers to agree on applying risk reduction measures or not.

Figure 6: Framework for Tolerability of Risk



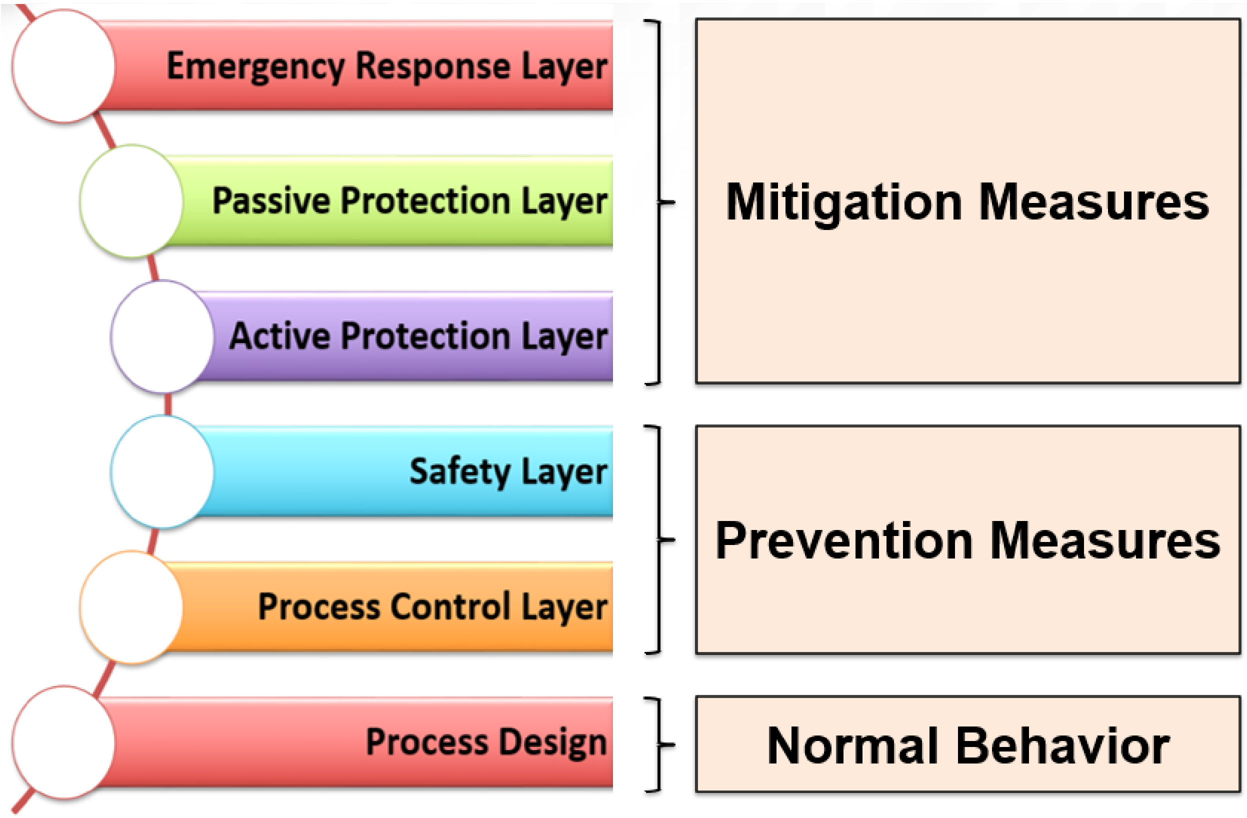
Source: HSE, 1989. “Risk Criteria for Land-Use Planning in the Vicinity of Major Industrial Hazards”, HMSO [18]

Reference [8] provides an overview of the state-of-the-art QRA worldwide risk tolerability criteria.

Risk Reduction Measures

Risks cannot be completely eliminated from the handling, use, process, and storage of hazardous materials [19]. However, both individual and societal risks at a minimum need to be in the tolerable if ALARP risk region. If not, the decision-makers need to look for alternatives in order to make the process safer and therefore, not posing intolerable risk to either individuals that work in the hazardous facility or public located in the surroundings. Thus, the implementation of specific risk reduction measures (i.e., prevention, control and mitigation safeguards) will be needed. Furthermore, note that if the individual and/or societal risks are found to be in the tolerable if ALARP risk region, there may be a need to study the possibility of implementing additional risk reduction measures in order to prove that the ALARP principle is met (i.e., a gross investment does not result in a small decrease of the actual risk). Figure 7 illustrates the different levels of Layers of Protection available for a given hazardous process:

Figure 7: Layers of Protection Measures

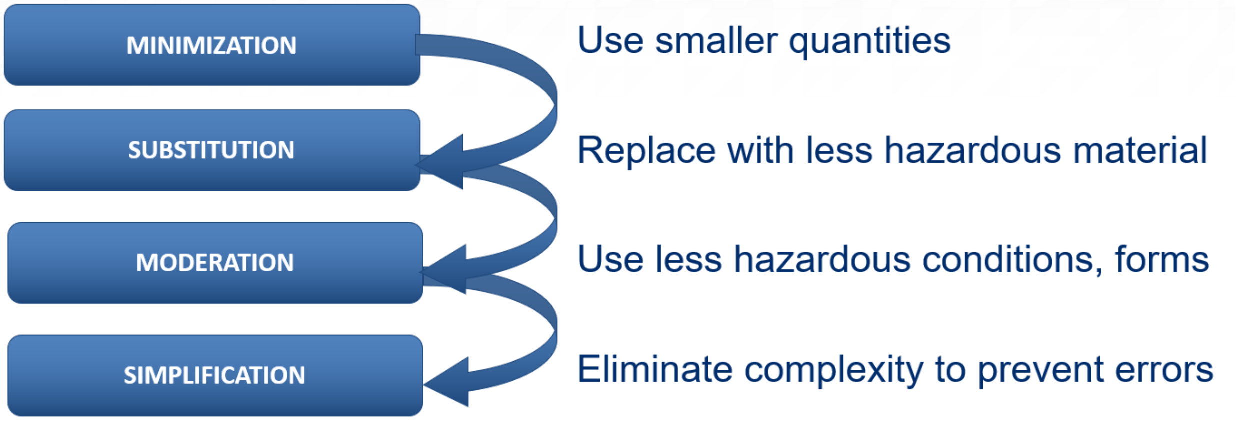


Source: ioMosaic Corporation

As illustrated in Figure 7, the preferred Layer of Protection measure in order to reduce the actual risk of a process hazardous facility would be to have in place an inherently safe design. For example, faced with the hazard posed by a flammable solvent, designers might seek to substitute this solvent for a less flammable substance [19]. Another good example of an inherent safer design would be to change the trucks and the hose feeding butane tanks for a process piping if it is known that the likelihood of occurrence of a leak in the hose due to the loading and un-loading activities is higher than the frequency failure of a 4" piping. Figure 8 below illustrates the four (4) different principles considered by the Center for Chemical Process Safety (CCPS) when referring to inherently safer design [20]:

- Minimization
- Substitution
- Moderation
- Simplification

Figure 8: Inherently Safer Design Principles



Source: CCPS, 2008. “Inherently Safer Chemical Processes: A Life Cycle Approach” [20]

If it is not possible to make the design inherently safe because the plant is already designed or it would result in a very high investment, the next option would be to use prevention measures, for example: basic process controls, process alarms and operator intervention, Safety Instrumented Systems (SIS) and emergency depressuring systems. However, it might be difficult for basic process controls/alarms to detect a small leak in the process. Thus, there may be a need to implement Independent Layers of Protection (IPLs) specifically intended to detect and isolate potential leaks (i.e., SIS). Although implementing specific IPLs to detect and isolate a release from a LOC may be very effective to reduce the consequences (e.g., toxic dispersion), it might not be the best option in terms of investment. When implementing a specific IPL, usually the risk reduction factor (RRF) is calculated in order to determine which reduction factor is necessary so that the risk levels in the facility are deemed at least tolerable if ALARP. Reference [10] provides some guidance on risk reduction measures, and explains concepts such as RRF, Probability of Failure on Demand (PFD_{avg}), etc., and reference [11] addresses specifically SIS.

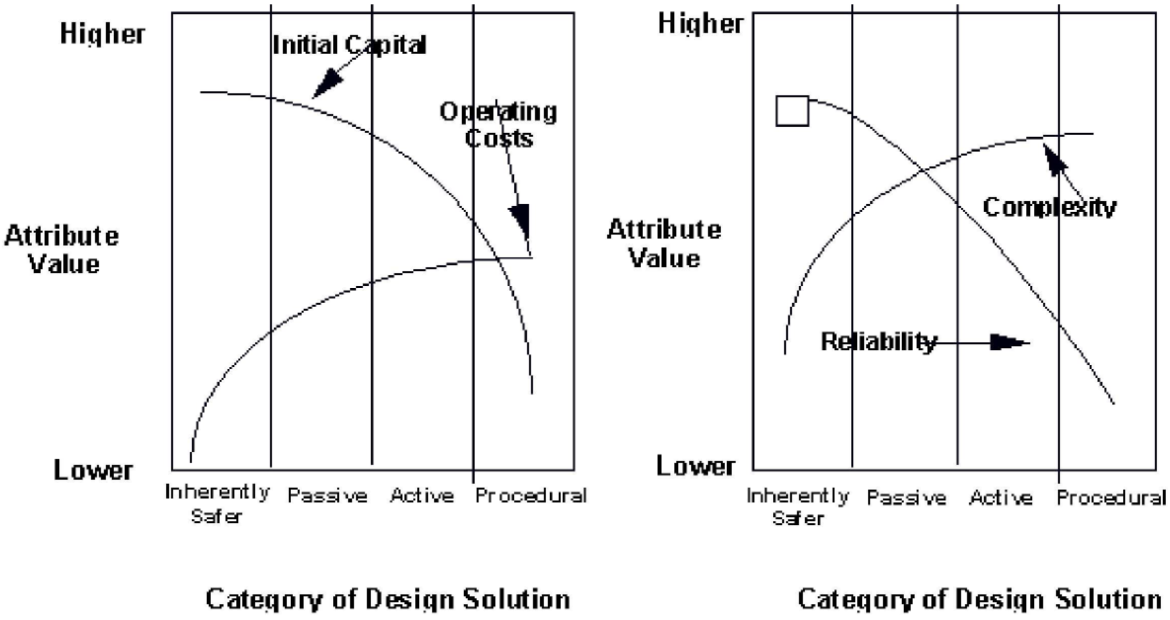
Additionally, reference [12] outlines a detailed methodology to calculate required risk reduction in the event that the facility risk levels are deemed not tolerable.

Finally, if it is not possible to make the design inherently safer by changing the process, or implement prevention measures, the next option to lessen the risk is to install mitigation measures. Some examples of a mitigation measure are: changing the storage tank dike to a smaller size in order to reduce the liquid pool diameter resulting in a lower thermal radiation hazard; ensuring mechanical integrity of a vessel that operates at high pressure by inspecting it more often; installing fire and gas detectors with alarms so the public in the surroundings of a hazardous facility are alerted in the event of an unwanted release; installing new Emergency Relief Systems (ERS) in order to avoid possible fracture of a process equipment due to an overpressure event (e.g., tube rupture in a heat exchanger, loss of heating to an upstream column resulting in more light components entering the downstream column); training both the workforce and the public on how to react in the event of a release resulting in a toxic cloud (i.e., staying indoors with the windows closed in order to avoid contact with the harmful chemical). Another mitigation measure used in chemical process facilities to reduce the consequence of undesired events is the implementation of Fire and Gas (FGS) Detection Systems. Generally, the philosophy of FGS follows internal corporate guidelines as well as related standards such as International Society of Automation (ISA) 84.00.TR.07 [21]. Reference [11] fully addresses the philosophy, zone definition and categorization, performance targets, and detector coverage verification of FGS.

As discussed, there are risk reduction measures that can eliminate, prevent, or mitigate the risks in a hazardous facility. In the end, the decision makers need to agree to which Layer of Protection needs to be implemented in order to reduce the individual and/or societal risk from an intolerable or tolerable if ALARP risk regions to a tolerable if ALARP or broadly acceptable risk regions. Choosing among the different types of risk reduction measures is not simply a matter of selecting the most reliable option. Thus, this decision needs to be based on the following key factors (see Figure 9 below):

- Initial investment needed. Design a process to be inherently safe may be the most reliable approach but it may not be within the facility budget (i.e., investment too high). However, note that overall, the cost associated to design a process to be inherently safer is lower than installing prevention or mitigation measures.
- Reliability of the IPLs. Installing basic controls and relying on operation intervention to detect potential leaks might be less expensive than implementing dedicated IPLs to automatically detect and isolate releases from a given LOC. However, the reliability of a SIS is much higher than for a basic control. Furthermore, using basic controls for detecting very specific scenarios may be difficult, resulting in the need to change all the process control philosophy of the facility.

Figure 9: Typical Behavior of Design Solution: Cost and Reliability



Source: Melhem, G.A., 2019: "Advanced Consequence Analysis; Fluid Flow, Emergency Relief Systems Design, Thermal Hazards Assessment, Emission, Dispersion, Fire and Explosion Dynamics" [19]

Tools for Risk-Based Approach Development

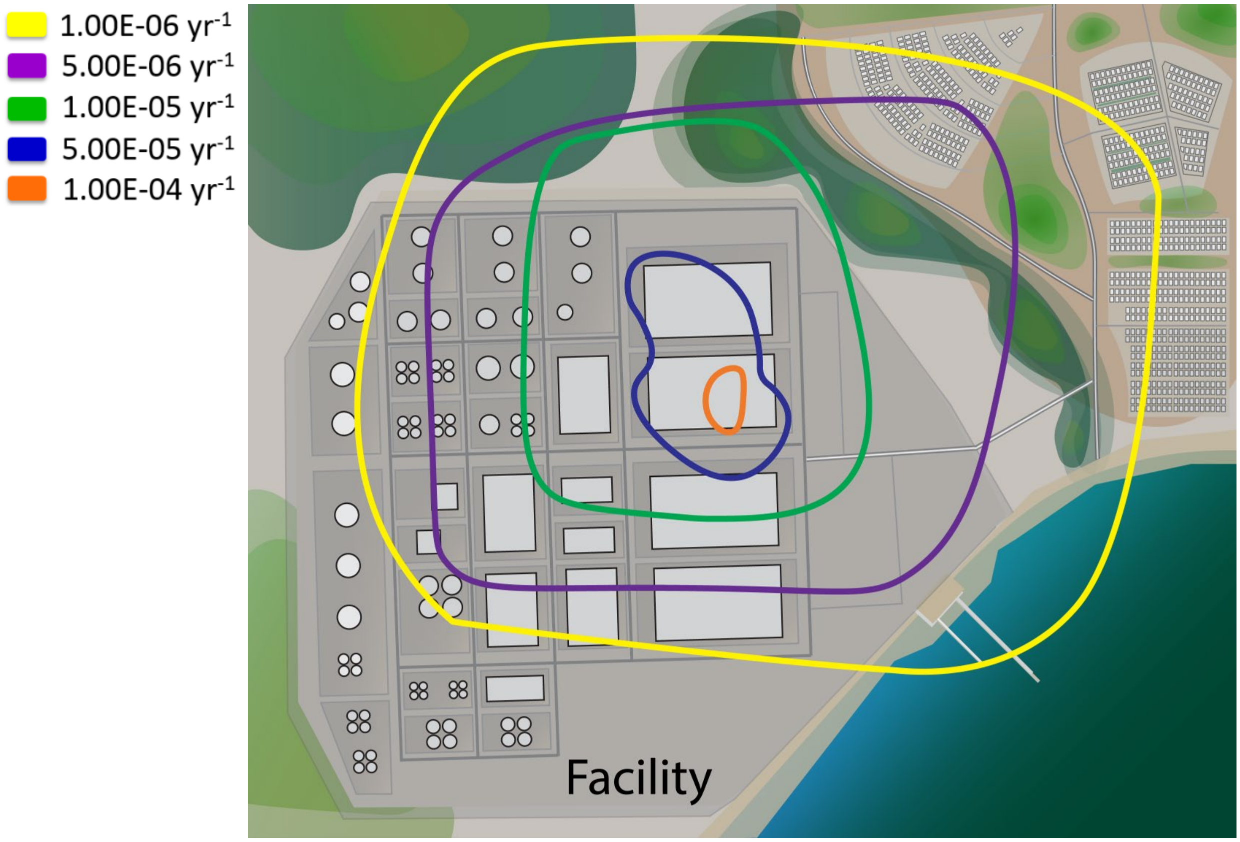
There are different tools for representing the risks associated to a facility that handles hazardous materials. This section is intended to capture the different tools that can be used to further study and fully understand the meaning of the risk results once all the steps in a risk-based approach are conducted. The available tools in order to develop and capture a complete risk-based assessment are the following:

- Individual Risk Contours: used for facility siting and land-use planning decision making (explosions, fires, and/or toxic dispersions), emergency response planning, fire and gas mapping studies, environmental analysis, business analysis.
- FN Curves: used to determine that the facility workforce and the public surrounding the area of interest are exposed due to undesired events such as pool fires, toxic clouds, flame jet, explosions, etc.
- Exceedance Curves: used by the decision-makers to correlate the level of damage that a given location of interest (i.e., process equipment, infrastructure/building, individual) at which is impacted from any hazard present in the facility (i.e., overpressure, thermal radiation, and toxicity).
- Risk Indices: provide guidance on what is the status of the facility in terms of individual and societal risks; as these are indices, it is allowed to conduct statistical analyses (e.g., identifying the most contributing process unit to a one-hundred (100) refinery in terms of risk level) and sensitivity analyses (e.g., effect on the risk indices explained below when modelling a process unit with new Independent Layers of Protection installed).

Individual Risk Contours

The Individual Risk Contours (IRC) are used to characterize the individual risk and consist of iso-risk lines overlaid on the site topography at locations where a hypothetical individual staying there for 24 hours per day and 365 days per year is subject to a defined probability of harm due to exposure to hazards from a loss of containment event. See Figure 10 for an example of the associated IRC to a process unit in a facility handling hazardous materials using Process Safety Office® SuperChems™ [17]:

Figure 10: Individual Risk Contours Example



Source: Process Safety Office® SuperChems™ [17]

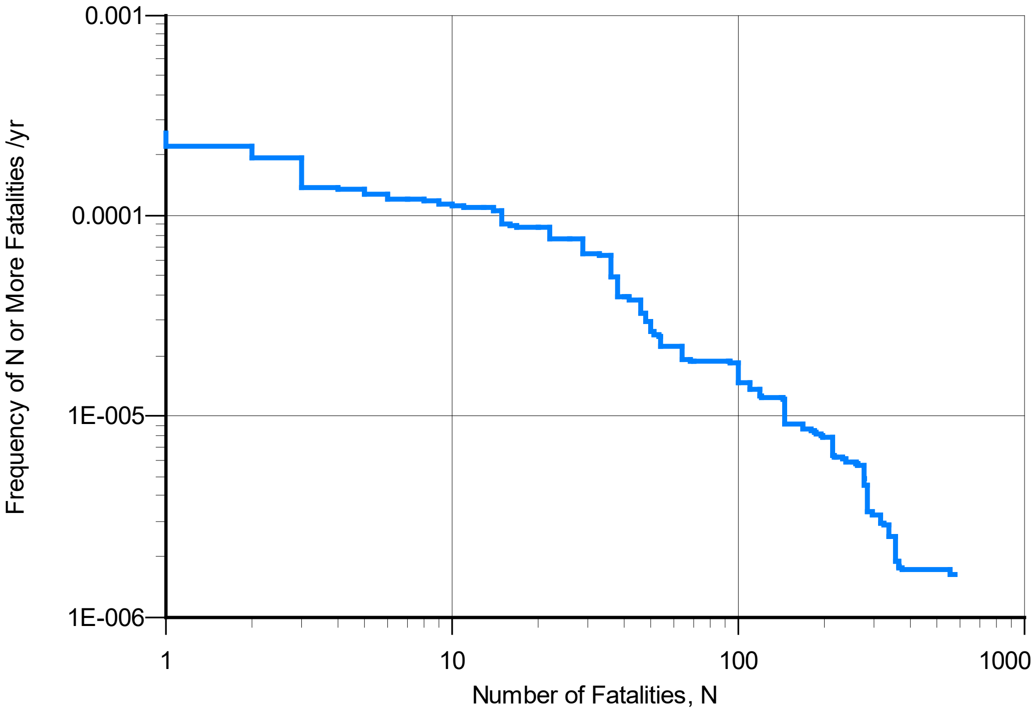
The IRC illustrated in Figure 10 above represent the risk levels from 1.00E-04 yr^{-1} to 1.00E-06 yr^{-1}. It can be observed that the higher is the risk level, the lower is the area of affectation (e.g., 1.00E-04 yr^{-1}, orange-colored contour, versus 1.00E-06 yr^{-1}, yellow-colored contour).

These iso-risk lines represent the risk level as a result of undesired events (i.e., LOCs) considering all hazards associated to the process unit under study (i.e., overpressure, thermal radiation, and toxicity). This graphical representation is a good tool for the decision makers to decide: (1) whether a facility needs to be re-located (i.e., facility siting and land-use planning decision making), (2) emergency response planning in the event of an accident (e.g., possible escape routes); (3) optimized location of fire and gas detectors (i.e., fire and gas mapping study); (4) areas of affection of toxic chemicals (i.e., decide to either re-locate or avoid installing a new process unit with a high concentration of toxic substances near a pond that contains several maritime species); and (5) possibility of studying the need of implementing additional safeguards as a result of a PHA recommendation (e.g., in terms of risk, the actual risk levels may be in compliance with the adopted risk tolerability criteria). For a more detailed explanation on how to predict the individual risk contours for a given facility, please refer to [7].

FN Curves

Societal risk is often depicted on a cumulative graph called an F-N curve. The horizontal axis is the number of potential fatalities. The vertical axis is the cumulative frequency F per year of N or more fatalities occurring. F-N curves are an indicator used by authorities as a measure of social disruption in case of large accidents. Because it is a cumulative curve, the curve always drops away (or has a negative slope) with increasing N (see Figure 11 for an example of an FN Curve).

Figure 11: FN Curve Example



Source: Process Safety Office® SuperChems™ [17]

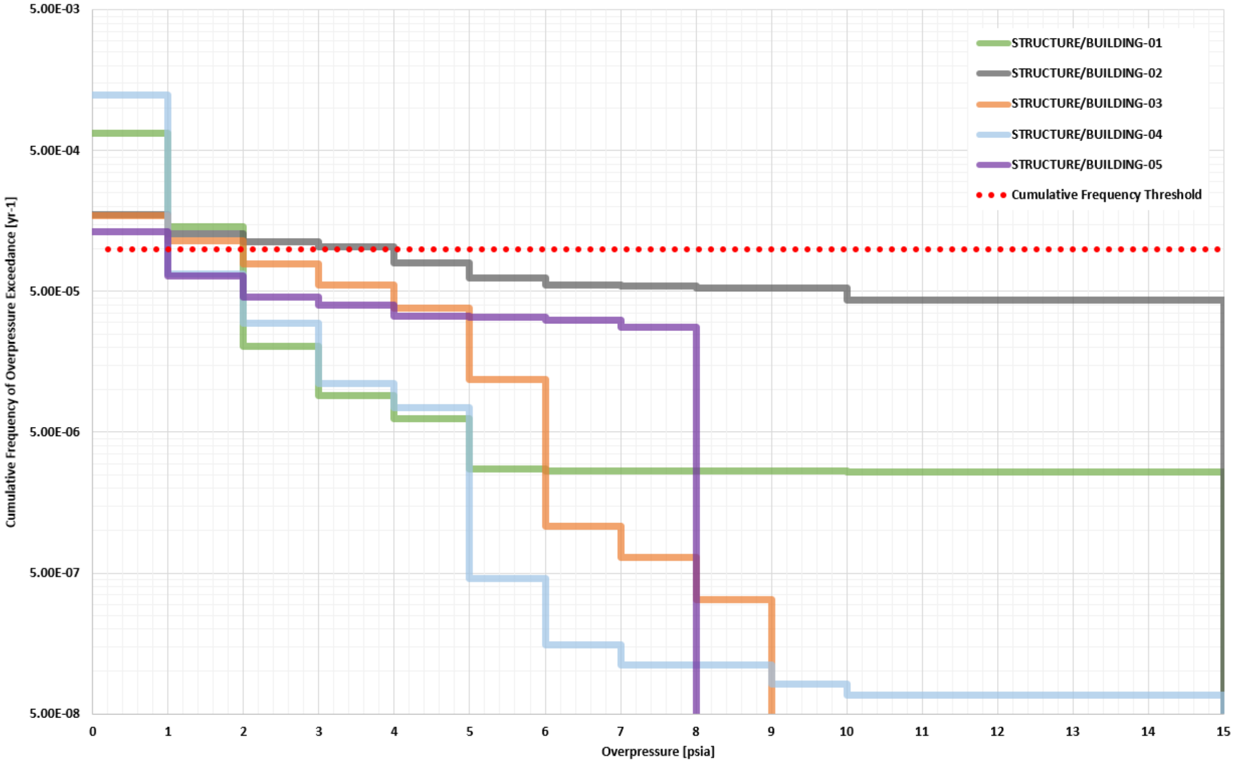
An F-N Curve is often used to quantify the societal risk for the public surrounding a facility. However, an FN Curve can be also used to determine the actual societal risk level for the facility workforce. Note that based on some concepts discussed above, an individual working for a hazardous facility may derive a benefit from working in it (i.e., salary compensation), while an individual located outside the facility fence is not expected to receive any benefit from the activities carried day to day in the facility (i.e., public). Thus, there is a need to define different risk regions depending on the target of interest (i.e., workers versus public) and the risk evaluated (i.e., individual risk versus societal risk).

Reference [7] explains in more detail the meaning and how to properly construct a FN Curve.

Exceedance Curves

The Exceedance Curve (EC) approach was developed following the issue of the 2003 version of the Chemical Industries Association (CIA) guidance [22] specifically for overpressure, and it is widely used for facility siting studies. Exceedance curves can be used as a probabilistic description of the potential for a target location to experience various levels of effects; i.e., heat radiation from fires, overpressure-impulse from explosions, and concentrations from flammable and/or toxic dispersions. The construction of an EC normally requires a series of steps that depend on the hazard under study (i.e., overpressure, thermal radiation, toxicity). An example of a Overpressure Exceedance Curves (OECs) for multiple buildings/infrastructures is illustrated in Figure 12 below:

Figure 12: Overpressure Exceedance Curves Example



Source: Process Safety Office® SuperChems™ [17]

Figure 12 illustrates the OECs for five (5) buildings analyzed during the development of a Quantitative Risk Assessment (QRA) for an entire refinery. All results presented in this manuscript have been generated by using Process Safety Office® SuperChems™ [17]. The cumulative frequency threshold is 1.00E-004 yr^{-1} based on well-known thresholds for building structural analysis [6].

Other well-known thresholds for thermal radiation and toxicity hazards can be also found in reference [6], which provides an overview of the state-of-the-art damage criteria due to all possible hazards for people, structures, and process equipment. Additionally, it can be observed that the while cumulative frequency decreases, the overpressure at which the building/structure is impacted increases. The OEC method allows the user to determine which structure/building is affected at a cumulative frequency of interest by an overpressure of a certain value or more. Thus, the EC approach can be useful to determine which location (i.e., process equipment, building structure, individual) is affected at a cumulative frequency of interest based on worldwide well-known thresholds/end points [6].

Risk Indices

The following risk indices can be used to help the decision makers on which element (e.g., process unit, LOC) contributes more to the overall risk (i.e., statistical analysis). These risk indices are also valuable for identifying which parameter has the most effect on the individual and/or societal risk (i.e., sensitivity analysis). Furthermore, these parameters are a good way of tracking the progress that a facility is doing in terms of process safety (e.g., one would expected that the Individual Risk (IR) index to decrease between two QRA studies considering that IPLs recommended from a PHA study are actually implemented) [7].

- Individual Risk (IR) is defined as “The risk to a person in the vicinity of a hazard. This includes the nature of the injury to the individual, the likelihood of the injury occurring, and the time period over which the injury might occur.”
- Average Individual Risk (IR_{avg}) is defined as “The average of all individual risk estimates over a defined population.” IR_{avg} is reported for the total population (IR_{avg} – Total) and also for the population at risk (IR_{avg} – Exposed).
- Maximum Individual Risk (IR_{max}) is defined as the maximum value of individual risk observed at any point within the computational domain, for example the refinery unit or area being analyzed.
- Fatal Accident Rate (FAR) is calculated from the average individual risk, and is normally used as a measure of employee risk in an exposed population. This is the number of fatalities occurring during 1,000 working lifetimes (10E+08 hours). FAR is reported for both the total population (FAR – Total) and the population at risk (FAR – Exposed).
- Average Rate of Death (ROD) or Potential Loss of Life (PLL) is the estimated average number of fatalities in the population from all potential incidents.
- Total Risk (IR_{TOT}) is calculated by summing the total of all individual risk values for each cell within the computational domain.

Domino Effect – Escalation

Before outlining the details of escalation due to explosions or fires, it is important to understand explosions and structure blast loading phenomena [23], the basics of the Single Degree of Freedom (SDOF) approach and the importance of Pressure-Impulse Diagrams [24]. Likewise, related to fires, it is critical to be able to define the different type of industrial fires, e.g., pool fires, jet fires, flash fires, and fireballs, and understand the value of the Dynamic Thermal Stress Analysis (DTSA) approach [25]. Finally, it is important to mention that domino effect and escalation is not expected to occur due to hazardous dispersions [26].

Domino effects resulting in escalation triggered by explosions or fires in a facility handling hazardous materials are well-known phenomena that can result in severe accidents [27], [28], [29], [30] and [31]. Three concepts must be defined and understood when assessing a domino accident: (1) primary event, (2) secondary target, and (3) secondary scenario. A primary event is defined as the accident scenario of concern or initiating event, and its final outcomes are expressed in terms of physical effects; e.g., thermal radiation, overpressure. Secondary targets are equipment items that may be damaged by the primary event and, if damaged, the associated secondary scenarios have the potential to cause final outcomes escalating the primary event, i.e., secondary scenario.

Based on the tools developed during a risk-based assessment as discussed above, an approach is proposed to cover a LOC resulting in escalation due to thermal radiation or overpressure. The approach combines exceedance curves development and criteria from overpressure thresholds for explosions, while for fires, it combines exceedances curves development and criteria from heat flow thresholds. Exceedance curve development ensures that all primary events with potential to impact target equipment are considered, the cumulative frequency estimated, and the exceedance level of overpressure or heat flow is determined. Criteria from overpressure and heat flow thresholds allow predicting the target damage level and associated potential secondary scenarios for escalation.

Domino effect or Escalation analysis can be conducted by following two (2) different approaches: (1) a consequence-based approach; (2) a risk-based approach. As discussed earlier in this manuscript, the risk-based approach is considered the best tool to perform a risk-based assessment as it considers the likelihood of occurrence of all outcomes. When conducting a risk-based approach for escalation analysis due to explosions or fires, the following different methodologies can be applied:

- Threshold approach due to either explosions [27] or fires [30]
- Single Degree of Freedom (SDOF) approach due to explosions [28]
- Missile Impact approach, due to explosions [29]
- Dynamic Thermal Stress Analysis (DTSA) approach due to fires [31]

On one hand, the threshold approach for either fires or explosions is based on well-known thresholds from recognized references [32], [33]. However, based on the literature reviewed, there is uncertainty on the threshold values published from different sources because the design features of the target (i.e., process equipment, building) are usually not considered by the original references reporting the damage thresholds. On the other hand, the SDOF and DTSA approaches are more advanced approaches specifically intended to address escalation due to explosions and fires respectively. Finally, an advanced and dedicated approach is described to address escalation and domino effect due to projectile fragmentation.

The SDOF approach [28] is based on the fact that for practical design purposes, it is convenient to adopt approximate methods which permit rapid analysis of even complex structures with reasonable accuracy. These methods usually require that both the structure and the loading be idealized in some degree. It is frequently possible to reduce the system to a single degree of freedom, SDOF (system in which only one type of motion is possible; i.e., the position of the system at any instant can be defined in terms of a single coordinate). Structural elements can be represented by an equivalent SDOF, and even though such elements are parts of a complete structure, it is often permissible to treat them independently [24].

The Missile Impact approach [29] is based on following vessel burst scenarios. Fragment projection is usually caused by internal explosions (physical explosions, confined explosions, BLEVEs, runaway reactions) causing the catastrophic failure of vessels and the transfer of part of the explosion energy to the projected fragments. Fragments may be projected very far from the collapsed vessel (up to more than 1 km), and these have the potential to trigger secondary accidents causing the loss of integrity of the target vessel. When a fragment hits a target vessel, it may pierce the vessel shell (perforation), stop at some depth of penetration (embedment) or bounce back (ricochet). Thus, the target can be damaged either by penetration or by plastic collapse [34].

The DTSA approach [31] is based on determining the Time To Failure (TTF) of an equipment exposed to external fire. The TTF represents the available time lapse for the activation of emergency procedures and of mitigation measures, as well as for the deployment of emergency teams aimed at the mitigation and/or suppression of the primary fire; i.e., the complete and correct activation of the planned specific emergency measures should prevent, in general, escalation triggered by fire. Hence, reliable tools for the prediction of the TTF are required in order to determine the likelihood of escalation [25]. Since fire is the primary event, an accurate model to predict the heat load due to fire is required.

Finally, it can be observed that different approaches exist in order to address escalation events due to explosions or fires. At the end, to choose one approach or the other (i.e., threshold method versus SDOF for explosions and DTSA for fires) will depend on the degree of complexity required by the analysis to be performed. Furthermore, when addressing explosions, it is important to consider escalation due to flying fragments, as explained above.

Applications

A complete risk-based assessment allows the decision-makers to use the results of the study to several applications, such as:

1. Facility Siting,
2. Land-Use Planning,
3. Emergency Planning,
4. Fire and Gas Mapping Study,
5. Environmental Analysis, and
6. Cost and Business Analysis.

Below, the different applications derived from a complete risk-based assessment are explained in more detail.

Facility Siting

Based on API RP 752 [2], a risk-based facility siting assessment may be expressed as numerical values of individual risk, aggregate risk, or exceedance values. They can also be expressed as graphical formats which include cumulative frequency versus consequence curves, or matrices with numerical axes. Facility Siting is the direct application when a quantitative risk assessment is performed. There are a multitude of scenarios in a typical chemical processing plant that can lead to a LOC. Depending on the release conditions, mixture characteristics and possible chemical reactivity, wind speed, atmospheric stability, etc., several outcomes can occur resulting in a possible accident. These scenarios can range from a small leak to a catastrophic vessel failure. Thus, based on the results obtained from the risk evaluation (e.g., Individual Risk Contours, FN Curves) and comparing these risks to a worldwide risk tolerability criteria, it can be extracted: (1) whether the location of a facility or process unit within the hazardous facility presents intolerable risk to the workforce; (2) whether the public surrounding the area should be evacuated or risk reduction measures (i.e., inherent safer process design, mitigation, or prevention) need to implemented to reduce the risk level (i.e., land-use planning). Facility Siting and Land-Use Planning decision-making is based on the following hazard types:

- Explosions
- Fires
- Flammable or Toxic Dispersions

Explosions

The interaction of blast waves with plant structures and buildings is a complex process [23]. The severity of an explosion depends on the characteristics of each LOC, and depending on the location of specific infrastructures/buildings, the damage to these targets can be calculated in terms of structural damage or vulnerability to the individuals within this location (e.g., operators located in the Central Control Room) [35]. The damage that impacts a given infrastructure is based on the overpressure and impulse from an explosion, and can be directly correlated to fatality, major injury, and minor injury (i.e., dedicated FN Curves per affected location). CCPS and CIA criteria consider only overpressure as the main parameter to be studied when addressing vulnerability analysis. However, other criteria such as DoD considers also the impulse of an explosion. Reference [35] provides a more detailed explanation on facility siting and land-use planning based on explosions.

Fires

When addressing facility siting, considering mainly fires that result in a thermal radiation hazard, it is useful to combine exceedance curve with worldwide recognized thermal radiation thresholds with the aim to identify which buildings require mitigation measures for risk reduction. Additionally, dedicated FN curves are developed per each building under analysis, resulting in valuable information for manager's decision making ranking and defining the most appropriate actions to be taken. For a more detailed explanation on facility siting and land-use planning based mainly on fires, please refer to [36].

Dispersions

In this case, the main intention of the facility siting would be to focus on which buildings/locations are impacted by toxic releases from a given LOC. After selecting the appropriate damage criteria to be used, e.g., based on thresholds or probit analysis, building infiltration calculations are conducted. The concept of building infiltration can be defined as the air change rate associated with a specific building, the outdoor concentration reaching the building, and the exposure duration. Finally, toxic F-N Curves can be constructed for each affected building, allowing the user to identify the total number of expected fatalities of building occupants due to toxicity as a function of cumulative frequency. For a more detailed explanation on facility siting and land-use planning based mainly on dispersions, please refer to [37].

Land-Use Planning

Land-use planning advice for existing or new development of houses surrounding a site is based on the individual risk results (i.e., IRC) that a quantitative risk-based assessment provides. As explained above in this manuscript, the IRC need to be compared to worldwide risk tolerability criteria in order to decide whether the location of existing or new buildings is appropriate or not. For example, for the purpose of providing land-use planning advice, HSE [38] defines a *Consultation Distance*, within which are usually three zones around the major hazard (i.e., Inner Zone, Middle Zone, and Outer Zone). When using a risk-based approach, the zone boundaries correspond to levels of individual risk of dangerous dose or worse (i.e., fatality). Furthermore, HSE [38] differentiates between vulnerable public (e.g., schools, hospitals, elders, etc.) and non-vulnerable public, which affects the broadly acceptable, tolerable if ALARP, and not tolerable risk regions (i.e., the risk thresholds vary according to the public categorization). Thus, planning for future developments or modification of existing housing near a hazardous facility can be based on the results from a QRA when compared to applicable risk tolerability criteria. Note that risk tolerability criteria for land-use planning purposes normally are more stringent than general risk tolerability criteria as it is strictly focused on public population.

Emergency Planning

The challenge for emergency planners in the hazardous materials area is to choose concentrations of hazardous materials that can be used to define reasonable boundaries of a hazard zone [19]. A hazard zone could be defined as the area where the population exposed would need to be notified in order to take measures against possible LOCs having a hazardous impact (e.g., shelter in place, evacuate the population, provide protective equipment, etc.). There is a need to identify tolerable airborne concentrations for these hazards based on the population expected to be exposed in the event of an undesired release of a hazardous substance to the atmosphere. Reference [6] provides an overview of the tolerable airborne concentrations. Furthermore, it addresses damage criteria based on fires and explosions for both people and buildings/structures.

Fire and Gas Mapping

In a facility that handles hazardous substances, usually fire and gas detectors are located either on the site fence and/or the process units that operate with high quantities of toxic or flammable chemicals. However, the location of these detectors is usually not optimized and as a result, there are not enough detectors to cover areas with obstructions due to piping, equipment, etc. Thus, the main purpose of the Fire and Gas (FGS) mapping study is to identify and assess the proper placement and performance of detectors by simulating idealized fire and gas release scenarios (LOCs) throughout the application of 3D Models on working sites of a given chemical facility. Generally, gas (flammable and toxic) and fire detection systems are addressed in this type of assessment. Fire and gas mapping consists of the following steps:

- FGS Philosophy Considerations
- FGS Zone Definition and Categorization
- FGS Performance Targets
- FGS Detector Coverage Verification
- FGS Functional Safety Availability Verification

Based on the results obtained in the risk evaluation, the predicted individual risk contours due to toxicity and thermal radiation hazards are a starting point in order to conduct a FGS mapping assessment. Furthermore, based on the statistical and sensitivity analyses conducted during the development of a risk-based assessment (i.e., risk indices), it is possible to identify the most contributing scenarios. Thus, the placement of the detectors can be directly correlated to ensure that the most severe LOCs affecting the risk levels in the facility are covered in a higher percentage than scenarios that do not present as high of consequences. Consequently, it can be concluded that in order to conduct a FGS mapping study, it is necessary to have prior knowledge about the possible toxic and flammable dispersions that could occur in a site, and a risk-based assessment is the best methodology to represent those. Reference [11] explains how to conduct a complete FGS mapping study.

Environmental Analysis

A QRA study considers all the possible unwanted releases from all the process and non-process equipment located in a facility that handles hazardous materials. In the QRA framework, the consequences/impacts of explosions, fires, and hazardous dispersions to the workforce and public are generally addressed. Reference [14] provides and overview of the different damage criteria for people and structures used when a QRA study is conducted. However, it is important to mention that an accident with hazardous substances may also result in damage to the environment. Examples of environmental damage are:

- Contamination of groundwater by oil spills. As a result, large areas may become unfit for drinking-water preparation.
- Contamination of surface waters by spills or releases of toxic substances. As a result, life may not be supported in a watercourse for a prolonged period of time.
- Contamination of surface soil by deposition of harmful substances like dioxins and asbestos. As a result, large areas may become unfit for agriculture and human habitation, and clean-up may be needed.

Thus, a Quantitative Environmental Analysis (QEA) is focused on quantifying the risks of environmental impacts caused by accidental releases. Generally, an accidental release can lead to impacts in three environmental compartments: Air, Soil, and Surface water [14].

Cost and Business Analysis

Process Safety and Loss prevention focus on protecting the workers, public located in the surroundings of a facility, the environment, and also company investments. As a result, a QRA study can help meet the business needs of a company. A risk-based approach to design safety enables designers to answer the needs of all process safety stakeholders without compromising on safety or spending too much on excessive prevention and mitigation measures [19].

Particularly, the FN-curves, can be also used for a cost and business analysis. Generally, the axes of a FN-Curve are represented in the following manner: (1) the Y axis is the cumulative frequency of occurrence, and (2) the X axis is the number of expected fatalities. For this type of analysis, the X axis can be changed for another parameter such as business cost, revenue and an economic FN-Curve can be developed. By using a certain cumulative frequency of occurrence threshold, this type of FN-Curve can help the decision-makers decide whether additional investment is needed in order to decrease risk.

Conclusions

Process Safety and Loss Prevention field was born out of the need to avoid personnel injury, i.e., workforce and public, property damage, environmental impact and operation interruption (i.e., economic impact, due to several relevant accidents during the last fifty (50) years, e.g., Bhopal, Seveso, Buncefield, Flixborough, etc.) A Quantitative Risk-Based Assessment (QRA) is considered to be the foundation of process safety and loss prevention. Generally, there are two (2) main approaches to conduct a risk assessment: consequence-based or risk-based. The issue that arises by using a consequence-based approach is that the likelihood of occurrence is not considered, and therefore, it does not account for the frequency of an undesired event. A complete QRA consists of six main steps:

1. Hazard Identification, which consists of the identification of all Loss Of Containment scenarios (LOCs) with the potential to lead to an explosion, fire, or toxic hazards in a process facility.
2. Frequency Analysis, which estimates the likelihood of occurrence of all LOCs via analysis of historical data, specific plant data (if available), worldwide references with generic process equipment failure rates, and/or dedicated fault and event trees; i.e., bow-tie analysis;.
3. Consequence Analysis, which quantifies the effects and impacts of all potential outcomes that could occur from a given LOC, based on damage criteria for fires, explosions, and toxic hazards for personnel, structures, and process equipment.
4. Risk Analysis, which quantifies the risk level as a function of the likelihood of occurrence (i.e., frequency analysis) of possible undesired events (LOCs) and the magnitude of their associated impacts (i.e., consequence analysis), and it can be divided into two (2) categories: individual risk and societal risk.
5. Risk Tolerability Criteria, which consists of comparing the estimated risks to a worldwide recognized risk tolerability criteria to determine if the risk levels are deemed to be tolerable or not.
6. Risk Reduction, which consists of implementing risk reduction measures such as inherent safer process design, prevention, and/or mitigation in order to decrease the individual and/or societal risks to at least a tolerable if ALARP (As Low as Reasonably Practicable) risk region. Some examples of applicable safeguards or Independent Protection Layers (IPLs) are Safety Instrumented Systems (SIS), Fire and Gas detectors Systems (FGS), etc.

The completeness of risk-based assessment is based on the development of four (4) critical tools:

1. Individual Risk Contours used to characterize individual risk.
2. FN Curves, a requirement used by authorities to estimate the societal risk for facility workforce and/or public located in the surroundings of the process hazardous facility.
3. Exceedance Curves, approach that helps decision-makers to decide which location of interest (i.e., process equipment, building) needs further analysis based on the target being affected by a cumulative frequency of interest by overpressure, thermal radiation, or toxicity hazards.
4. Risk Indices, which allow the user to conduct valuable statistical and sensitivity analyses. The combination of the QRA results with other engineering tools, such as Dynamic Thermal Stress Analysis (DTSA) approach, Equivalent Elasto-Plastic SDOF (Single Degree Of Freedom) analysis, etc., allow managers to reinforce the decision-making process. Furthermore, when a complete QRA study is conducted, it is possible to identify severe accidents due to domino effect and escalation as a result of primary explosions such as vessels bursting, projectile fragmentation, fires, etc.

QRA applications are wide and very valuable to the decision makers, and some examples are the following:

- Facility Siting due to explosions, fires, and toxic and/or flammable dispersions.
- Land-Use Planning, applicable to existing and new housing developments near a hazardous facility.
- Emergency Planning, identifying escape routes in the event of an undesired release.
- Fire and Gas Mapping to properly locate fire and gas detectors onsite and reduce the risk.
- Cost and Business Analysis, used to protect the company investments in addition to workforce and public, as well as the environment.
- Environmental Analysis, to analyze the impacts to the environment in the event of an unwanted release.

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