APPLYING A SYSTEMATIC APPROACH TO RISK AND COST EVALUATION.

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ABSTRACT

Safer, more cost-effective operations can be obtained by applying a systematic approach to risk-and cost evaluation of process hazards. Appropriate risk assessment (process hazards analysis) focuses on normal operations/ conditions, credible abnormal conditions, human factors, procedures (including contingencies), maintenance, and facility design and siting. The philosophy is to minimize personnel exposure, minimize quantities of energetic/hazardous material, promote “Safety by Design” and to use appropriate procedures, standards, and training. This paper covers the fundamental elements of risk-assessment and provides level setting guidelines so that the scope of the analysis is bounded and taken to the right depth.

Three risk/cost trade-off methods are also presented in this paper for determining the break-even value for risk reduction costs. The objective of a risk/cost trade-off analysis is to aid the decision making process as risk mitigating measures and associated costs are considered. A risk/cost trade-off analysis is most effective when used in conjunction with a risk assessment that accurately focuses on critical and credible failure scenarios. Selection of one of the three methods depends on the criticality of the failure scenario and the precision required. Risk reduction cost that is less than the break-even value will increase a company's annual cash flow and return on investment. Each method is outlined and associated limitations discussed.

Appropriate risk assessment and risk/cost trade-off analysis enables a company's resources to be spent in the areas that are most important for the protection of employees, the public, and the environment while maximizing cost effectiveness.

ELEMENTS OF A RISK ASSESSMENT

Level Setting

Prior to beginning a risk assessment analysis the hazards analyst and/or the process hazards analysis team need to bound the analysis and to determine the depth of analysis needed in the various process sections and in the facility. The OSHA Process Safety Management Regulation (29 CFR 1910.119) and the EPA Risk Management Programs Regulation (40 CFR Part 68) may help drive this decision for covered processes. The toxicity, reactivity, and locations of hazardous materials are all factors to consider. The proper combination of assessment techniques will in the long run also be the most cost-effective.

The elements of level setting are as follows:

- Prioritization of operations and equipment
- Hazard identification
- Hazard ranking
- Identification of critical scenarios

Prioritize Hazardous Operations/ Equipment

Prioritizing ensures that the most time and effort is spent on those parts of the operations/ process with the most need and the worst consequences if an accident occurs. When prioritizing operations/ equipment for evaluation, one should consider the potential risk to:

- People
- Adjacent operations
- Community
- Environment
- Equipment/ facilities

Potential risk severity can be evaluated by assessing the following:

- Reactivity and toxicity of the material
- Quantity of hazardous material
- Related incident, accident, or near accident history
- The potential for operator error
- Existing conditions etc.

The complexity of the applied methodology should reflect the complexity and potential risk of the prioritized operation/ process. (1) The various hazards analysis methods available and some guidelines on selection of the most appropriate method or combination of methods will be discussed below.

The hazards analysis should focus on areas that are most critical and credible. In addition to the normal operations and conditions in the process, the credible abnormal operations and resultant consequences must also be considered. Many times it is the combination of several relatively unlikely events coming together at once that cause an accident. Otherwise, accidents would occur more routinely than they do. Human factors can be very significant. The likelihood of human error can often be far greater than the likelihood of equipment failure or other events affecting an operation.

Proper training and appropriate procedures will always be important. If an existing procedure is no longer adequate then bad operator decisions may occur which could make a bad situation worse. Contingency procedures should exist for the most severe consequences of an incident or process upset. Other items often overlooked in prioritizing the hazards of operations or equipment are the operations associated with maintenance. Maintenance operations may be as potentially hazardous as regular operations. Many times maintenance personnel are not given adequate training and maintenance procedures are not as closely scrutinized as they should be.

Proper prioritization requires a top level review of <u>all</u> operations/ equipment to ensure resources are spent first on the areas that pose the greatest risk.

Select Appropriate Analysis Technique(s)

Selection of the appropriate hazard analysis methodology is important because it allows the Process Hazards Analysis (PHA) team to effectively and efficiently identify failure scenarios and recommendations for corrective action. Recommendations for risk mitigation are the product of a proper hazards analysis. "Safety by Design" should be the emphasis of these recommendations. Eliminating personnel exposure is another benefit of "Safety by Design." When "Safety by Design" is not feasible then a procedure followed by appropriate training is required.

As mentioned above, the technique or combination of techniques used for hazard identification should be appropriate for the operation or process being reviewed. Some of the methodologies available for process hazards analysis are qualitative in nature and others are more quantitative in nature. The following techniques are of a qualitative nature and are described in the order of the most simple to the most complex:

Job Safety Analysis (JSA) - In this analysis the steps in an operation are observed by the analyst/ Hazards Analysis Team and the potential hazards determined to which an employee is exposed while performing these steps. Solutions to these potential hazards must then be developed and implemented. The information provided from the JSA can then be used to train employees how to perform their jobs safely.

Checklist - This analysis consists of listing critical safety items or procedural steps to be done before the process is performed. Common lists include codes, standards, regulations, or company safety practices that must be met for safe operation. Checklist analyses are commonly combined with other types of hazards analyses to meet all the needs of the project.

What-if Analysis - This is a relatively unstructured team brainstorming approach. "What-if" questions are posed by the team and the consequences/ hazards, safeguards/ design safety, and recommendations developed and recorded. The method is most applicable to relatively simple processes.

What-if/ Checklist - This is a team brainstorming approach with the Checklist being used to generate the "what-if" questions and to help make the analysis more complete.

Logic Diagrams - This technique uses a high-level, simplified version of Fault Tree Analysis to find the credible ways that a top event may occur. Multiple events can be considered qualitatively using logic symbols such as “And” and “Or” gates. In combination with other methods of analysis it can be use to decide which parts of the process are more critical and need to be addressed by another technique.

HAZOP - The Hazard and Operability Study (HAZOP) is a more structured team brainstorming technique than What-if Analysis. The HAZOP uses guide words to determine how deviations from the design intent can occur in equipment, actions, or materials, and to establish if the consequences of these deviations can result in a hazard. The HAZOP technique is a qualitative, single failure analysis and may not address well the situation of multiple component failures.

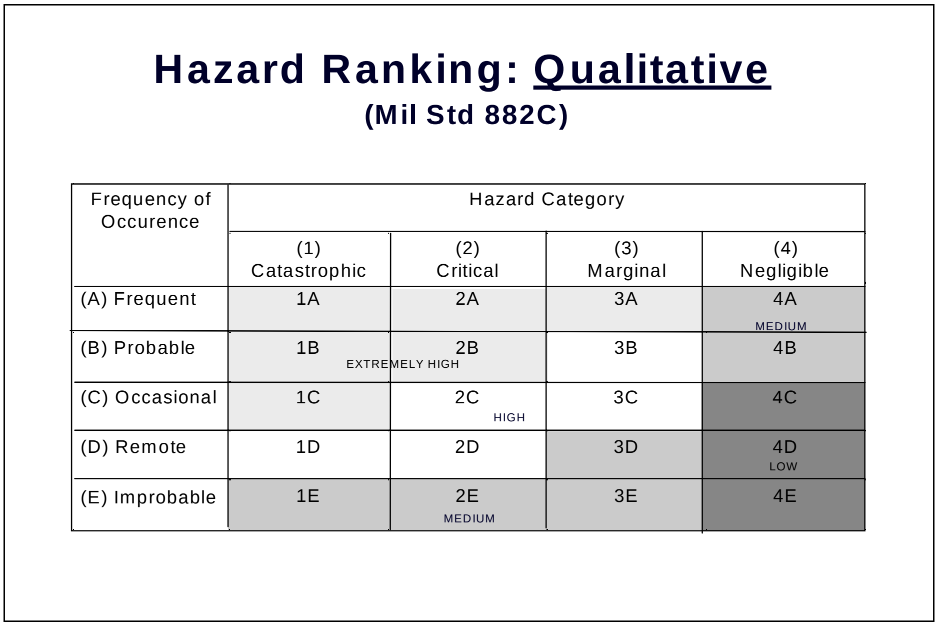
FMEA - In a Failure Modes and Effects Analysis (FMEA) the PHA team uses a detailed, system safety approach to address each item of equipment or operation in the process flow and to determine the failure modes for each item. The failure causes, potential effects, and existing design safety are identified and recommendations made to correct deficiencies.

Qualitative Risk Assessment

Qualitative hazard ranking is frequently done in the HAZOP and FMEA analyses by using the Hazard Category Ranking of MIL-STD-882C or some other qualitative system to estimate the severity and likelihood of an undesirable event. This ranking method could be used in conjunction with any of the PHA methodologies. For each potential event a Hazard Category as defined in Figure 1 is chosen.

The hazard categories can be used as a guide to the ranking of the recommendations from the analysis. Usually the priorities of the recommendations are ranked as follows:

- EXTREMELY HIGH: 1A, 2A, 3A, 1B, 2B, 1C
- HIGH: 1D, 2C, 2D, 3B, 3C
- MEDIUM: 1E, 2E, 3D, 3E, 4A, 4B
- LOW: 4C, 4D, 4E



Hazard Ranking: <u>Qualitative</u>

(Mil Std 882C)

Frequency of Occurence	Hazard Category			
	(1) Catastrophic	(2) Critical	(3) Marginal	(4) Negligible
(A) Frequent	1A	2A	3A	4A MEDIUM
(B) Probable	1B EXTREMELY HIGH	2B	3B	4B
(C) Occasional	1C	2C HIGH	3C	4C
(D) Remote	1D	2D	3D	4D LOW
(E) Improbable	1E	2E MEDIUM	3E	4E

Figure #1

Qualitative Hazard Ranking is facilitated by Mil. Std. 882C

<u>Quantitative Risk Assessment</u>

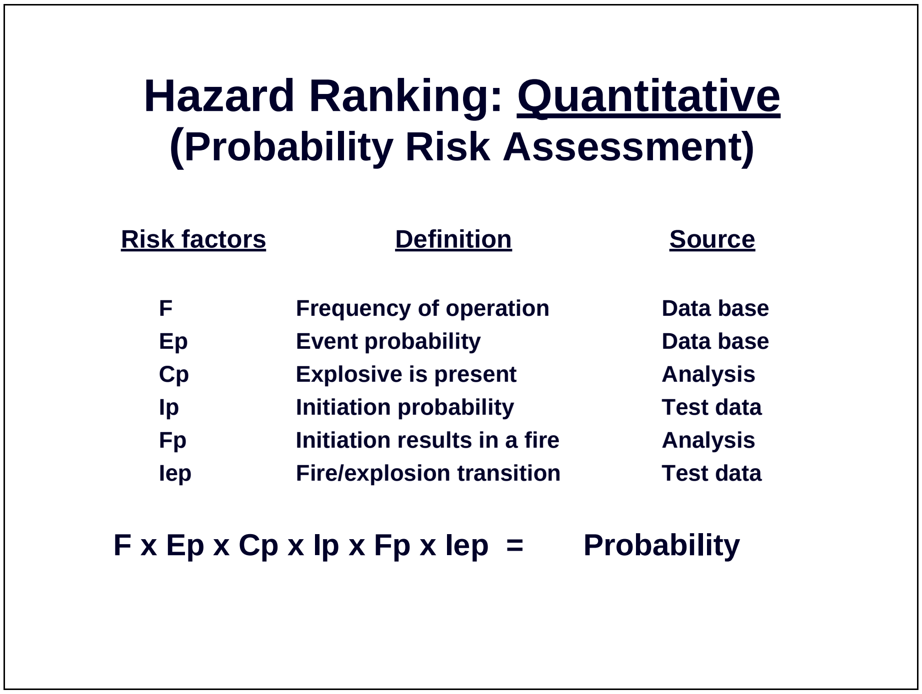
Quantitative risk assessment techniques can be applied to those critical scenarios identified by the PHA team using qualitative analysis techniques. The following hazards analysis, data analysis, and modeling techniques are of a more quantitative nature than the techniques discussed earlier and should be applied in these cases:

Fault Tree Analysis - Fault Tree Analysis is an analytical process where a top undesirable event is specified and a formal logic process is used to find all the credible ways by which the undesirable event can occur. The fault tree is the graphical representation of the combination of faults such as component failures, human errors, and other events that lead to the top event. Fault Tree Analysis is most useful for complicated, interactive systems where the top event can result from several paths. The probability of a top event and can be calculated when failure information is available on the equipment, human error, and other events leading to it.

Probability Risk Assessment - Probability data can be used for input to a fault tree or for calculations comparing in-process energy to material response (such as propellant or explosive impact, friction, or electrostatic discharge sensitivity). Figure 2 shows how data from different sources can be combined to determine the overall probability of an undesirable event occurring.

Energies in the process for mechanical, chemical, electrical, and thermal stimuli can be determined by testing and measurement, calculation, or by mathematical modeling. Sometimes combinations of these methods are used. For example, in the scale-up of a propellant ingredient feeding system there was concern for the electrostatic energy conditions for the larger system. Sub-scale tests were made where electrostatic energy buildup was measured for ingredients with a range of electrostatic discharge sensitivity. From this data a model was developed to predict the electrostatic charging conditions and available energy on a larger scale. The larger scale was then operated using the less sensitive materials first to prove out the prediction. The model was shown to be accurate and the predicted values were then used to determine the risk probabilities for the system. (2)

The sensitivity of the reactive material in the process must be determined using a technique that can yield quantitative data that can be compared to the operational energy for the potential event. Preferably, sensitivity data such as impact, friction, and electrostatic discharge data would be determined using equipment that has been calibrated to yield results in engineering units that can then be compared to the energy of the operation in similar engineering units. In some cases the material response can be calculated or modeled in other ways.



Hazard Ranking: Quantitative
(Probability Risk Assessment)

Risk factors	Definition	Source
F	Frequency of operation	Data base
Ep	Event probability	Data base
Cp	Explosive is present	Analysis
Ip	Initiation probability	Test data
Fp	Initiation results in a fire	Analysis
Iep	Fire/explosion transition	Test data

F x Ep x Cp x Ip x Fp x Iep = Probability

Figure #2

Quantitative Hazard Ranking requires determining the values of the various risk factors

Probit Analysis - One of the best ways to quantify material response data and compare it with the energy of operation is probit analysis. In this statistical method, quantal (all or nothing) material response data are analyzed to compute the probability of material response at a given energy stimulus. It is assumed that the percentage of samples tested that respond with a reaction will increase at some fixed ratio as the magnitude of the energy is increased. Thus a linear regression equation may be used to describe the relationship between the stimulus and probability of response. From this line the initiation probability can be determined for selected energy input. Figure 3 shows the relation of the distribution of data to the probability and safety margin areas. Figure 4 gives an example probit line.

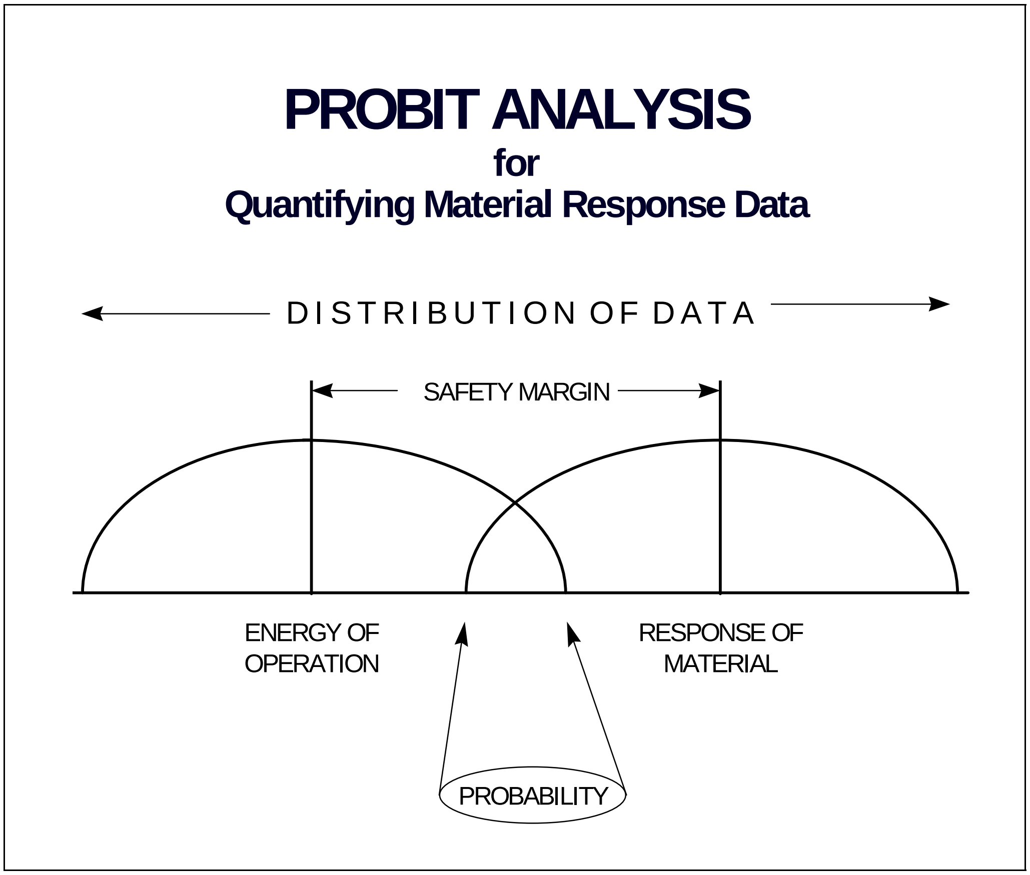


Figure #3

Probit Analysis determines the probability of initiation over a wide range of in-process conditions

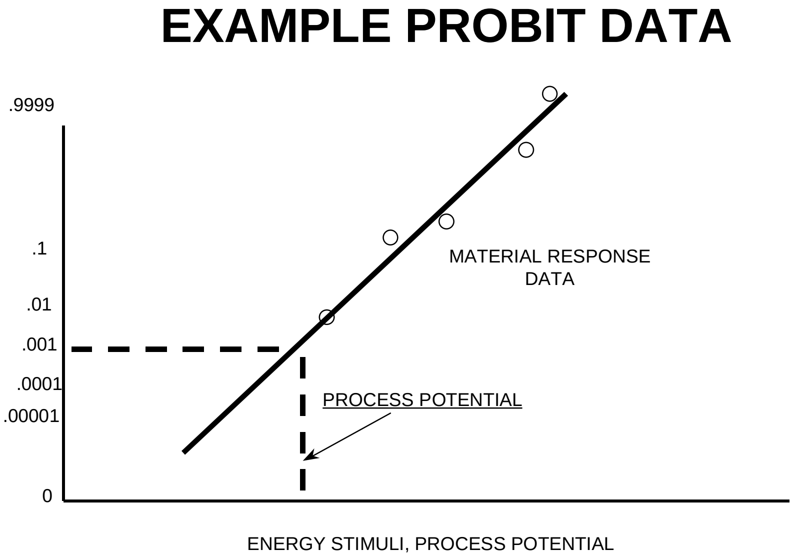


Figure #4

Probit plots of material response data allow comparisons with in-process energies

RISK/ COST TRADE-OFF ANALYSIS

Risk/ Cost Trade-off Analysis is an additional quantitative procedure that provides the break-even value for risk reduction costs. Level setting is also applicable here to help select the method of calculation that is most appropriate for the company based on the perceived cost/ risk. Three methods for performing Risk/ Cost Trade-off Analysis are discussed in the paragraphs that follow.

Level No. 1 – Risk Score Analysis

Risk Score Analysis is a first-cut approach in determining the risk trade-off (DuPont, 1985). The Risk Score is the product of numerical ratings or weights assigned to "Consequences," "Exposure," and "Probability." These assigned values are arbitrary and flexible based on the judgment and experience of the analyst making the calculation. DuPont (1985) outlines the numerical range for each of these areas and the qualitative descriptions. In cases where multiple hazards exist for a given operation, each one is evaluated separately and their Risk Scores added.

Once the Risk Score value is determined, the proposed risk reduction and cost effectiveness can be evaluated. This is done by using the nomograph entitled "Cost Effectiveness Analysis" (DuPont, 1985). The Risk Score, an estimated risk reduction, and an estimated cost for correction are combined to determine the cost effectiveness.

Limitations

The qualitative nature of the approach allows for a substantial range of variability in the analysis results. Example No. 1 illustrates the possible variation of the Risk Score by reasonably varying the Exposure Factor and the Probability (likelihood) Factor. The Costs for Correction may not reflect the costs associated with a specific industry, and the figures are in 1976 dollars.

Level No. 2 - Risk Trade-off Based on Fixed Assets

A risk trade-off analysis based on fixed assets provides reasonable results with a minimal amount of effort. It requires that the probability of a major incident (P_{MI}) per operation be established using quantitative risk analysis techniques. The analyst is then required to define the magnitude of the potential damage and loss of fixed assets only (i.e., building, bay, equipment, product, product components, etc.). The dollar value of the direct and indirect cost of these fixed assets is then determined.

The potential Annual Loss (LE), based on fixed assets, is the product of the P_{MI} per operation, the number of operations per year, and the fixed assets at risk.

$$LE = (P_{MI}/op)*(\#\ op/year)*(\$\ Fixed\ Assets\ at\ risk)$$

The Expected Annual Loss for five (5) years is <u>assumed</u> to be the Risk Reduction Costs (RRC) to break-even (RRC_{BE}). Note: 5 years was chosen as an average accepted time period that industry would expect for payback. The time period should be based on the specific company's criteria for time to break-even.

$$RRC_{BE} = 5*(LE)$$

Expenditures less than or in close proximity to this amount provide increased Return on Investment (ROI) for the area involved and would be considered a wise investment. If risk reduction requires significantly more than this amount, then a Level No. 3 analysis may be warranted to determine the actual break-even value based on all potential losses.

Limitations

The break-even value for risk reduction expenditures for this level of analysis may be considerably lower than the value calculated for Level No. 3 since only the fixed assets are accounted for. This value should be considered a "ball park" number. If the risk can be reduced to an acceptable level by spending this amount, then one can be assured that the expenditures are well below the actual break-even value.

Level No. 3 – Risk Trade-off Based on All Potential Losses

A risk trade-off based on all potential losses is a rigorous approach to determine the break-even value for expenditures for risk reduction. The following is an outline for this approach:

1. Determine the probability of a major incident per operation (P_{MI}/op) using quantitative risk analysis techniques.

2. Define the magnitude of the potential damage and loss (i.e., plant, building, bay, equipment, death, injury, etc.)

3. Determine the associated dollar loss by breaking it down as follows:
    a. Direct and Indirect Fixed Assets
    b. Production/Program Impact Costs
    c. Liability for Personnel Death, Injury, and Damage
        Fatality -
        Injury -
        Personal property damage -
        Change in insurance premiums -
    d. Accident Investigation and Associated Costs

Major Accident	$1,000,000 to $2,500,000 (multiple buildings)
Moderate Accident	$ 250,000 to $1,500,000 (single building)
Minor Accident	$ 100,000 to $ 500,000 (bay and equipment)

4. Calculate the Expected Annual Loss (LE) due to the incident.
    LE = (P_{MI}/op)*(# of op/year)*(Total $ from step 3)

5. Calculate the Annual Cash Flow (ACF) for the affected area.
    ACF = (1 - Tax Rate_A)*(Annual Revenue - All Annual Expenses) + (Tax Rate_B)*(Annual Depreciation)
    Where: Tax Rates A and B may be different
    All Annual Expenses = Expected Annual Loss (LE) + Maintenance Costs + Operating Costs + Engineering Support + Insurance Costs + ...

Note: This is the Annual Cash Flow at the current level of risk.

6. Calculate the Return on Investment (ROI) <u>at the current</u> level of risk.
   ROI = (ACF) / (C + RRC)
   Where: C = The total initial capital outlay (from 3a above).
   RRC = Risk Reduction Costs.
   RRC = 0, since no additional costs have yet occurred to reduce the risk beyond the current level.

7. Recalculate the LE_{b1} and the ACF_{b1} based on Company's acceptable risk level (e.g., P_{MI} = 1E-06/operation). LE_{b1} and ACF_{b1} are the baseline values.

8. Determine the break-even value for the Risk Reduction Costs (RRC_{BE}) using the values from step 7 and the ROI calculated in step 6.

   $RRC_{BE} = (ACF_{b1}) / (ROI) - C$

   Note: The Return on Investment increases when the actual risk reduction costs are less than the break-even value.

   The ROI decreases when the actual RRC are greater than the break-even value.

Limitations

The accuracy and availability of the data from various groups limit this rigorous analysis.

<u>Example No. 1</u>

Risk Score Analysis for Energetic Material Container Filling Operation

Scenario:

Operators over-fill energetic material container and fail to properly clean up prior to moving equipment and tooling. Friction initiation of energetic material.

Determine:

A) The Risk Score for the scenario.
B) The Break-even Value for cost effectiveness.

Solution A

1. Simplified Approach
   Consequence Factor = <u>25</u>
   Fatality; damage greater than $1,000,000
   Exposure Factor = <u>1.5</u>
   Unusual (Spills have occurred)
   Probability Factor = <u>1.0</u>
   Would be remotely possible coincidence
   Note: The rating for this could easily vary from 0.5 to 3.0.
   <u>Risk Score = (25)*(1.5)*(1.0) = 37.5</u>

2. Consequence Factor Approach Based on Fixed Asset
   Consequence Factor = $[(\text{Damage}) / (100)]^{0.4}$
   Given: $1,000,000 potential loss of fixed assets
   Consequence Factor = $[(1{,}000{,}000) / 100]^{0.4}$ = <u>40</u>
   Exposure Factor = <u>1.5</u>
   Probability Factor = <u>1</u>
   <u>Risk Score = (40)*(1.5)*(1) = 60</u>

3. Graphical Approach
   Attached is the graphical solution for this scenario. The Risk Score range is from <u>10 to 92</u>. This graph clearly illustrates the possible variation of the Risk Score by reasonably varying the Exposure Factor and the Probability (Likelihood) Factor. The risk score is dependent on the background and judgment of the analyst.

Solution B

Refer to the attached "Cost Effectiveness Analysis" Nomograph. The break-even value for cost effectiveness has a range of <u>$1,200 to $25,000</u>. Based on a risk reduction of 75% and the variability of the Risk Score from Solution A, the cost expenditures are justified.

Example No. 2

Risk Trade-off Based on Fixed Assets

Given:

$P_{MI} = 1.4 \times 10^{-4}$ / op
Number of operations per year = 50 (op/year)
Capital Investment = $1,000,000 (Direct and Indirect Fixed Assets)

Determine:

The break-even value for Risk Reduction Costs.

Solution:

LE = (P_{MI}/op)*(# op/year)*($ Fixed Assets at Risk)
Thus,
LE = (1.4×10^{-4}/op)*(50 op/year)*($1,000,000) = $7,000
RRC_{BE} = 5*(LE) = 5*($7,000) = <u>$35,000</u> = RRC_{BE}
Where: RRC_{BE} is the Break-even Value for Risk Reduction Costs based on fixed assets.

Example No. 3

Risk Trade-off Based on All Potential Losses

Given:

$P_{MI} = 1.4 \times 10^{-4}$/op
Accepted risk = 1×10^{-6}/operation
Annual Depreciation = $100,000
Number of operations per year = 50 op/year
Capital Investment = $1,000,000
Total Revenues - Total Annual Operating Expenses = $250,000
Total loss resulting form an incident = $2,750,000
Assuming:
$1,000,000 Capital costs of new unit without inflation
$ 750,000 Lost product for 3 weeks down time.
<u>$1,000,000</u> Liability claims for two operators.
$2,750,000
Tax $Rate_A$ = 0.34
Tax $Rate_B$ = 1

Determine:

The break-even value for Risk Reduction Costs.

Solution:

1. P_{MI}/Operation = 1.4 x 10^{-4}/op

2/3. Total Expected Loss = $2,750,000

4. LE = (P_{MI}/op)*(# op/year)*($ Total Expected Loss)
LE = (1.4 x 10^{-4}/op)*(50 op/year)*($2,750,000)
<u>LE = $19,250/year</u>

5. ACF = (1-Tax Rate_A)[Annual Rev. - (LE + All Other Annual Expenses)] + (Tax Rate_B)*(Annual Depreciation)
ACF = (0.66) [$250,000 - $19,250] + $100,000 = <u>$252,295 = ACF</u>

6. ROI = ACF/(C + RRC)
Where: RRC = 0 and LE = $19,250
ROI = $252,295/($1,000,000) = 0.25 = <u>25% = ROI</u>

7. LE_{b1} = (1 x 10^{-6} / op)*(50 op/year)*($2,750,000)
LE_{b1} = <u>$137.5/Year</u>
ACF_{b1} = (0.66)($250,000 - $137.5) + 100,000 = <u>$264,909</u> = ACF_{b1}
Where: LE_{b1} and ACF_{b1} are the baseline values at 1 x 10^{-6}/op.

8. RRC_{BE} = [(ACF_{b1})/(ROI)] - C
RRC_{BE} = [($264,909)/(0.25)] - ($1,000,000) = <u>$59,636</u> = RRC_{BE}
Where: RRC_{BE} is the Break-even Value for Risk Reduction Costs.

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BIOGRAPHY

Bob Ford graduated from the University of Utah with a B.S. degree in Mechanical Engineering.

His career started with **Phillips Petroleum** performing non-destructive testing, assisting with the implementation of a refinery's maintenance system, and conducting fire fighting training for operators.

He worked for **Hercules Incorporated** applying various risk management disciplines such as:

- Process hazards analysis
- Probabilistic risk assessment
- Risk/cost tradeoff analysis
- Material characterization and process simulation testing

His responsibilities included leading the risk assessment efforts for specialty chemical processes, robotics systems, and a major energetic material manufacturing facility.

Bob served as the Director of the **Safety Management Services** group for **Alliant Techsystems**. The Safety Management Services Group provided risk management consulting services for commercial and government clients

Bob founded and is currently the president of **Safety Management Services, Inc.** (SMS, Inc.). SMS, Inc. comprised of engineers and scientists that have experience in applying risk management methodology to a wide variety of energetic and hazardous material processes. SMS, Inc. assists clients with OSHA and EPA regulatory compliance, hazards analysis, hazardous material characterization testing, mechanical integrity, ergonomics, accident investigation, and other risk management services.

He has been intimately involved with:

- Development and implementation of OSHA and EPA regulatory compliance programs for major corporations.
- Process Hazards Analysis of a wide spectrum of hazardous chemical processes.
- Development of mechanical integrity programs for critical processes and equipment.
- Assisting corporations and local municipalities in the application of regulations pertaining to facility siting.
- Training of corporate and plant personnel on various risk management and regulation topics.
- Providing risk management training, on a frequent basis, to technical professional organizations. (e.g., AICHE, ASSE, JANNAF, NSC, etc.)

His favorite time is spent with his wife Ellen and their 4 children, camping, training horses and barefoot water skiing.