A Simple Problem to Explain and Clarify the Principles of Risk Calculation

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> ***When a thought is too weak to be expressed simply, it should be rejected.***
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> — **Marquis de Luc Vauvenargues**
> *Refléxions et Maximes* (1746)

Abstract

Many texts and case studies on quantitative risk analysis have been published. They usually explain the frequency and consequence calculations in detail, but do not explain how these results are combined to produce specific measures of risk. The risk measures seem to appear from the underlying data as if by magic. In this example problem, the background, frequency, and consequence data for a risk analysis are highly simplified, so that the actual risk calculations can be understood easily. The example problem has been extremely useful in explaining the principles of Chemical Process Quantitative Risk Analysis (CPQRA) calculations to engineers, plant management, and other customers of CPQRA studies. The example also illustrates the complexity of risk. Even though the problem is extremely simple and uses trivial models, a large number of valid, but numerically different, risk estimates can be generated. Even for this very simple example, there is no single answer to the question "What is the risk?"

Introduction

In *Flatland* (Abbott, 1884), Edwin Abbott uses a highly simplified, two dimensional universe to explain the concepts of multi-dimensional geometry. Similarly, Dionys Burger's *Sphereland* (Burger, 1965) uses the same approach to explain multi-dimensional, non-linear geometry. Both books explain complex ideas by reducing them to simple geometry, illustrating the ideas and facilitating an understanding of how they apply to our world. Abbott and Burger also use their books as a vehicle for social commentary on their societies (Victorian England and modern Europe, respectively). This approach (without the social commentary) will be used in this paper to explain the concepts of Chemical Process Quantitative Risk Analysis (CPQRA), particularly the methods used to combine incident frequency and consequence estimates to produce various measures of risk. A CPQRA study in a universe much simpler than ours will

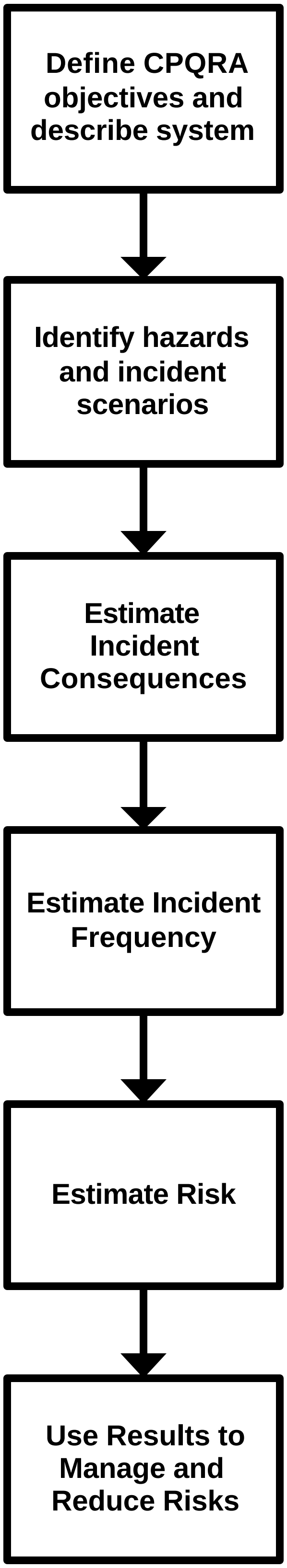

Figure 1: CPQRA Procedure

be described, allowing us to concentrate on the risk calculations rather than on complex incident frequency and consequence calculations.

The example in this paper has evolved over several years, and has proven useful in explaining the concepts of CPQRA to engineers and managers at Rohm and Haas plants which are the subject of CPQRA studies. The simple example allows an understanding of how the various risk measures are calculated and what they mean. It also clearly illustrates the complexity of the concept of risk — this example has many numerically different risk measures which can be calculated. An understanding of the different risk measures is important when using CPQRA and quantitative risk estimates as a risk management tool. All users of the risk estimates must understand the risk measure, and ensure that the numbers used in any risk comparisons are calculated on the same basis.

Background and General Information

Riskland is a very simple universe, where most phenomena occur as simple step functions. The Riskland Chemical Company (RCC) operates in this universe, and has determined that a CPQRA study is appropriate as a part of the process risk management program for one of its hazardous installations. RCC follows the general CPQRA procedure as outlined by CCPS (1989), shown schematically in Figure 1.

In the Riskland universe, the following apply:

- All hazards originate at a single point.
- Only two weather conditions occur. The atmospheric stability class and wind speed are always the same. Half of the time the wind blows from the northeast, and half of the time it blows from the southwest.
- There are people located around the site. The specific population distribution will be described later in the example, when the information is needed.
- Incident consequences are simple step functions. The probability of fatality from a hazardous incident at a particular location is either 0 or 1.

These simple conditions, and the description of the impact zones of incidents as simple geometric areas, allows easy hand calculation of various risk measures. The techniques used to derive the risk measures from the underlying incident frequency and consequence information are the same as for a complex CPQRA study using sophisticated models intended to represent our world as accurately as possible. The concepts are the same; the difference is in the complexity of the models used, the number of incidents evaluated, and the complexity of the calculations.

Incident Identification

RCC applies appropriate incident identification techniques, including historical information (plant and process specific, as well as generic industrial experience), checklists, and one or more of the hazard identification methodologies described in the *Guidelines for Hazard Evaluation Procedures* (CCPS, 1992). This is perhaps the most critical step in a CPQRA, because any hazards not identified will not be evaluated, resulting in an underestimate of risk. RCC's hazard identification and process safety reviews identify only two hazardous incidents which can occur in the facility:

I. An explosion resulting from detonation of an unstable chemical.

II. A release of a flammable, toxic gas resulting from failure of a vessel.

Incident Outcomes

The identified incidents may have one or more outcomes, depending on the sequence of events which follows the original incident. For example, a leak of volatile, flammable liquid from a pipe might catch fire immediately (jet fire), might form a flammable cloud which could ignite and burn (flash fire) or explode (vapor cloud explosion). The material also might not ignite at all, resulting in a toxic vapor cloud. CCPS (1989) refers to these potential accident scenarios as *incident outcomes*. Some incident outcomes are further subdivided into *incident outcome cases*, differentiated by the weather conditions and wind direction, if these conditions affect the potential damage resulting from the incident.

RCC reviewed the identified incidents for their facility to determine all possible outcomes, using an event tree logic model. Incident I, the explosion, is determined to have only one possible outcome (the explosion), and the consequences and effects are unaffected by the weather. Therefore, for Incident I there is only one incident outcome and one incident outcome case. This can be represented as a very simple (in fact, trivial) event tree with no branches, as shown in Figure 2.

Incident II, the release of flammable, toxic gas, has several possible outcomes (jet fire, vapor cloud fire, vapor cloud explosion, toxic cloud). RCC determines that, in their facility, only two outcomes can occur. If the gas release ignites there is a vapor cloud explosion. If the vapor cloud does not ignite, the result is a toxic cloud extending downwind from the release point. Because there are only two possible weather conditions in Riskland, three incident outcome cases are derived from Incident II as shown in the event tree in Figure 2.

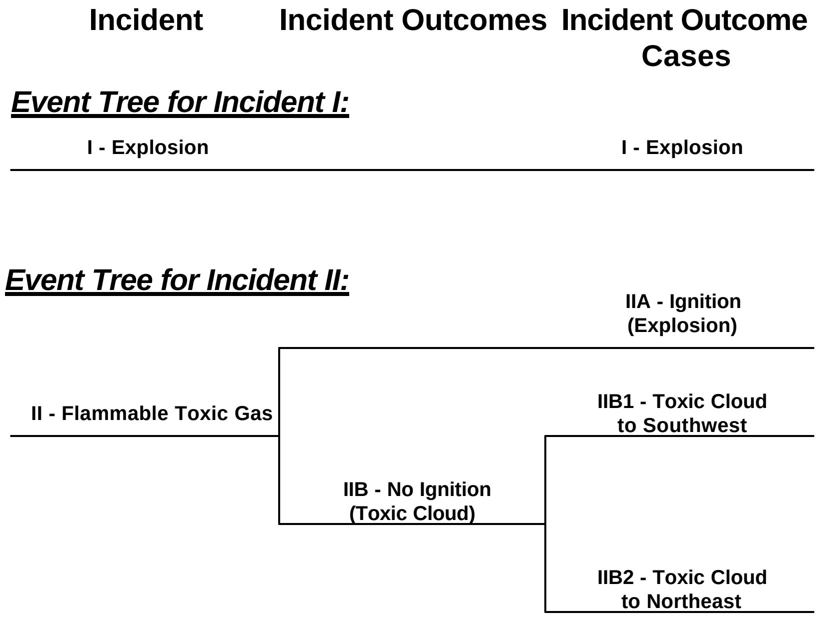

Figure 2: Event Trees for the Two Incidents

Consequence and Impact Analysis

Determining the impact of each incident requires two steps. First, a model estimates a physical concentration of material or energy at each location surrounding the facility — for example, radiant heat from a fire, overpressure from an explosion, concentration of a toxic material in the atmosphere. A second set of models estimates the impact that this physical concentration of material or energy has on people, the environment, or property — for example, toxic material dose-response relationships. These models are described in Chapter 2 of the *Guidelines for Chemical Process Quantitative Risk Analysis* (CCPS, 1989).

The application of consequence and impact models to the Riskland facility results in very simple impact zone estimates for the identified incident outcome cases:

- Incident Outcome Case I (explosion) — the explosion is centered at the center point of the facility; all persons within 200 meters of the explosion center are killed (probability of fatality = 1.0); all persons beyond this distance are unaffected (probability of fatality = 0).
- Incident Outcome Case IIA (explosion) — the explosion is centered at the center point of the facility; all persons within 100 meters of the explosion center are killed (probability of fatality = 1.0); all persons beyond this distance are unaffected (probability of fatality = 0).

- Incident Outcome Cases IIB1, IIB2 (toxic gas clouds) — all persons in a pie shaped segment of radius 400 meters downwind and 22.5 degrees width are killed (probability of fatality = 1.0); all persons outside this area are unaffected (probability of fatality = 0).

Figure 3 illustrates these impact zones.

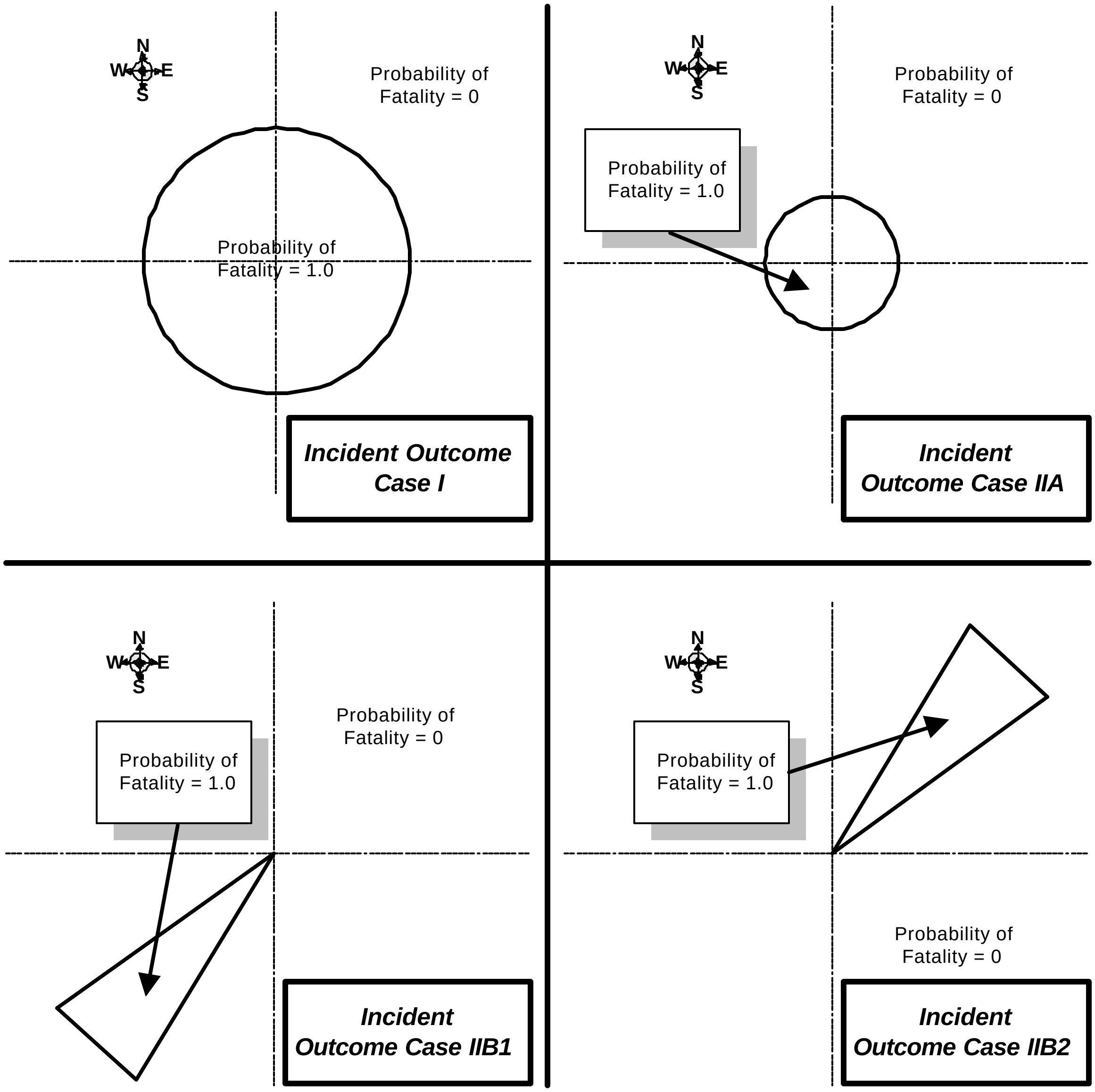

Figure 3: Impact Zones for Incident Outcome Cases

Frequency Analysis

Many techniques are available for estimating the frequency of incidents (CCPS, 1989, Chapter 3), including fault tree analysis, event tree analysis, and the use of historical incident data. RCC applies an appropriate set of models and historical incident and failure rate data and estimates the following frequencies:

- Incident I — Frequency = 1 x 10^{-6} events per year
- Incident II — Frequency = 3 x 10^{-5} events per year
- Incident II — Ignition Probability = 33%

These estimates along with the specified weather conditions (wind blowing from the Northeast 50% of the time, and from the Southwest 50% of the time) give the frequency estimates for the four incident outcome cases, as shown in the event trees of Figure 4.

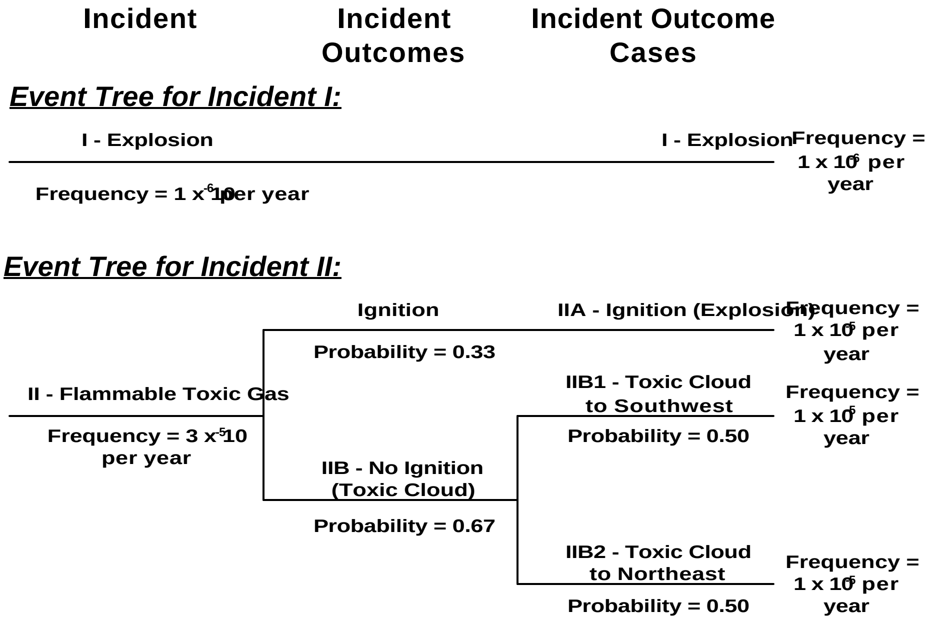

Figure 4: Frequency Estimates for Incidents, Incident Outcomes, and Incident Outcome Cases

Individual Risk Estimation

Individual risk is defined by CCPS (1989) 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."

Individual risk is useful in understanding and managing risk at a location where people might be present. It is also useful in understanding the risk to a particular person, or a group of people, based on knowledge of the geographical location of that person or those people.

In this example, the nature of the injury for both individual and societal risk calculations will be immediate fatality resulting from fire, explosion, or exposure to toxic vapors.

Individual Risk Contours

Individual risk at any point is given by the following equations (CCPS, 1989):

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \qquad (1)$$

$$IR_{x,y,i} = f_i \, p_{f,i} \qquad (2)$$

where:

$IR_{x,y}$ = the total individual risk of fatality at geographical location x, y (probability of fatality per year)
$IR_{x,y,i}$ = the individual risk of fatality at geographical location x, y from incident outcome case i (probability of fatality per year)
n = the total number of incident outcome cases considered in the analysis
f_i = frequency of incident outcome case i, (per year)
$p_{f,i}$ = probability that incident outcome case i will result in a fatality at location x, y

This example problem has been set up so that this calculation is simple, because each incident outcome case has an equal impact (probability of fatality $p_{f,i} = 1$) throughout its geographical impact zone. Therefore, within the impact zone for each incident outcome case, the individual risk from that incident outcome case $IR_{x,y,i}$ is equal to the frequency of that incident outcome case (Equation 2). Outside the impact zone, $IR_{x,y,i}$ is zero.

The simple impact models make it easy to do the calculations graphically. The four impact zones from the four incidents are superimposed on a map of the region of the plant and its surroundings as shown in Figure 5. The total individual risk of fatality at each geographical location is then determined by adding the individual risk from all incident outcome case impact zones that impact that location (Equation 1). For example, in the area labeled "C" in Figure 5, application of Equation 1 gives the results listed in Table 1.

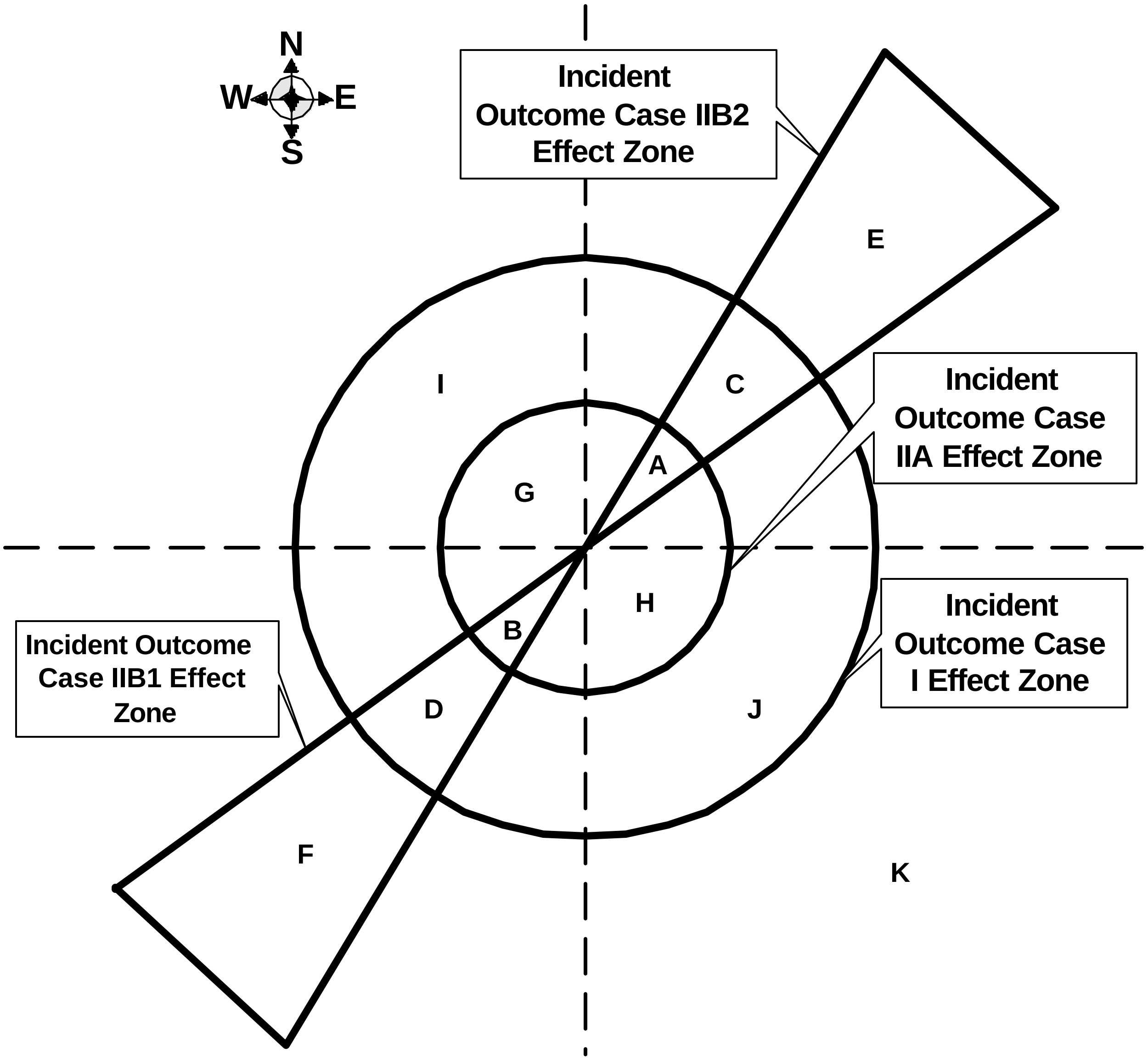

Figure 5: Individual Risk Contour Map

Table 1: Individual Risk Calculation for Area "C" in Figure 5

Incident Outcome Case	f_i (per year)	$P_{f,i}$	IR_i (per year)
I	10^{-6}	1	10^{-6}
IIB2	10^{-5}	1	10^{-5}
		$IR = 3\ IR_i =$	1.1×10^{-5}

Table 2: Individual Risk Results

Region (See Figure 5)	**Incidents Impacting Region**	**Total Individual Risk of Fatality (per year)**
A	I, IIA, IIB2	$2.1 \text{ X } 10^{-5}$
B	I, IIA, IIB1	$2.1 \text{ X } 10^{-5}$
C	I, IIB2	$1.1 \text{ X } 10^{-5}$
D	I, IIB1	$1.1 \text{ X } 10^{-5}$
E	IIB2	$1.0 \text{ X } 10^{-5}$
F	IIB1	$1.0 \text{ X } 10^{-5}$
G	I, IIA	$1.1 \text{ X } 10^{-5}$
H	I, IIA	$1.1 \text{ X } 10^{-5}$
I	I	$1.0 \text{ X } 10^{-6}$
J	I	$1.0 \text{ X } 10^{-6}$
K	None	0

A similar calculation for the other areas in Figure 5 gives the results summarized in Table 2. Figure 5 is an **individual risk contour** plot for this example problem, with the individual risk values for each area listed in Table 2. Note that for most CPQRAs, the individual risk contours are plotted for orders of magnitude of risk (for example, 10^{-4}, 10^{-5}, etc.). In this example, the specific values of risk calculated are plotted.

Individual Risk Profile, or Risk Transect

The individual risk profile (risk transect) is a graph showing the individual risk as a function of distance from the source of the risk in a particular direction. For the example problem, Figure 6 is the individual risk profile in the northeast direction.

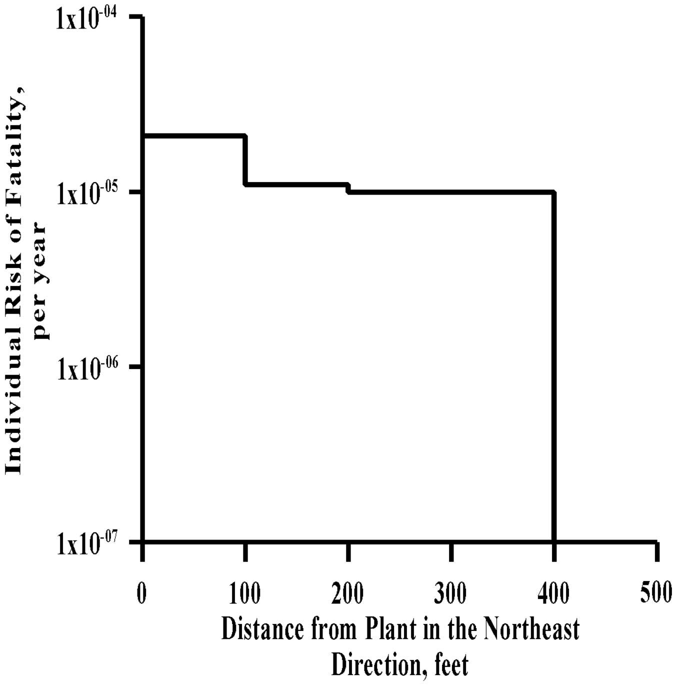

Figure 6: Individual Risk Transect in the Northeast Direction

Other Individual Risk Measures

In developing the individual risk contour map and the individual risk transect (Figures 5 and 6), no information about the surrounding population was needed. Figure 5 represents the risk to a person if he were to be at a particular location 100% of the time (8760 hours per year). For the example problem, several other individual risk measures can be calculated with additional data on the population surrounding the plant. Figure 7 shows the location of people in the area surrounding the RCC facility.

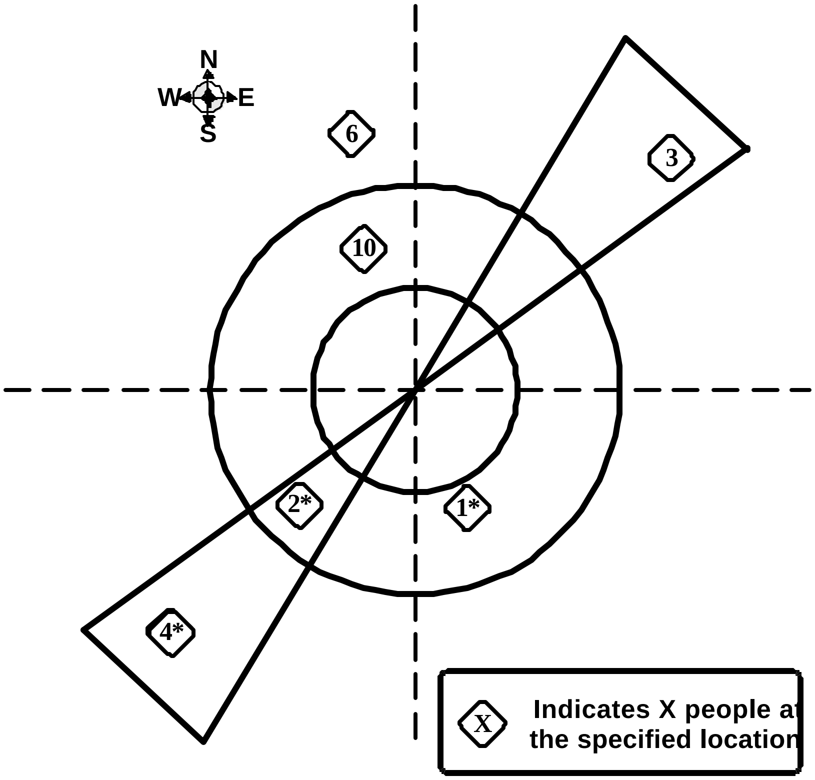

Figure 7: Population Distribution

Note: * — indicates that the people are employees in on-site buildings

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The **maximum individual risk** is the highest value of individual risk at any geographical location. For the example, the absolute maximum individual risk (regardless of whether or not there is any person at that location) is 2.1 x 10^{-5} per year, at all locations in Regions A and B in Figure 6. The maximum individual risk for any actual person is 1.1 x 10^{-5} per year, for the two people approximately 200 meters southwest of the facility. Note that these are **not** the people closest to the plant — the person in the southeast quadrant is actually closer to the plant. The prevailing wind directions in this example result in a higher risk to people somewhat farther away from the facility, but located in a direction toward which the wind blows more frequently.

The **average individual risk** is the average of all individual risk estimates over a defined population. It is important to define a population which does not include a large number of people at little or no risk, as this will give a low bias to the result. Average individual risk is given by CCPS (1989) as:

$$IR_{AV} = \frac{\sum_{x,y} IR_{x,y} P_{x,y}}{\sum_{x,y} P_{x,y}} \qquad \textbf{(3)}$$

where:

IR_{AV} = average individual risk in the exposed population (probability of fatality per year)
$P_{x,y}$ = number of people at location x, y

Applying Equation 3 to the population in the example (Figure 7), averaging only over the population which is subject to risk from the facility (individual risk > 0) gives:

$$IR_{AV} = [(3)(10^{-5}) + (1)(10^{-6}) + (2)(1.1 \text{ x } 10^{-5}) + (4)(10^{-5}) + (10)(10^{-6})] / (3 + 1 + 2 + 4 + 10)$$

$$IR_{AV} = (1.03 \text{ x } 10^{-4}) / 20$$

$$IR_{AV} = 5.2 \text{ x } 10^{-6} \text{ per year (for the exposed population)}$$

If all people in the area, even those who incur no risk from the facility, are included in the individual risk calculation, the denominator in the above calculation is 30, and the average individual risk is:

$$IR_{AV} = (1.03 \text{ x } 10^{-4}) / 30$$

$$IR_{AV} = 3.4 \text{ x } 10^{-6} \text{ per year (for the total population)}$$

Another average individual risk which might be of interest is the average individual risk to on-site employees (the people marked * in Figure 7). The average individual risk for the RCC employee population (those people in Regions D, F, and J of Figure 5/Table 2) is:

$$IR_{AV} = [\underset{\text{Region D}}{(2)(1.1 \text{ x } 10^{-5})} + \underset{\text{Region F}}{(4)(10^{-5})} + \underset{\text{Region J}}{(1)(10^{-6})}] / (1 + 2 + 4)$$

$$IR_{AV} = (6.3 \text{ x } 10^{-5}) / 7$$

$$IR_{AV} = 9 \text{ x } 10^{-6} \text{ per year (for the RCC employee population)}$$

The **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. Using the average individual risk for the RCC employee population, *FAR* is calculated from the following equation:

$$FAR = (1.14 \text{ x } 10^{4})\ IR_{AV} \text{ (for the employee population)} \qquad \textbf{(4)}$$

where IR_{AV} has units of probability of fatality per year, and *FAR* has units of fatalities per 10^8 man-hours of exposure. Applying Equation 4 to the example gives:

$$FAR = IR_{AV}\,(1.14 \text{ x } 10^{4})$$

$$= (9 \text{ x } 10^{-6})(1.14 \text{ x } 10^{4})$$

$$= 0.1 \text{ fatalities} / 10^{8} \text{ man-hours of exposure}$$

Societal Risk Calculation

Societal risk measures the risk to a group of people (CCPS, 1989). Societal risk measures estimate both the potential size and likelihood of incidents with multiple adverse outcomes. In this example, the adverse outcome considered is immediate fatality resulting from fire, explosion, or exposure to toxic vapors. Societal risk measures are important for managing risk in a situation where there is a potential for accidents impacting more than one person.

F-N Curve

A common measure of societal risk is the Frequency-Number (F-N) Curve. The first step in generating an F-N Curve for the example problem is to calculate the number of fatalities resulting from each incident outcome case, as determined by:

$$N_i = \sum_{x,y} P_{x,y} \, p_{f,i} \qquad \textbf{(5)}$$

where:

N_i = number of fatalities resulting from Incident Outcome Case *i*

For the example, $p_{f,i}$ in Equation 5 equals 1. Because the impact zones for the example are simple, this calculation can be done graphically by superimposing the impact zones from Figure 3 onto the population distribution in Figure 7, and counting the number of people inside the impact zone. Table 3 summarizes the estimated number of fatalities for the four incident outcome cases.

Table 3: Estimated Number of Fatalities from Each Incident Outcome Case

Incident Outcome Case	Frequency F_i (per year)	Estimated Number of Fatalities N
I	1.0×10^{-6}	13
IIA	1.0×10^{-5}	0
IIB1	1.0×10^{-5}	6
IIB2	1.0×10^{-5}	3

The data in Table 3 must then be put into cumulative frequency form to plot the F-N Curve:

$$F_N = \sum_i F_i \text{ for all incident outcome cases } i \text{ for which } N_i \geq N \qquad \textbf{(6)}$$

where:

F_N = frequency of all incident outcome cases affecting N or more people, per year
F_i = frequency of incident outcome case i, per year

Table 4 summarizes the cumulative frequency results. The data in Table 4 can be plotted to give the societal risk F-N Curve in Figure 8.

Table 4: Cumulative Frequency Data for F-N Curve

Number of Fatalities N	**Incident Outcome Cases Included**	**Total Frequency F_N (per year)**
3 +	I, IIB1, IIB2	2.1×10^{-5}
6 +	I, IIB1	1.1×10^{-5}
13 +	I	1.0×10^{-6}
> 13 +	None	0

Other Societal Risk Measures

Other societal risk measures can also be calculated for this example. The **average rate of death (ROD)** is the estimated average number of fatalities in the population from all potential incidents. The ROD is calculated using Equation 7:

$$ROD = \sum_{i=1}^{k} f_i N_i \qquad \textbf{(7)}$$

where:

ROD = average rate of death, fatalities per year

Applying the data in Table 3 for the estimated number of fatalities resulting from each incident outcome case to Equation 7:

$$\begin{aligned} ROD &= (1.0 \text{ x } 10^{-6}/\text{yr})(13) + (1.0 \text{ x } 10^{-5}/\text{yr})(0) + 1.0 \text{ x } 10^{-5}/\text{yr})(6) \\ &\quad + (1.0 \text{ x } 10^{-5}/\text{yr})(3) \\ &= 1 \text{ x } 10^{-4} \text{ fatalities per year} \end{aligned}$$

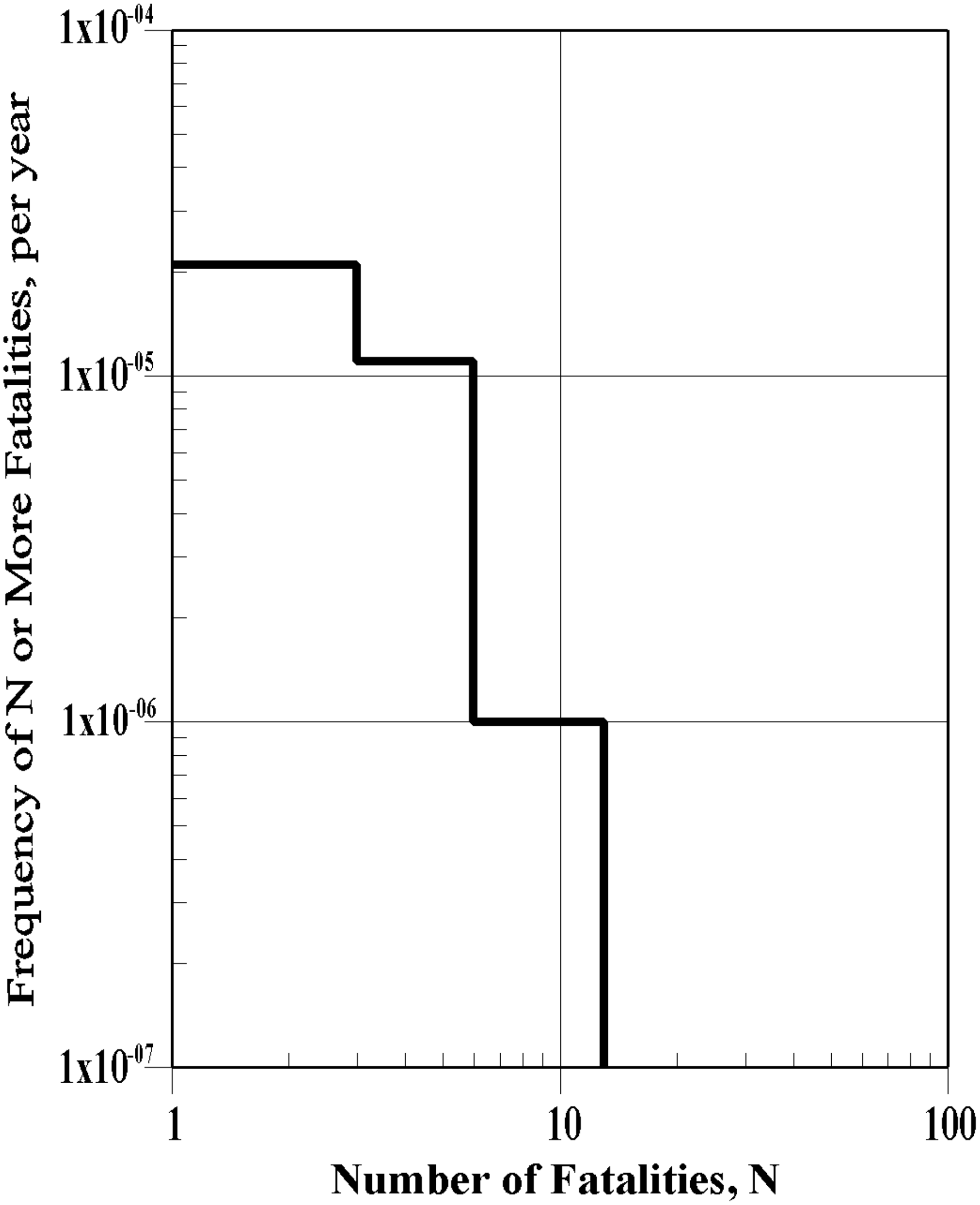

Figure 8: Societal Risk F-N Curve

API 752 (API, 1995) uses **aggregate risk** as a tool for managing the risk associated with occupied buildings in a process plant. Aggregate risk is defined as "societal risk applied to a specific group of people within a facility" (CCPS, 1996). In this example, the people indicated by an asterisk in Figure 7 are RCC employees working in on-site buildings. The aggregate risk calculation considers only this population, and it will be assumed that the people are present all of the time. Table 5 summarizes the number of fatalities for each incident outcome case for the employee population. This data can be put into cumulative frequency form as shown in Table 6, and the resulting aggregate risk curve is shown in Figure 9.

Table 5: Estimated Number of Fatalities for the Employee Population in On-Site Buildings from Each Incident Outcome Case

Incident Outcome Case	Frequency F_i (per year)	Estimated Number of Fatalities in the Employee Population in On-Site Buildings, N
I	1.0×10^{-6}	3
IIA	1.0×10^{-5}	0
IIB1	1.0×10^{-5}	6
IIB2	1.0×10^{-5}	0

Table 6: Cumulative Frequency Data for Aggregate Risk Curve for Employee Population in On-Site Buildings

Number of Fatalities in Employee Population in On-Site Buildings, N	Incident Outcome Cases Included	Total Frequency F_N (per year)
3 +	I, IIB1	1.1×10^{-5}
6 +	IIB1	1.0×10^{-5}
> 6 +	None	0

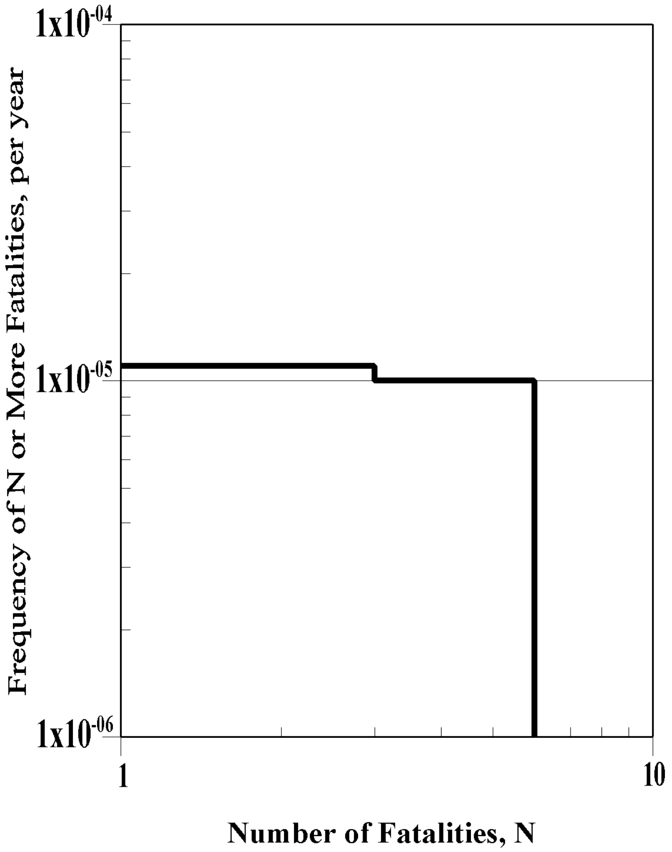

Figure 9: Aggregate Risk Curve for Employee Population in On-Site Buildings

The **aggregate risk index** (CCPS, 1996) is the average rate of death, as calculated for the people in on-site buildings in a plant. For the example problem, applying Equation 7 using the estimated number of fatalities from each incident outcome case considering the employee population only (the data in Table 5), the aggregate risk index is:

$$\textit{Aggregate Risk Index} = (1.0 \times 10^{-6}/\mathrm{yr})(3) + (1.0 \times 10^{-5}/\mathrm{yr})(6)$$
$$= 6.3 \times 10^{-5} \text{ fatalities per year}$$

The **Equivalent Social Cost Index (ESC)** is a societal risk measure which attempts to account for society's aversion to large incidents. The calculation is the same as for the Rate of Death, except that the number of fatalities is raised to a power to increase the contribution of large incidents to the ESC Index:

$$ESC = \sum_{i=1}^{n} f_i N_i^p \qquad \textbf{(8)}$$

where:

p = risk aversion power factor ($p > 1$)

Risk aversion power factors of 1.2 and 2 have been suggested (CCPS, 1989). Using these factors, Equivalent Social Cost (ESC) indices for this example, using the total population, are:

$p = 1.2 \qquad ESC = 1.4 \times 10^{-4}$
$p = 2.0 \qquad ESC = 6.2 \times 10^{-4}$

The units of Equivalent Social Cost are not meaningful.

Summary of Risk Results

This simple example illustrates the complexity of risk. Although the example considers only the acute risk of fatality, fourteen different measures of risk were calculated, as summarized in Table 7. These measures

Table 7: Summary of Risk Results for the Riskland Example Problem

Risk Measure	Result
Individual Risk	
Risk Contours	See Figure 5 and Table 2
Risk Transect	See Figure 6
Maximum	2.1×10^{-5} per year
Maximum for Actual Person	1.1×10^{-5} per year
Average, Exposed Population	5.2×10^{-6} per year
Average, Total Population	3.4×10^{-6} per year
Average, Employee Population	9×10^{-6} per year
Fatal Accident Rate (FAR)	0.1 fatalities per 10^8 man-hours of exposure
Societal Risk	
F-N Curve	See Figure 8
Aggregate Risk Curve	See Figure 9
Average Rate of Death	1.0×10^{-4} fatalities per year
Aggregate Risk Index	6.3×10^{-5} fatalities per year
Equivalent Social Cost Index, Total Population ($p = 1.2$)	1.4×10^{-4}
Equivalent Social Cost Index, Total Population ($p = 2$)	6.2×10^{-4}

consider different aspects of risk, and all are valid risk estimates which might be valuable in the appropriate decision making context. For example, a risk study undertaken to determine if the risk to employees in on-site occupied buildings is tolerable, aggregate risk may be the appropriate risk measure. Maximum individual risk to nearby residents and societal risk to the surrounding community might be the best measures to use in order to understand and manage the risk to neighbors.

One can easily envision a number of other risk measures which could be calculated, considering, for example, environmental risk, risk of injury, long term health risk, economic risk, and others. This simple example problem clearly shows that there is no single, simple answer to the question, “What is the risk of this facility?” That question is much too broad.

Application to Risk Management and Decision Making

While this example problem is intended to demonstrate the calculation procedures used to combine frequency and consequence data to produce various specific risk measures, it also illustrates the importance of clearly defining the risk measures to be used in any risk management program which includes quantitative evaluation of risk. When comparing the risk of facilities or design options, it is essential that the risks are calculated on the same basis for the comparison to be meaningful. Similarly, if quantitative guidelines are to be used as a part of an organization’s risk management program, the guidelines must be clearly defined in terms of the risk measure to be used, and the calculational procedures used to obtain the measures which will be compared to the guidelines. Failure to clearly define the risk measures used in a risk management program will result in confusion and may lead to inconsistent decisions.

Summary

This example Chemical Process Quantitative Risk Analysis problem is intended to teach the methodology of CPQRA calculations. For a real risk analysis, these calculations are extensive and use much more sophisticated models. The calculations are usually done using computer programs, and the methodology of the calculations may not be clear, even to an analyst who does risk analyses routinely. Should all risk analysts be required to complete at least one simple risk analysis manually, giving them an opportunity to understand what the computer program is doing in a more complex study?

This sample problem is also useful for explaining risk analysis methods and measures to users of risk analysis studies. It explains the meaning of the various risk measures to plant and company management, and to technical staff who must support the work of the risk analyst by providing much of the required data. Before starting a QRA on a facility or plant design, the sample problem can be used to quickly illustrate the kind of input data which will be required, and the format of the results of the completed study.

The example illustrates that risk is complex, and that it can be measured in many different ways. The different measures provide information about different aspects of risk — for example, risk to an individual, risk to a particular group of people, average risk, maximum risk. A complete risk management program may have to consider several of these risk measures, and it is essential that all participants in the risk management process understand the meaning and use of the risk measures considered.

Acknowledgments

This example problem has evolved through a number of years of use in explaining the concepts of risk analysis to Rohm and Haas personnel throughout the world, to Rohm and Haas customers, and to outside organizations. It was first developed for presentation at an American Institute of Chemical Engineers "Day in Industry" for college faculty (Hendershot, 1988), and a condensed version was later published by Theodore, et. al. (1989). I thank all of the engineers and managers from Rohm and Haas Company and other companies who have contributed many suggestions to improve the example over the years. I also thank Art Dowell of Rohm and Haas Texas, Inc., and Bill Bridges of JBF Associates, Inc., for reviewing the manuscript of this paper and providing many constructive comments. The Center for Chemical Process Safety (CCPS) Risk Analysis Subcommittee has reviewed this problem and made a number of suggestions to further enhance it. A version will be included in the Second Edition of the CCPS *Guidelines for Chemical Process Quantitative Risk Analysis*, to be published later this year.

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