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Quantitative Risk Analysis of a Complex Chemical Process and Utilizing the Results for Risk Reduction Decisions

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Abstract

In the chemical, petrochemical, petroleum, and related industries, a broad range of qualitative and quantitative methodologies are employed to understand the impact of release of hazardous materials and the probability or frequency of these releases. These evaluations provide an understanding of risk. One of the common quantitative methods to understand the impact of the release of hazardous materials is Consequence Analysis often required by regulations. When coupled with qualitative or semi-quantitative frequency estimates based on site, company, or industry knowledge, good risk based decisions can be made in most cases. Very rare high consequence events present a difficult problem because risk reduction can involve a broad range of options, and range from low to high cost. For many of these situations, adequate understanding can be obtained when quantitative consequence analysis studies are coupled with more quantitative frequency analysis methods such as fault tree or event tree analysis.

However, when the range of mitigation options is broad, and/or when the cost of mitigation is high, these studies may not produce adequate information to help guide business decisions, and a Quantitative Risk Analysis (QRA) may be justified. A QRA that addresses all types of accident scenarios, their expected frequencies, location of populations, and frequencies of weather conditions occurring, can lead to a full understanding of process risks. Once a baseline QRA is completed for a facility, it can also be used to determine the impact of process and operational changes to reduce the risk. By conducting QRAs for several facilities, using a consistent set of assumptions, a business can develop a complete understanding of the primary contributors to overall risk. Additionally, based on the impact and cost of the various improvements, decisions can be made to maximize the risk reduction benefits and allocate finite resources across all facilities. In this paper, details will be provided on a study conducted across a global business to understand and cost-effectively reduce risks.

Background

Various regulations require the implementation of process safety management programs at chemical process plants. Different rules have been promulgated to protect workers, public, and the environment. These rules require an analysis of hazards associated with handling dangerous chemicals and implementation of systems to improve process safety. Companies in the U.S.A. are required to conduct consequence analyses, either as part of the Process Hazards Reviews (required by OSHA) and/or as part of Risk Management Plans (required by EPA), and submit reports to government agencies. In many European countries, such as The Netherlands & United Kingdom, risk based regulations have been developed for urban planning, requiring a quantitative understanding of both consequence and frequency (Ale, 1991; HSE 2001). The government agencies can require that a detailed quantitative risk analysis be conducted. Similar rules have been implemented or are being developed in many other countries, like Australia, Singapore, etc.

In the U.S.A, and in many other countries, Process Hazards Analyses (PHAs) are required to understand the nature of the hazards, and assure adequate mitigation measures are taken to control these hazards. These studies are done for new facilities, and are done on a cyclical basis for existing facilities. As part of the PHA process, qualitative consequence analyses are conducted to determine the range of safety and health effects of the failure to control hazards.

For many scenarios addressed in PHAs, a qualitative consequence analysis is followed with a qualitative assessment of the likelihood of the events. This provides the PHA team with some understanding of the potential risks to both on-site and off-site populations. The PHA team may recommend that a better understanding of risk be obtained, and conduct a quantitative consequence analysis and a quantitative analysis of the event likelihood. Usually, this is done to examine whether additional protection can be effectively added by either reducing the impact or adding safety interlocks, testing or other safeguards that will reduce the potential event's likelihood. Inherently Safer Process design & implementation is one of the approaches that can be used for risk reduction. In some situations, a fault-tree analysis may need to be performed for the specific event in question. In rare circumstances, a comprehensive Quantitative Risk Assessment (QRA) that considers many potential events may be recommended to help a business determine the best means of developing a comprehensive understanding of risks, and to provide sufficient detail to guide complex risk reduction decisions. QRAs are costly, and the effort should not be undertaken unless justified by the business.

Further details are provided below on the PHA process, typical Consequence Analyses, and the application and value of QRAs in reducing risk.

Process Hazards Analysis

Process Hazards Analysis is defined as the application of organized, methodical approaches to identify, evaluate, and control the hazards associated with process facilities. It includes some or all of the following activities: hazard identification, consequence analysis, hazards evaluation, human factors evaluation, facility siting evaluation, inherently safer process evaluation, risk analysis, and development of recommendations.

OSHA's Process Safety Management and EPA's Risk Management Program regulations require that all covered plant operations, in the U.S.A., must conduct PHAs. PHAs are used to identify, evaluate, and develop methods to control significant hazards associated with hazardous processes and operations, and document the results. These are used for emergency planning, and training of personnel involved in operating & maintaining the process. Additionally plants, both domestic and abroad, need to comply with internal standards and local regulations.

While implementation of the process safety management systems may vary, a PHA team uses a variety of qualitative to quantitative methodologies to identify and analyze the hazards. Techniques such as What-If, What-if/Checklist, HAZOP, etc. are commonly used.

Consequence Analysis

Consequence Analysis is defined as the development of potential scenarios describing hazardous events that may occur due to loss of engineering or administrative controls and the evaluation of resulting impact on site personnel, off-site communities, and the environment. Consequences are analyzed independent of the event's probability or frequency of occurrence.

A Consequence Analysis consists of evaluating the direct, undesirable impact of potentially hazardous events, such as fires, explosions, and toxic releases, resulting from loss of engineering and administrative controls for the process. This evaluation includes estimating release amounts and conditions, evaluating consequences and affected areas of impact, and determining the resulting safety and health effects. The PHA team must identify and understand the consequences of a wide range of possible hazardous events associated with the process.

Such consequence analyses helps the PHA team develop an understanding of the type, severity, and number of potential injuries, possible property damage, and significant environmental effects, at both on-site and off-site locations. When combined with either a qualitative or quantitative understanding of event frequency, effective risk reduction recommendations can be made.

In many cases, a "worst case" event is the starting point for consequence analysis. Should a worst case event occur, the impact to humans and the business could be severe. However, PHA teams should be careful not to make recommendations simply because the consequences are high. Resources may be wrongly allocated by addressing the consequences alone. Hazardous events that have lesser consequences, and much more likely to occur, may pose a higher risk.

For example, for a process that handles chlorine, a PHA team might identify a range of events ---- catastrophic, large, medium, & small. Chorine is a hazardous chemical that has specific Emergency Planning Guideline Concentrations (ERPG) concentrations that are toxic endpoints defined by American Industrial Hygienists Association (1998). The ERPG-3 and ERPG-2 levels are 20 ppm and 3 ppm, respectively. ERPG-2 is the concentration above which irreversible injuries and/or symptoms that could impair a person's ability to take protective action could occur. ERPG-3 is the concentration above which life threatening health effects could be experienced or later develop. Figures 1 through 3 show the ERPG-3 impact areas for the range of chlorine releases; under D atmospheric stability and 5 m/s wind speed. The ERPG-2 impact distance can extend beyond 25 miles under certain conditions. The impact area may be very large for the "worst case" scenario, however the likelihood of such an event is very low. In contrast, the smaller releases have a much smaller impact area, but the likelihood of such events is greater.

Frequency analysis

Frequency is the number of occurrences of an event per unit of time and may be quantitative (1.0E-03 events/year) or semi-quantitative, for instance, an event is considered unlikely to occur during a single plant's lifetime but could occur once if there were a number of similar plants.

In some cases, particularly an event with potentially high consequences, the PHA team may feel that a qualitative understanding of the event's frequency is not sufficient and that a more formal evaluation is needed. In these situations a fault tree analysis is generally the tool of choice although an event tree may also provide the necessary information. For events limited to on-site consequences, the predicted event frequency, or interval between incidents (IBI) when combined with the potential consequences can be used to generate measures of risk. These include Individual Hazard Index (IHI), the number of fatal injuries per 100MM exposure hours or a Process Hazards Index (PHI), the mean time to a fatality in years.

For the process discussed in the previous section, available industrial data (Lees, 1996), fault-tree, and event-tree analyses were used to quantify the frequencies of the events. It was determined that the catastrophic failure has an event frequency of 6E-06 per year, whereas, the small event has an event frequency of 3E-04 per year. Therefore, it is important to understand both the consequences and the frequencies of the events, in each specific set of circumstances, in allocating resources for reducing risk. In quantifying risk for such a process, it is important to also analyze the variability of meteorological conditions and incorporate the actual population exposed.

Understanding Overall Risk

In most circumstances, the PHA teams can make recommendations and achieve risk reduction for processes where there is a clear connection between events and their impacts. Many of these recommendations can be achieved with the efficient expenditure of resources. When resource intensive decisions are involved in reducing risks, a detailed Quantitative Risk Analysis may be recommended. A QRA can be very effective in helping a multi-site and operations business improve both strategic and tactical decisions, leading to better allocation of resources.

One DuPont business has manufacturing operations in several countries on three continents with many of these sites manufacturing or processing hazardous materials that could have off-site impact in the event of a release, fire or explosion. In the late 1990's, this business identified the need to quantitatively understand the risk of these hazardous materials operations for the purposes of most effectively utilizing our resources (money and people) to manage this risk. Though the technology existed (as described further in this paper) to quantitatively evaluate the risk, no business process existed in DuPont to effectively utilize the results of multiple QRA studies.

In developing a business process for the management of these risks a number of criteria need to be considered. First, the process needed to be part of the life cycle management of the facility. A QRA on a site supplements other efforts and programs to manage safety. Second, the process needed to incorporate consistent methodologies that use the same assumptions and have similar levels of detail in the input data across sites and process units so that results can be compared unit to unit and site to site. Third, the process had to be designed to allow for staged implementation across the business and in a way that individual studies are useful but multiple studies can be taken into consideration when developing an overall risk management strategy. Fourth, the results of the process needed to be understandable by non-technical business leaders with a minimum amount of effort. And finally, there had to be quantitative measures for evaluating risk reduction alternatives but with enough flexibility to allow for good technical and business judgement. A business process, that incorporates all these criteria for success, was developed and implemented. It is further discussed in the sections below.

A business also needs to develop a planned approach to conducting detailed QRA studies. With limited resources for implementation of the business process mentioned above, multiple studies could not all be conducted at the same time. Therefore the business needed criteria for developing the order in which sites should be analyzed. Considerations for the site prioritization include:

- Amount of Chemical of Concern: Routine and maximum inventory of hazardous chemicals and the consequence analyses from PHAs are an important variable to consider when identifying sites that have high priority for analysis
- Number of People Residing Near the Facility: Facilities in urban areas have higher priority for analysis than those in rural settings.
- Importance of the Facility to the Business: Those sites with higher business impact if an event were to occur are a higher priority for analysis.
- Community Relation Issues: An active community where there is interest in risk due to chemical facilities should be taken into account when developing QRA priorities.
- Legal or Regulatory Requirement to Evaluate: Some localities require QRA for off-site hazard potential.
- Incident History: Facilities with a history of accidental releases need to be considered higher on priority list than facilities without significant historical incidents.
- Judgement: Good engineering and business judgement must be used along with the other criteria above.

Described in the section below is the overall QRA methodology used to maintain consistency among all the operations and locations. Such consistency is important to generate results that are comparable and will lead to rational risk reduction decisions.

Quantitative Risk Assessment (QRA)

Quantitative risk assessments must be carried out in a methodical way and include the effects of all significant failures along with their appropriate probability. A flowchart showing typical steps is shown in Figure 4 (CCPS, 2000). For the studies discussed in this paper, the software package SAFETI® was used.

Further details are provided here on the specific approach taken in conducting QRAs:

Define the Potential Accident Scenarios

This involves the identification of potential failures, which result in the release of material from its normal containment. In this study, the following classes of releases: "small hole" (about 5 mm), "medium hole" (about 25 mm), "large hole" (about 50 mm up to about 100 mm) and "catastrophic failure" (release of material in 1 to 10 minutes); were considered. Process information such as pressures, temperatures, mass, pumping rate, etc. along with interlock strategies, relevant operating procedures and so on were collected so that reasonable release conditions, release rates and release times would be used in the risk calculations. Where significant variations in storage temperature, storage mass or other parameters existed, these were included as additional incidents in the studies.

Evaluate the Event Consequences

Meteorological input for the studies was site specific and usually reflected at least two years of actual data. It was always divided into day and night profiles and into seasonal variations, as appropriate.

The potential accident scenarios are input into the model (SAFETI®) a few at a time to first check the consequence model results using the actual meteorological data. In dealing with gases that are stored as liquids in pressure vessels, it is important to carefully analyze the prediction of droplet size and rainout. Where appropriate, special technical models that predict release rates, droplet size and percent rainout were used. Where appropriate, input to the SAFETI® model was modified (using the user defined input option) for the relevant scenarios, and the consequences again evaluated and checked.

Estimate the Potential Accident Frequencies

After defining an event, the various factors that affect the frequency of the event imposing a risk to the offsite population are introduced in a logical fashion. Factors that directly affect this frequency are:

- Likelihood of a particular release occurring
- Probability of the various meteorological conditions existing at the time of the release
- Effectiveness of response that may occur.

The effect of valves, safety devices, and process conditions were included, as they influence the release rate (quantity), duration, and phase. This analysis provides a comprehensive and representative spectrum of incidents that could occur.

Most of the events considered are predicted to occur infrequently and fortunately, the major events are very rare. Sources for the frequency data used in this analysis were obtained from historical failure data collected from sources in the chemical, petroleum, and utility industries. In addition, fault tree analyses were also performed for some of the scenarios to determine the associated failure frequencies for particular pieces of equipment.

Site-specific data (inspection records and methodology) were taken into account for determining the likelihood of tank failures. One adjustment made to the industrial average failure frequencies was in the case where an ongoing damage mechanism (corrosion, cracking, etc.) increases the likelihood of a failure occurrence by weakening the equipment. If the damage was sufficiently severe, the likelihood of failure in the presence of this damage may exceed the average likelihood of failure. In such a case, the frequency was typically adjusted upwards. The amount by which the frequency is increased is referred to as the "Damage Factor". In case of pipes within pipes adjustments were made to the frequency using a "Pipe within Pipe" factor per the Purple Book (1999) published by the Government of The Netherlands.

In addition, key automatic valves were evaluated based upon the testing interval. This provided predicted reliabilities for each valve analyzed. Other than the aforementioned items, additional site-specific failure rate developments included pumps (canned and single seal), flanges (with and without stainless steel bolts), ISO-tanks, tank trucks, and rail cars.

Estimate the Event Impacts

Event impacts are determined based on the consequence analyses that provide the impact zones. Exposure to an ERPG-3 concentration over a period of an hour can, as a rule of thumb, typically result in 0.1% probability of death to an exposed individual. The toxicology of the chemicals being considered in a QRA are represented by probit relationships that quantify the probability of fatalities resulting from exposure to high concentrations for a known period of time. It is a statistical curve fitting method that extrapolates data from animal studies for each of the chemicals. The constants for the probit equations used for all the toxic chemicals in a study, are based on data available in literature or, derived in-house.

The probit equation takes the following form: $Y = a + b (\ln [C^n t])$ where: Y is the probit; a, b, c are constants; C is the concentration in ppmv; and t is the exposure time, minutes. For chlorine the probit constants, developed by the U.S. Coast Guard (CCPS, 2000), are as follows: $a = -8.29$; $b = 0.92$; and $n = 2$. Probit values can range from negative to positive values and provide a relationship that is used to estimate the probability of an outcome from essentially 0% to 100%. For complex mixtures, or where the toxicology data does not exist, the probit constants were estimated with the help of toxicology experts at DuPont's Haskell Laboratory.

In addition to toxicological data, the other considerations that are important are the variability of weather at any location and the distribution of population. Meteorological data (wind speed, direction, and atmospheric stability) are needed to model the "actual" dispersion of releases. The meteorological data are broken into "normal working" and "shift-working" hours distributions. The raw meteorological data are obtained from local meteorological stations. The raw data are processed using a variety of tools to generate joint frequency distributions for use in the SAFETI® program. These joint-frequency distributions define the probabilities of stability & wind-speed combinations (e.g. F stability, 1.5 m/s windspeed) that occur from each wind direction. Figure 5 shows a typical chart for a location.

The population distribution around a facility is used to assess the potential adverse impact of an incident. Typically, the population on a plant site is highest during the daytime (or normal working) hours and is significantly lower during the night and weekend (shift working) hours. The opposite is normally true for residential areas. The population data for the offsite residential areas are determined based on information available from local, state and national governmental agencies, or may be estimated by observation. The population data for off site industries and 'special' areas such as schools, hospitals, sporting venues, etc. was also obtained. In the QRA, different population profiles are entered into the SAFETI® program for daytime and nighttime and includes seasonal variability when applicable.

The impact of a chemical release event is then analyzed based on the probability of fatality, weather, and population distribution. The result is in the form of predicted number of fatalities per year which tends to be a small number (e.g. for "worst-case" chlorine event --- 3E-04 fatalities per year; and small chlorine release --- 1E-04 fatalities per year)

Estimate the Risks

The next stage in a QRA for a site is to combine the results of the study to present the risk levels from the evaluated events. Both the individual risk and the societal risk due to the operations are calculated. Individual risk represents the frequency of an individual fatality due to the evaluated events. Societal risk is the sum of rates of fatalities for all the events also referred as the Societal Risk Index (SRI). Another index that was developed is the Process Hazards Index (PHI), the inverse of the SRI. The PHI represents the mean time to a fatality in years. A QRA also generates results that can be used to determine the cumulative frequency of "N" or greater predicted fatality (F-N) curves. Additional examples of these results are provided in the Case Study section below.

Evaluate the Risk

Once a QRA study is completed, the results can be used to understand the overall risks and particularly the events that are the major contributors. But first, some "Quality Assurance" should be performed to ensure that the predicted major contributors are in fact reasonable. The results can be categorized in many different ways to understand the risks of various chemicals, types of operation (e.g. storage, unloading, transport, etc.), types of releases, diurnal (day vs. night), and seasonal variability.

A QRA provides sufficient detail to identify the leading contributors to both individual and societal risks. These risks can be ranked by the various risk measures as IHI or PHI. The risk analyst, working with the operating, technical, and maintenance personnel, reviews the leading risk contributors, and develops risk mitigation measures targeted at reducing both the consequences and frequency of occurrence.

Identify and Prioritize Potential Risk Reduction Measures

The most value of a QRA study is in identification of the few (typically, 20%) events that contribute to majority (typically, 80%) of the risk, and the ability to quantify the impact of risk reduction measures. Once the major contributors have been identified in establishing the base case, reduction measures can be analyzed to determine & prioritize them. Some of the most effective measures are reduction in inventory of hazardous materials, and installation of additional safeguards (e.g. dikes, interlocks, etc.).

Once the risk reduction focus areas have been identified, alternatives are generated usually by operations and technical personnel familiar with the operation. As these ideas are generated, a risk analyst uses these alternatives to predict the risk reduction that would be expected if these were implemented. In the case of multiple options that address one particular operation or piece of equipment, these scenarios can be compared using multiple measures of risk such as PHI, risk contour size, F-N curve changes or any other appropriate risk measure. Other factors such as capital cost, operating cost, technical feasibility, reliability of the operation, supply chain impacts and effects on other risks must also be taken into consideration when deciding which alternative may be the best to pursue.

Case Study

Detailed QRA's were conducted for a DuPont business that has multiple operations across the globe. Further information is provided here about four of the sites.

Site A is a large user of a common hazardous material and produces other chemicals that are used as raw materials in many operations within and outside DuPont. This site is located near a large city in the U.S. The main hazardous chemical was shipped to the facility from a supplier, stored in large storage vessels, and consumed in the manufacturing process. Several options were analyzed, and it was determined that eliminating the large storage vessels would result in major risk reduction. In order to maintain needed production, additional railcars containing the hazardous chemical were kept on site. Figures 6, 7, and 8 show the risk contours, F-N curve, and events contribution to the SRI for the base case evaluation.

Site B is similar to Site A, but also includes further processing of the materials to produce polymers and other products. This site is located in another country outside the U.S. The typical operations at this facility included the storage and handling of a range of hazardous materials in the manufacturing processes. Again several options were analyzed, significant risk reduction was realized by reducing distillation column inventories, and reducing storage quantity.

Site C is another operation that makes large quantities of a hazardous chemical and is a user of many others in the production of a variety of industrial chemicals. This site is also located near a major metropolitan area in the U.S. It is anticipated that major risk reduction will be achieved by eliminating large storage vessels and providing "tank within tank" storage alternatives.

Site D is a complex operation where hazardous chemicals are used to generate non-hazardous products. It is located outside the U.S. in a densely populated region. Significant risk reduction was achieved by eliminating storage vessels, and through process changes.

Risk Reduction

Once a baseline QRA is conducted, the next step is to identify risk reduction opportunities (RRO), quantify their impact, and prioritize them. Typically, there are four cases to consider when prioritizing RROs:

- Multiple sites included in the analysis with one or more sites posing a significantly higher risk than the others
- A single site where one operation poses significantly more risk than other operations on the site
- Multiple sites where all have similar risks
- Single site where no single operation drives the risk

RRO decision making is relatively straightforward for the first two cases above. In order to have a significant reduction in risk for the site/business, RROs must be implemented at the site or unit that poses the highest risk and continue to be implemented until that site/unit poses similar risk as the other operations. Cost effective, practical RROs should be implemented at these sites/units depending on the business tolerance for risk and any governmental requirements.

For the case study being discussed, many RROs were evaluated at the four sites. Significant risk reduction was achieved by eliminating storage, reducing inventories, and process changes, as appropriate. To determine the options that achieve the greatest reduction in risk and are cost-effective, a business-wide process such as the following is used:

- Analyze the potential impact of RROs on risk measures

- Evaluate cost of all the RROs
- Determine the value (change in risk per dollar spent)
- Rank order the RROs
- Isolate & implement the RROs that have the biggest impact.

After implementing the RROs that have the biggest impact, it is necessary to make sure that a process for continuous improvement has been implemented.

Figures 9, 10, and 11 show the impact of the RRO's implemented at Site A. Table 1 shows the risk reduction in terms of PHI change, achieved at each of facilities. To avoid cluttering this paper the detailed graphs/pictures (representing all risk measures) corresponding to the RRO changes have not been shown for all the sites.

Conclusions

A variety of qualitative to quantitative methodologies are used in industry to understand and reduce risks from hazardous operations. Regulations and internal standards require businesses to conduct consequence analyses to determine the impact of releases, as part of the Process Hazards Analyses process. These evaluations allow a business to make only limited risk reduction decisions. Consequence analyses covers a wide range of possible hazardous events but is focused on providing the extent of toxic/flammable impact without considering the likelihood of the events. In many cases, PHA teams address the frequency of releases in a qualitative manner and are successful in making cost effective recommendations to reduce risk. Decisions to reduce the consequences of extremely rare, high consequence events could be very costly, may not lead to significant risk reduction, and divert resources from measures that could have a much greater risk reduction impact. Where scenarios are complex and operations are in multiple locations, a business wide strategy to reduce risk is required to properly allocate resources.

A comprehensive quantitative risk analysis (QRA) that addresses all types of accident scenarios, their expected frequencies, location of populations, and frequencies of weather conditions occurring, can help identify the events that contribute most to the risk. Once a baseline QRA is completed for a facility, it can also be used to determine the impact of process and operational changes intended to reduce the risk. By conducting QRAs for several facilities, using a consistent set of assumptions, a business can identify the primary contributors to overall risk. Additionally decisions can be made to maximize the risk reduction benefits for finite resources. In this paper, details have been provided on a case study conducted across a global business in DuPont to understand and reduce risks. The approach was effective in significantly reducing risk in a cost-effective manner.

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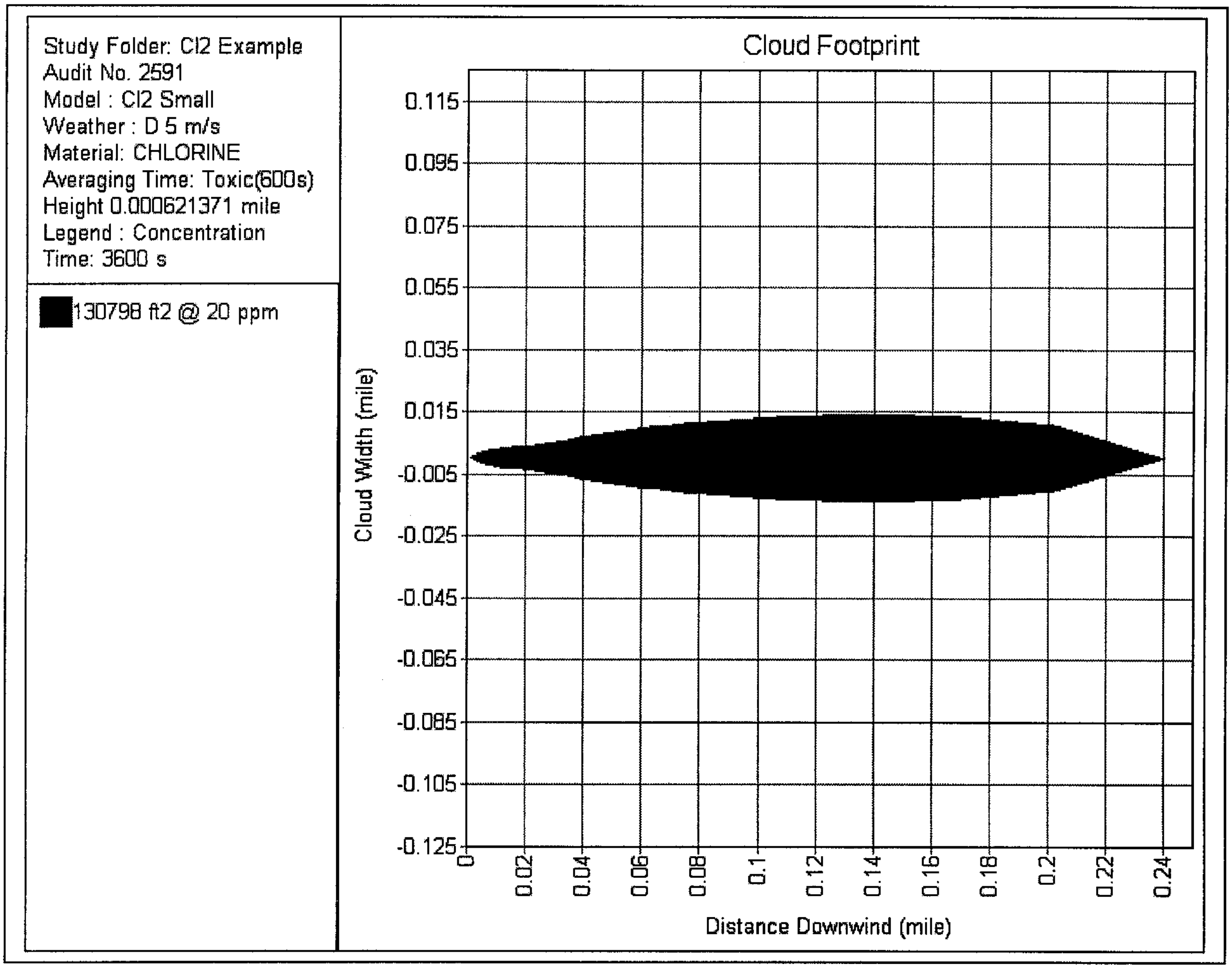

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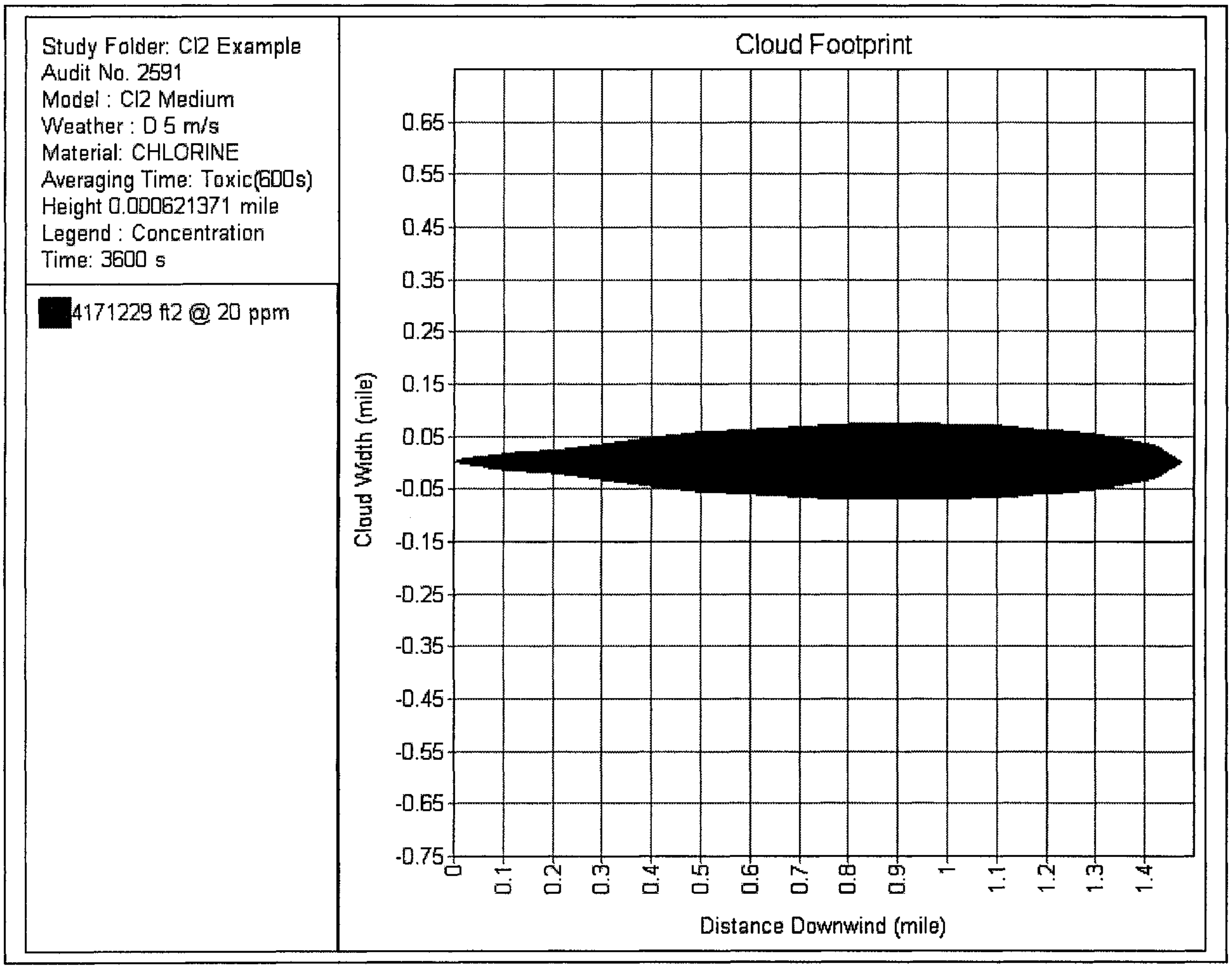
Audit No. 2591
Model : Cl2 Small
Weather : D 5 m/s
Material: CHLORINE
Averaging Time: Toxic(600s)
Height 0.000621371 mile
Legend : Concentration
Time: 3600 s

■ 130798 ft2 @ 20 ppm

Figure 1: “Small” Cl_2 Release; D Stability 5 m/s Wind Speed



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Model : Cl2 Medium
Weather : D 5 m/s
Material: CHLORINE
Averaging Time: Toxic(600s)
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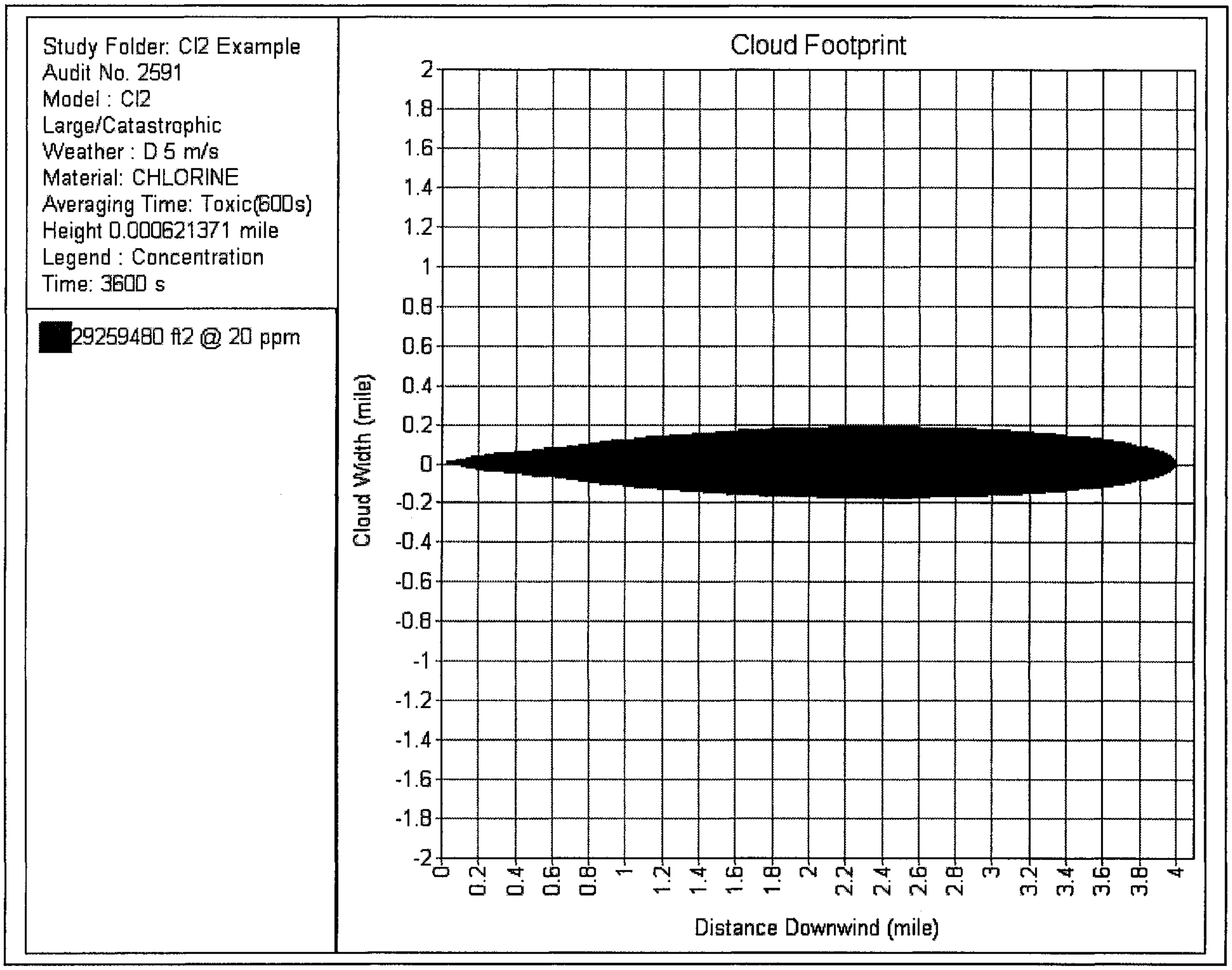
Legend : Concentration
Time: 3600 s

■ 4171229 ft2 @ 20 ppm

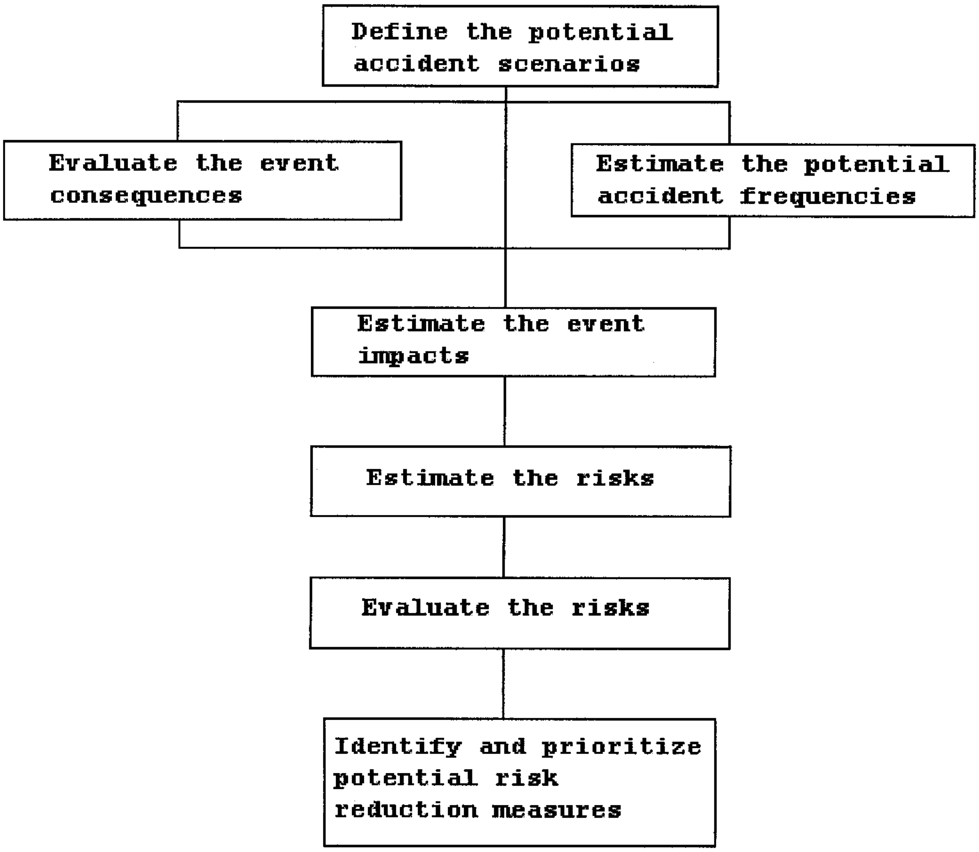
Figure 2: “Medium” Cl_2 Release; D Stability 5 m/s Wind Speed



Study Folder: Cl2 Example
Audit No. 2591
Model : Cl2
Large/Catastrophic
Weather : D 5 m/s
Material: CHLORINE
Averaging Time: Toxic(600s)
Height 0.000621371 mile
Legend : Concentration
Time: 3600 s

■ 29259480 ft2 @ 20 ppm

Figure 3: “Large/Catastrophic” Cl_2 Release; D Stability 5 m/s Wind Speed



CPQRA Flowchart (from Guidelines for CPQRA, CCPS 2000)

Figure 4: QRA Flowchart

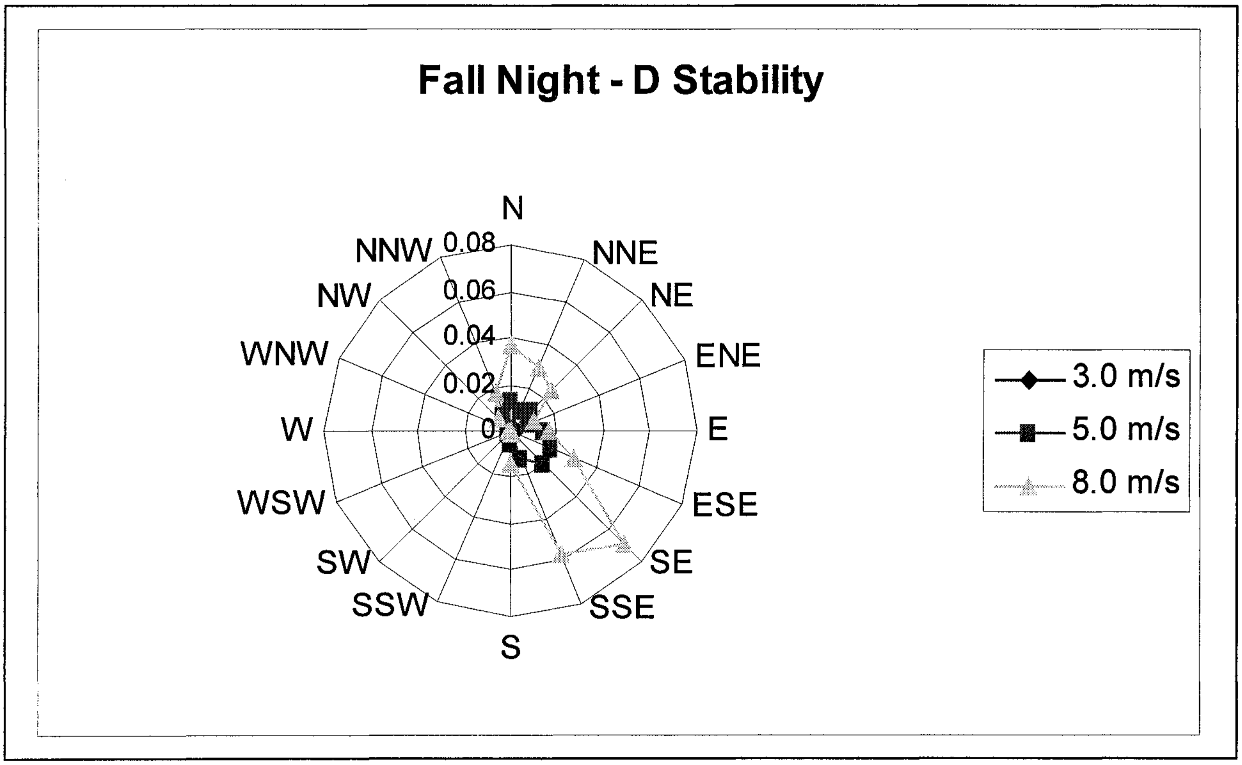


Figure 5: Typical weather frequency distribution

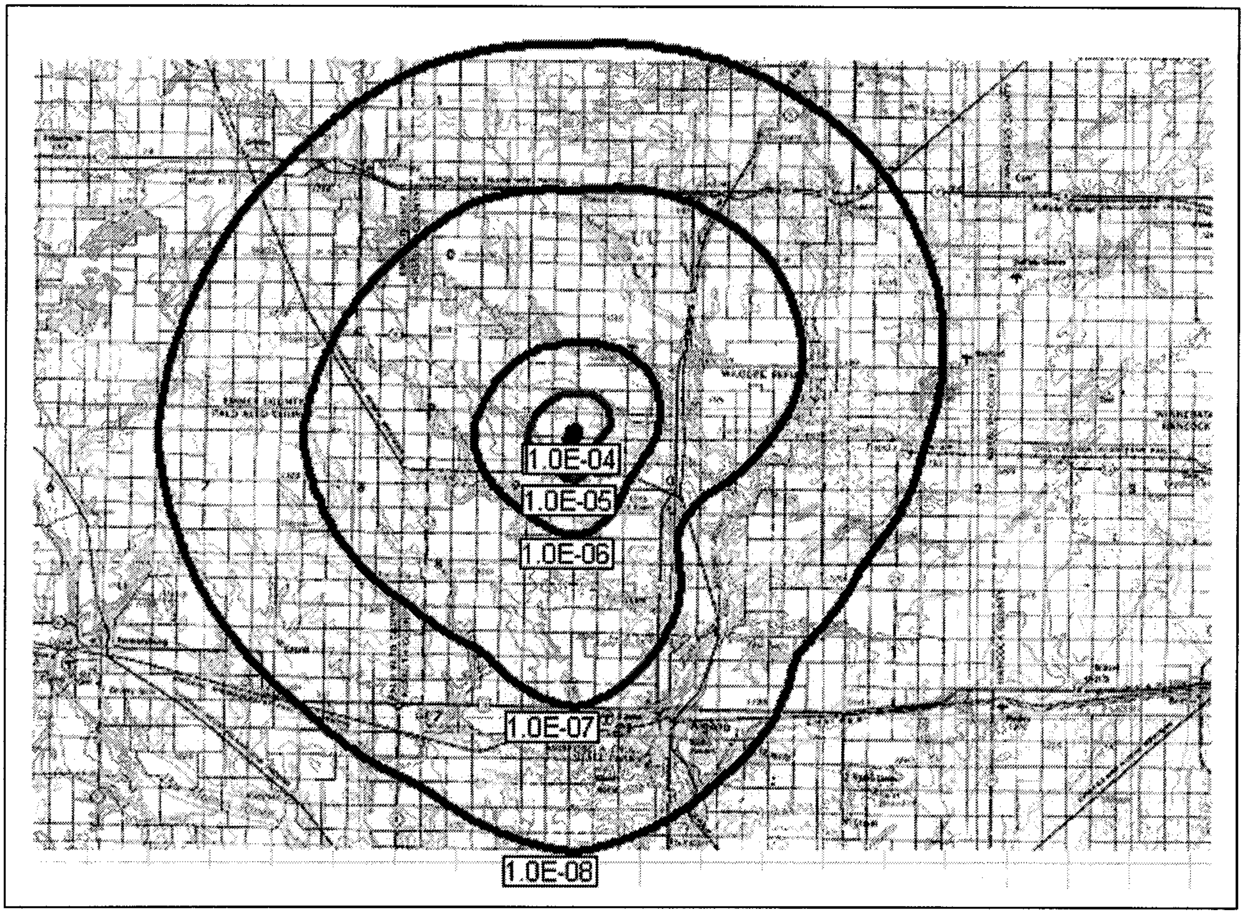


Figure 6: Site A --- Baseline Individual Risk Contour

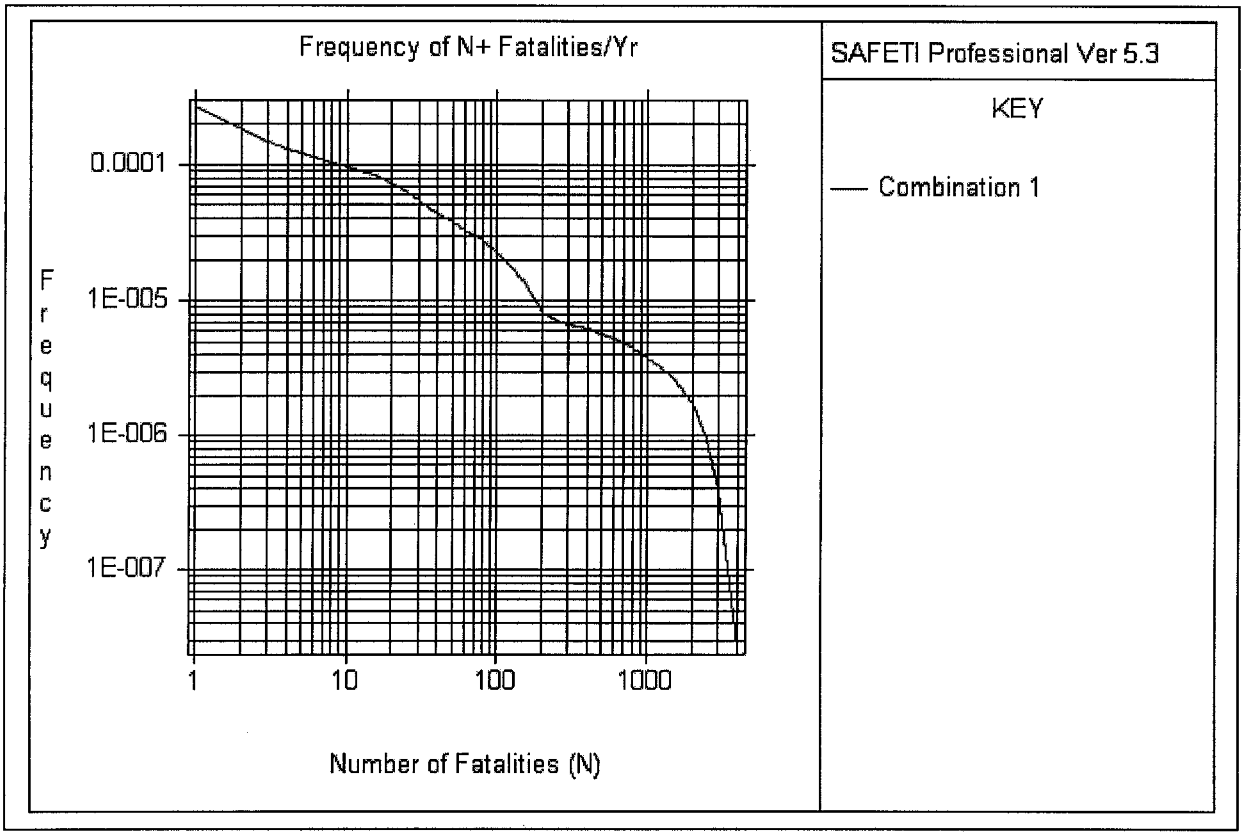


Figure 7: Site A --- Baseline F/N Curve

Ranking of Societal Risk

	Case Name	Average No. Fatalities Per Year	% of Total	Average Fatalities Per Outcome	Freq. of 0 - 1 Fatality Per Year	Freq. of 1 - 10 Fatality Per Year	Freq. of 10-100 Fatality Per Year	Freq. of 100-1000 Fatality Per Year	Freq. of 1000-10000 Fatality Per Year	Freq. of 10000+ Fatality Per Year	Frequency of zero Fatality Per Year
1	S4-Y	7.53E-03	51.1	2.22E+02	6.56E-06	1.22E-05	6.46E-06	3.08E-06	3.03E-06	0.00E+00	2.53E-06
2	S2-Y	3.82E-03	25.9	5.59E+00	2.64E-04	8.20E-05	6.23E-05	1.92E-05	0.00E+00	0.00E+00	2.57E-04
3	S5-Y	1.29E-03	8.8	2.98E+02	5.64E-07	1.40E-06	1.16E-06	5.35E-07	4.29E-07	0.00E+00	2.36E-07
4	S7-Y	5.09E-04	3.5	8.91E+01	6.76E-07	2.07E-06	1.88E-06	7.50E-07	5.65E-08	0.00E+00	2.87E-07
5	S3-Y	4.94E-04	3.4	1.46E+01	9.45E-06	1.14E-05	2.59E-06	1.98E-06	0.00E+00	0.00E+00	8.52E-06
6	S4-E	3.97E-04	2.7	2.22E+02	3.46E-07	6.46E-07	3.41E-07	1.63E-07	1.60E-07	0.00E+00	1.34E-07
7	S8-Y	2.70E-04	1.8	3.70E+02	6.25E-08	2.26E-07	2.27E-07	1.17E-07	8.71E-08	0.00E+00	1.00E-08
8	S2-E	1.94E-04	1.3	5.38E+00	1.39E-05	4.31E-06	3.94E-06	3.45E-07	0.00E+00	0.00E+00	1.35E-05
9	S5-E	6.86E-05	0.5	3.01E+02	2.97E-08	7.37E-08	6.11E-08	2.84E-08	2.26E-08	0.00E+00	1.25E-08
10	S6-Y	5.02E-05	0.3	8.77E+00	1.01E-06	3.21E-06	5.82E-07	5.69E-08	0.00E+00	0.00E+00	8.63E-07
11	S7-E	2.75E-05	0.2	9.12E+01	3.55E-08	1.09E-07	9.88E-08	3.95E-08	2.97E-09	0.00E+00	1.51E-08
12	S3-E	2.52E-05	0.2	1.41E+01	4.99E-07	5.99E-07	1.37E-07	1.05E-07	0.00E+00	0.00E+00	4.50E-07
13	S9-Y	1.81E-05	0.1	7.27E-02	5.69E-05	2.51E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.90E-04
14	S10-Y	1.76E-05	0.1	7.48E+00	1.02E-06	4.93E-07	1.79E-07	4.62E-08	0.00E+00	0.00E+00	6.13E-07
15	S8-E	1.38E-05	0.1	3.60E+02	3.15E-09	1.20E-08	1.19E-08	6.17E-09	4.58E-09	0.00E+00	5.29E-10
16	S11-Y	7.46E-06	0.1	6.49E+00	5.26E-07	2.82E-07	9.13E-08	2.25E-08	0.00E+00	0.00E+00	2.28E-07
17	S6-E	2.68E-06	0.0	8.90E+00	5.41E-08	1.68E-07	3.13E-08	2.99E-09	0.00E+00	0.00E+00	4.44E-08
18	S9-E	9.46E-07	0.0	7.22E-02	2.91E-06	1.32E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E-05
19	S10-E	9.05E-07	0.0	7.30E+00	5.38E-08	2.60E-08	9.43E-09	2.44E-09	0.00E+00	0.00E+00	3.23E-08
20	S12-Y	7.66E-07	0.0	2.22E+00	1.79E-07	7.98E-08	2.26E-08	0.00E+00	0.00E+00	0.00E+00	6.43E-08
21	S1-Y	4.09E-07	0.0	1.54E-03	1.28E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.53E-04
22	S11-E	3.89E-07	0.0	6.42E+00	2.80E-08	1.48E-08	4.81E-09	1.18E-09	0.00E+00	0.00E+00	1.17E-08
23	S1-E	2.11E-07	0.0	1.51E-03	6.76E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.33E-04
24	S12-E	3.90E-08	0.0	2.14E+00	9.43E-09	4.20E-09	1.19E-09	0.00E+00	0.00E+00	0.00E+00	3.38E-09

	Total	1.47E-02									

PHI 68 years

Figure 8: Site A --- Baseline Societal Risk Index and Process Hazards Index

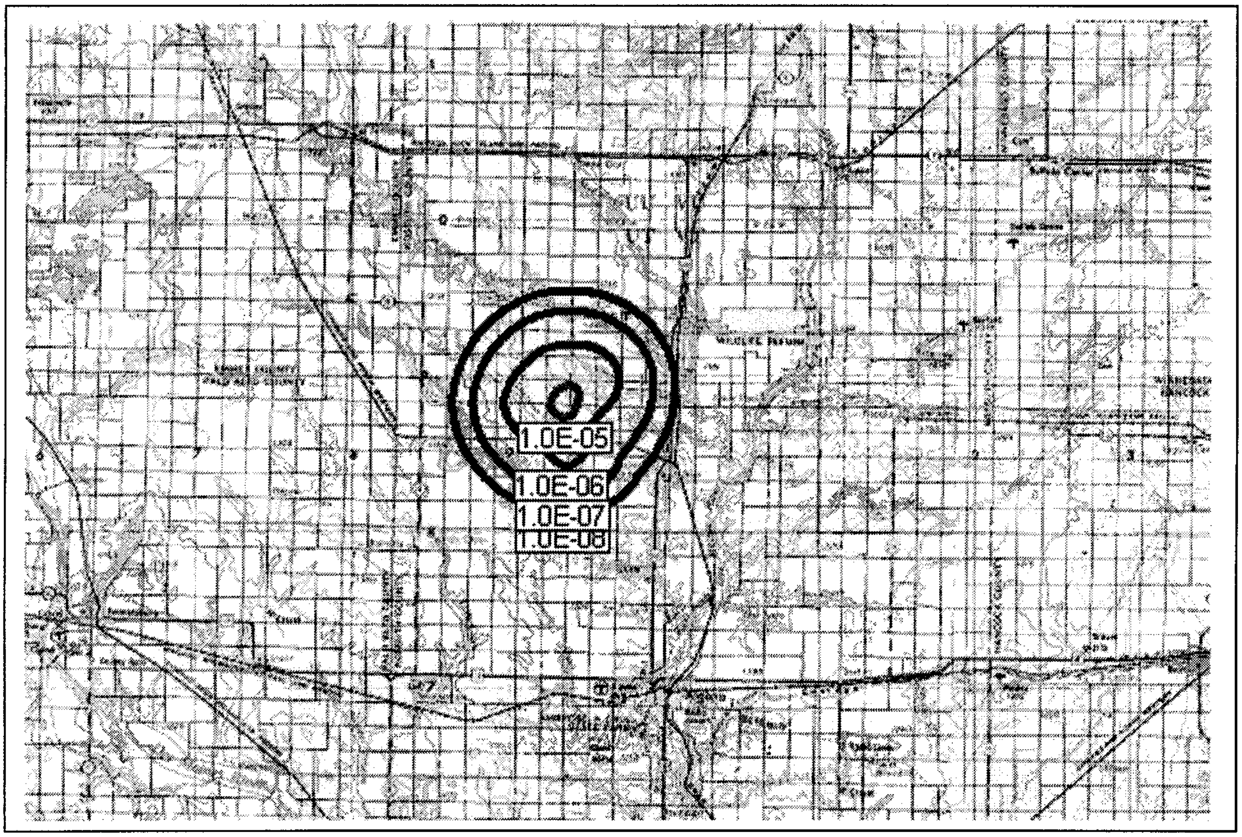


Figure 9: Site A --- Post-Mitigation Individual Risk Contour

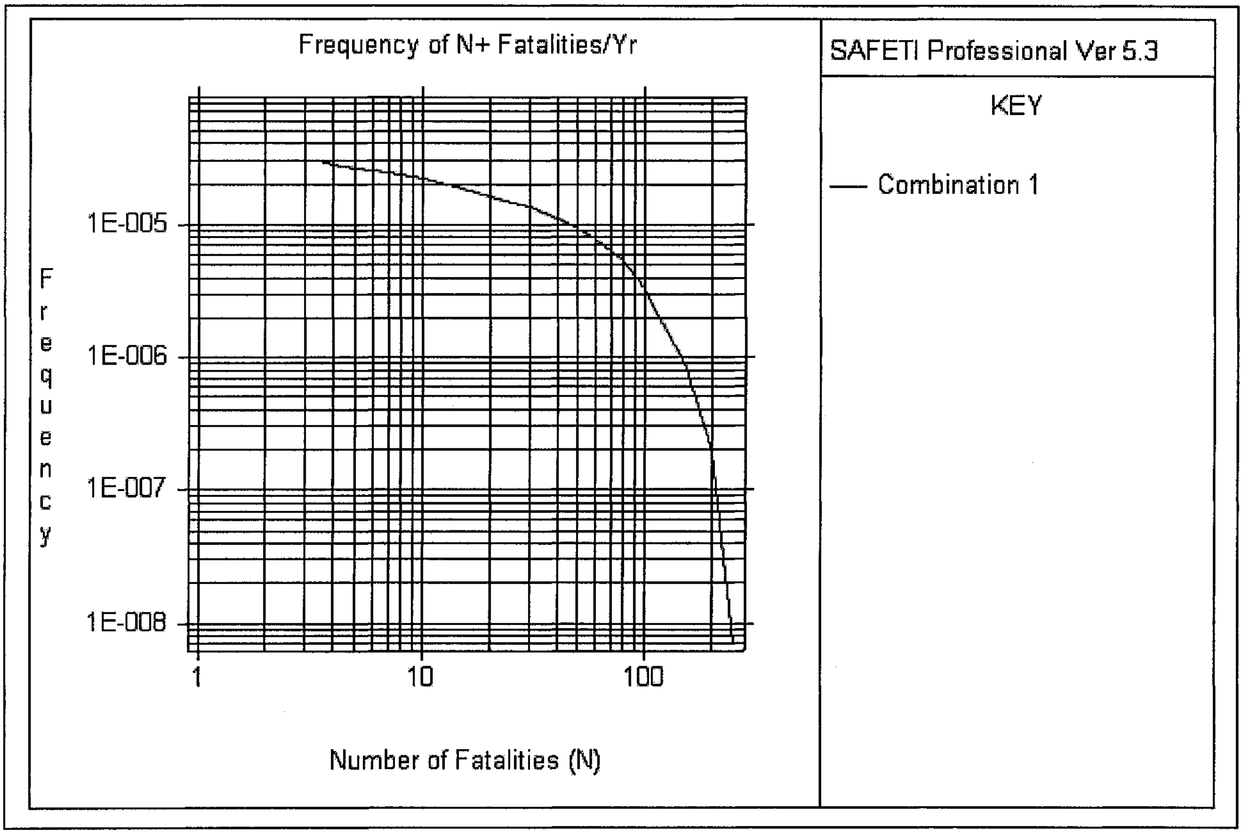


Figure 10: Site A --- Post-Mitigation F/N Curve

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   Ranking of Societal Risk
   Case Name               Average No.  % of Average    Freq. of   Freq. of   Freq. of   Freq. of   Freq. of   Freq. of   Frequency
                           Fatalities  Total Fatalities 0 - 1       1 - 10     10-100    100-1000   1000-10000  10000+     of zero
                            Per Year           Per      Fatality   Fatality   Fatality   Fatality   Fatality   Fatality   Fatality
                                                  Outcome    Per Year   Per Year   Per Year   Per Year   Per Year    Per Year  Per Year

  1 MDY                       9.15E-04  70.7 5.42E+00   6.96E-05   1.43E-05   1.87E-05   1.44E-06   0.00E+00   0.00E+00   6.50E-05
  2 LGY                       2.50E-04  19.3 1.37E+01   5.09E-06   6.65E-06   1.10E-06   1.07E-06   0.00E+00   0.00E+00   4.30E-06
  3 MDE                       4.63E-05   3.6 5.20E+00   3.98E-06   7.51E-07   9.83E-07   7.60E-08   0.00E+00   0.00E+00   3.10E-06
  4 CTY                       2.52E-05   1.9 8.29E+00   4.55E-07   1.78E-06   2.46E-07   5.17E-08   0.00E+00   0.00E+00   5.06E-07
  5 SRCY                      1.77E-05   1.4 7.12E-02   6.84E-05   1.12E-07   0.00E+00   0.00E+00   0.00E+00   0.00E+00   1.80E-04
  6 MRCY                      1.61E-05   1.2 6.84E+00   1.16E-06   4.15E-07   1.87E-07   6.58E-08   0.00E+00   0.00E+00   5.23E-07
  7 LGE                       1.28E-05   1.0 1.33E+01   2.69E-07   3.63E-07   5.82E-08   5.62E-08   0.00E+00   0.00E+00   2.13E-07
  8 LRCY                      6.42E-06   0.5 5.58E+00   5.91E-07   2.66E-07   9.45E-08   1.14E-08   0.00E+00   0.00E+00   1.87E-07
  9 CTE                       2.13E-06   0.2 1.33E+01   4.49E-08   6.05E-08   9.70E-09   9.37E-09   0.00E+00   0.00E+00   3.56E-08
 10 SRCE                      1.05E-06   0.1 8.02E-02   5.05E-06   5.89E-09   0.00E+00   0.00E+00   0.00E+00   0.00E+00   8.04E-06
 11 MRCE                      8.27E-07   0.1 6.67E+00   7.51E-08   2.06E-08   9.85E-09   3.47E-09   0.00E+00   0.00E+00   1.49E-08
 12 CRCY                      5.84E-07   0.0 1.69E+00   1.86E-07   8.89E-08   2.03E-08   0.00E+00   0.00E+00   0.00E+00   5.04E-08
 13 LRCE                      3.36E-07   0.0 5.55E+00   3.84E-08   1.18E-08   4.97E-09   5.97E-10   0.00E+00   0.00E+00   4.76E-09
 14 SMY                       8.59E-08   0.0 1.33E-03   4.88E-06   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   5.97E-05
 15 CRCE                      3.00E-08   0.0 1.65E+00   1.15E-08   4.25E-09   1.07E-09   0.00E+00   0.00E+00   0.00E+00   1.39E-09
 16 SME                       3.98E-09   0.0 1.17E-03   2.57E-07   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00   3.14E-06
                              --------
   Total                      1.29E-03


   PHI 775 years
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Figure 11: Site A --- Post-Mitigation Societal Risk Index and Process Hazards Index

Table 1: Risk Reduction Achieved at Four Sites

	Process Hazards Index (Years)	
Site	**Base Case**	**Post-Mitigation**
A	68	775
B	200	2000
C	175	1000
D	3	1000