Ballot ID:

Title: **Maximum Acceptable Safety Risk Target Calculation**

Purpose: To provide industry with a methodology for calculating a Safety Risk so owner-users can manage their RBI programs to a threshold for risk of injury (fatality) if they so desire (e.g., 1 X 10-5).

Impact: Will enable definition of a safety risk target as the maximum level acceptable for continued operation without requiring a mitigating action in terms of injuries/year.

Rationale: Currently the population density of a unit only has an impact on the consequence analysis if the financial consequence calculation is used and many owner-users are reluctant to place a dollar value on injuries and would prefer to manage to established acceptable safety risk targets which are already in place for initiatives such Process Hazard Analysis and Facility Siting studies.

The approach is very simply to use population density and the personnel injury consequence area, both of which are existing variables within API RP 581, to generate a safety consequence in terms of injuries, which in turn can be used to generate a safety risk. Risk targets can then be established and used for inspection planning if desired, in addition to the currently available program targets.

Technical Reference(s):

1. API RP 581 Part 1 – Inspection Planning Methodology, American Petroleum Institute, Washington, D.C, 20005
2. API RP 581 Part 3 – Consequence of Failure Methodology, American Petroleum Institute, Washington, D.C, 20005.

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Tracking Status

Submitted to Task Group		**Submitted to SCI**		**Submitted to Master Editor**	
Date	***Resolution***	***Date***	***Resolution***	***Date***	***Added***

Proposed Changes and/or Wording *{attach additional documentation after this point}*

The Level 2 consequence procedures presented in Part 3, Section 5 provide equations and background information necessary to calculate consequence areas for several flammable and toxic event outcomes. A summary of these events is provided in Part 3, Table 3.1.

To perform Level 2 calculations, the actual composition of the fluid stored in the equipment is modeled. Fluid property solvers are available that allow the analyst to calculate fluid physical properties more accurately. The fluid solver also provides the ability to perform flash calculations to better determine the release phase of the fluid and to account for two-phase releases. In many of the consequence calculations, physical properties of the released fluid are required at storage conditions as well as conditions after release to the atmosphere.

A cloud dispersion analysis must also be performed as part of a Level 2 consequence analysis to assess the quantity of flammable material or toxic concentration throughout vapor clouds that are generated after a release of volatile material. Modeling a release depends on the source term conditions, the atmospheric conditions, the release surroundings, and the hazard being evaluated. Employment of many commercially available models, including SLAB or dense gas dispersion (DEGADIS) [7], account for these important factors and will produce the desired data for the Level 2 analysis.

The event trees used in the Level 2 consequence analysis are shown in Part 3, Figure 5.3 and Figure 5.4. Improvement in the calculations of the probabilities on the event trees have been made in the Level 2 procedure. Unlike the Level 1 procedure, the probabilities of ignition on the event tree are not constant with release magnitude. Consistent with the work of Cox, Lees, and Ang [8], the Level 2 event tree ignition probabilities are directly proportional to the release rate. The probabilities of ignition are also a function of the flash point temperature of the fluid. The probability that an ignition will be a delayed ignition is also a function of the release magnitude and how close the operating temperature is to the autoignition temperature (AIT) of the fluid. These improvements to the event tree will result in consequence impact areas that are more dependent on the size of release and the flammability and reactivity properties of the fluid being released.

4.3 Risk Analysis

4.3.1 Determination of Risk

In general, the calculation of risk is determined in accordance with Equation (1.6), as a function of time. The equation combines the POF and the COF described in Section 4.1and Section 4.2, respectively.

$$R(t) = P_f(t) \cdot C_f \tag{1.6}$$

The POF, $P_f(t)$, is a function of time since the DF shown in Equation (1.1) increases as the damage in the component accumulates with time.

Process operational changes over time can result in changes to the POF and COF. Process operational changes, such as in temperature, pressure, or corrosive composition of the process stream, can result in an increased POF due to increased damage rates or initiation of additional damage mechanisms. These types of changes are identified by the plant management of change procedure and/or integrity operating windows program.

The COF is assumed to be invariant as a function of time. However, significant process changes can result in COF changes. Process change examples may include changes in the flammable, toxic, and nonflammable/nontoxic components of the process stream, changes in the process stream from the production source, variations in production over the lifetime of an asset or unit, and repurposing or revamping of an asset or unit that impacts the operation and/or service of gas/liquid processing plant equipment. In addition, modifications to detection, isolation, and mitigation systems will affect the COF. Factors that may impact the financial COF may include but are not limited to personnel population density, fluid values, and the cost of lost production. As defined in API 580, a reassessment is required when the original risk basis for the POF and/or COF changes significantly.

Equation (1.6) is rewritten in terms of area~~- and~~ financial, and safety-based risk, as shown in Equation~~s~~ (1.7) through~~and (1.8)~~ Equation (1.9).

$$R(t) = P_f(t) \cdot C_f^{area} \quad \text{for area-based risk} \tag{1.7}$$

$$R(t) = P_f(t) \cdot C_f^{fin} \quad \text{for financial-based risk} \tag{1.8}$$

$$R(t) = P_f(t) \cdot C_f^{inj} \quad \text{for safety-based risk} \tag{1.9}$$

In these equations:

C_f^{area} is the consequence impact area expressed in units of area;

C_f^{fin} is the financial consequence expressed in economic terms; and

C_f^{inj} is the financial consequence expressed in term of injuries.

Note that risk in Equation (1.7), Equation (1.8) and Equation (1.9) varies as a function of time because POF varies as a function of time. Figure 4.1~~Figure 4.1~~ illustrates that the risk associated with individual damage mechanisms can be added together by superposition to provide the overall risk as a function of time.

4.3.2 Risk Plotting

4.3.2.1 General

Plotting POF and COF values on a risk matrix is an effective method of representing risk graphically. POF is plotted along one axis, increasing in magnitude from the origin, while COF is plotted along the other axis. It is the responsibility of the owner–user to define and document the basis for POF and COF category ranges and risk targets used. This section provides risk matrix examples only.

4.3.2.2 Risk Matrix Examples

Presenting the risk results in a matrix is an effective way of showing the distribution of risks for components in a process unit without using numerical values. In the risk matrix, POF and COF categories are arranged so that the highest risk components are towards the upper right-hand corner.

Two risk matrix examples are shown in Figure 4.2 and Figure 4.3. In both figures, POF is expressed in terms of the number of failures over time, $P_f(t)$, or DF. COF is expressed in area ~~or~~ financial, or injury terms. Example numerical values associated with POF and COF (as area, ~~or~~ financial, or safety) categories are shown in Table 4.1 and Table 4.2. The matrices do not need to be square (i.e. 4x5 risk matrix, 7x5 risk matrix, etc.).

a) Unbalanced Risk Matrix (Figure 4.2)—POF and COF value ranges are assigned numerical and lettered categories, respectively, increasing in order of magnitude. Risk categories (i.e. Low, Medium, Medium High, and High) are assigned to the boxes with the risk category shading asymmetrical. For example, using Table 4.1 values, a POF of 5.00E-04 is assigned a Category 3 and a COF of 800 ft^2 corresponds to a Category B. The 3B box is Low risk category when plotted on Figure 4.2.

b) Balanced Risk Matrix (Figure 4.3)—Similar to Figure 4.2, POF and COF value ranges are assigned numerical and lettered categories, respectively, increasing in order of magnitude. In this example, risk categories (i.e. Low, Medium, Medium High, and High) are assigned symmetrically to the boxes. When values from Table 4.1 are used, a POF of 5.00E-04 failures/year is assigned a Category 3 and a COF of 800 ft^2 corresponds to a Category B. However, the 3B box in the Figure 4.3 example corresponds to a Medium risk category.

Note that all ranges and risk category shading provided in Table 4.1 and Table 4.2 as well as Figure 4.2 and Figure 4.3 are examples of dividing the plot into risk categories and are not recommended risk targets and/or thresholds. It is the owner–users' responsibility to establish the ranges and target values for their risk-based programs.

4.3.2.3 Iso-Risk Plot Example

Another effective method of presenting risk results is an iso-risk plot. An iso-risk plot graphically shows POF and COF values in a log-log, two-dimensional graph where risk increases toward the upper right-hand corner. Examples of iso-risk plots for safety, financial and injury COF are shown in Figure 4.4, Figure 4.5 and Figure 4.6, respectively. Components near an iso-risk line represent an equivalent level of risk. Components are ranked based on risk for inspection, and inspection plans are developed for components based on the defined risk acceptance criteria that has been set.

As in a risk matrix, POF is expressed in failures over time, $P_f(t)$, or DF while COF is expressed in area ~~or~~ financial, or safety terms. Risk categories (i.e. Low, Medium, Medium High, and High) are assigned to the areas between the iso-risk lines and dependent upon the level of risk assigned as a threshold between risk categories, as shown in Figure 4.4. For example, a POF of 5.00E-04 and a COF of $125,000 are assigned a Medium risk category.

4.3.3 General Comments Concerning Risk Plotting

Note the following when using the examples in Figure 4.2 through Figure 4.5:

a) as the POF values increase, the risk becomes more POF driven;

b) as the COF values increase, the risk becomes more COF driven.

In risk mitigation planning, equipment items residing towards the upper right-hand corner of the risk matrix will most likely take priority for inspection planning because these items have the highest risk. Similarly, items residing toward the lower left-hand corner of the risk matrix tend to take lower priority because these items have the lowest risk. A risk matrix is used as a screening tool during the prioritization process.

Using the examples in Figure 4.2 though Figure 4.5 in consideration to risk mitigation planning:

a) if POF drives the risk (the data drift toward the POF axis), the risk mitigation strategy may be weighted more towards inspection-based methods;

b) if COF drives the risk (the data drift toward the COF axis), the risk mitigation strategy may be weighted more towards engineering/management methods;

c) if both POF and COF drive risk, the risk mitigation strategy may require both inspection-based methods coupled with engineering and management methods.

It is the responsibility of the owner–user to:

a) determine the type of plot to be used for reporting and prioritization,

b) determine the risk acceptance criteria (POF and COF category ranges),

c) document the risk plotting process,

d) provide for risk mitigation strategies based upon the plot chosen.

4.4 Inspection Planning Based on Risk Analysis

4.4.1 Overview

Inspection planning based on risk assumes that at some point in time, the risk as defined by Equation (1.7), Equation (1.8) and Equation (1.9) will reach or exceed a user-defined area ~~or~~ financial, or safety risk target. When or before the user-defined risk target is reached, an inspection of the equipment is recommended based on the component damage mechanisms with the highest DFs. The user may set additional targets to initiate an inspection, such as POF, DF, COF, or thickness. In addition, inspection may be conducted solely to gather information to reduce uncertainty in the component condition or based on an engineering evaluation of the fitness for continued service rather than the RBI results.

Although inspection of a component does not reduce the inherent risk, inspection provides improved knowledge of the current state of the component and therefore reduces uncertainty. The probability that loss of containment will occur is directly related to the known condition of the component based on information from inspection and the ability to accurately quantify damage.

Reduction in uncertainty in the damage state of a component is a function of the effectiveness of the inspection to identify the type and quantify the extent of damage. Inspection plans are designed to detect and quantify the specific types of damage expected such as local or general thinning, cracking, and other types of damage. An inspection technique that is appropriate for general thinning will not be effective in detecting and quantifying damage due to local thinning or cracking. Therefore, the inspection effectiveness is a function of the inspection method and extent of coverage used for detecting the type of damage expected.

Risk is a function of time, as shown in Equation (1.7), Equation (1.8) and Equation (1.9), as well as a function of the knowledge of the current state of the component determined from past inspections. When inspection effectiveness is introduced into risk Equation (1.7), Equation (1.8) and Equation (1.9), the equations can be rewritten as Equation (1.10), Equation (1.11) and Equation (1.12):

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{area} \quad \text{for area-based risk} \tag{1.10}$$

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{fin} \quad \text{for financial-based risk} \tag{1.11}$$

$$R(t,I_E) = P_f(t,I_E) \cdot C_f^{inj} \quad \text{for safety-based risk} \tag{1.12}$$

4.4.2 Targets

A target is defined as the maximum level acceptable for continued operation without requiring a mitigating action. Once the target has been met or exceeded, an activity such as inspection is triggered. Several targets can be defined in an RBI program to initiate and define risk mitigation activities, as follows.

a) Risk Target—A level of acceptable risk that triggers the inspection planning process. The risk target may be expressed in area (ft^2/year), ~~or~~ financial ($/year) or safety (injuries/year) terms, based on the owner–user preference.

b) POF Target—A frequency of failure or leak (#/year) that is considered unacceptable and triggers the inspection planning process.

c) DF Target—A damage state that reflects an unacceptable failure frequency factor greater than the generic and triggers the inspection planning process.

d) COF Target—A level of unacceptable consequence in terms of consequence area (C_f^{area} ~~CA_f~~), ~~or~~ financial consequence (C_f^{fin} ~~FC~~), or safety consequence (C_f^{inj}) based on owner–user preference. Because risk driven by COF is not reduced by inspection activities, risk mitigation activities to reduce release inventory or ignition are required.

e) Thickness Target—A specific thickness, often the minimum required thickness, t_{min}, considered unacceptable, triggering the inspection planning process.

f) Maximum Inspection Interval Target—A specific inspection frequency considered unacceptable, triggering the inspection planning process. A maximum inspection interval may be set by the owner–user's corporate standards or may be set based on a jurisdictional requirement

It is important to note that defining targets is the responsibility of the owner–user and that specific target criteria is not provided within this document. The above targets should be developed based on owner–user internal guidelines and overall risk tolerance. Owner–users often have corporate risk criteria defining acceptable and prudent levels of safety, environmental, and financial risks. These owner–user criteria should be used when making RBI decisions since acceptable risk levels and risk management decision-making will vary among companies.

4.4.3 Inspection Effectiveness—The Value of Inspection

An estimate of the POF for a component depends on how well the independent variables of the limit state are known and understood. Using examples and guidance for inspection effectiveness provided in Part 2, Annex 2.C, an inspection plan is developed, as risk results require. The inspection strategy is implemented to obtain the necessary information to decrease uncertainty about the actual damage state of the equipment by confirming the presence of damage, obtaining a more accurate estimate of the damage rate, and evaluating the extent of damage.

An inspection plan is the combination of NDE methods (i.e. visual, ultrasonic, radiographic, etc.), frequency of inspection, and the location and coverage of an inspection to find a specific type of damage. Inspection plans vary in their overall effectiveness for locating and sizing specific damage and understanding the extent of the damage.

Inspection effectiveness is introduced into the POF calculation using Bayesian Analysis, which updates the POF when additional data are gathered through inspection. The extent of reduction in the POF depends on the effectiveness of the inspection to detect and quantify a specific damage type of damage mechanism. Therefore, higher inspection effectiveness levels will reduce the uncertainty of the damage state of the component and reduce the POF. The POF and associated risk may be calculated at a current and/or future time period using Equation (1.10), Equation (1.11) and Equation (1.12).

Examples of the levels of inspection effectiveness categories for various damage mechanisms and the associated generic inspection plan (i.e. NDE techniques and coverage) for each damage mechanism are provided in Part 2, Annex 2.C. These tables provide examples of the levels of generic inspection plans for a specific damage mechanism. The tables are provided as a matter of example only, and it is the responsibility of the owner–user to create, adopt, and document their own specific levels of inspection effectiveness tables.

4.4.4 Inspection Planning

An inspection plan date covers a defined plan period and includes one or more future maintenance turnarounds. Within this plan period, three cases are possible based on predicted risk and the risk target.

a) Case 1—Risk Target Is Exceeded During the Plan Period—As shown in Figure 4.7, the inspection plan will be based on the inspection effectiveness required to reduce the risk and maintain it below the risk target through the plan period.

b) Case 2—Risk Exceeds the Risk Target at the Time the RBI Date—As shown in Figure 4.8, the risk at the start time of the RBI analysis, or RBI date, exceeds the risk target. An inspection is recommended to reduce the risk below the risk target by the plan date.

c) Case 3—Risk at the Plan Date Does Not Exceed the Risk Target—As shown in Figure 4.9, the risk at the plan date does not exceed the risk target and therefore no inspection is required during the plan period. In this case, the inspection due date for inspection scheduling purposes may be set to the plan date so that reanalysis of risk will be performed by the end of the plan period.

The concept of how the different inspection techniques with different effectiveness levels can reduce risk is shown in Figure 4.7. In the example shown, a minimum of a *B Level* inspection was recommended at the target date. This inspection level was sufficient since the risk predicted after the inspection was performed was determined to be below the risk target at the plan date. Note that in Figure 4.7, a *C Level* inspection at the target date would not have been sufficient to satisfy the risk target criteria.

4.5 Nomenclature

~~A_n~~	~~is the cross-sectional hole area associated with the n^{th} release hole size, mm^2 ($in.^2$)~~
~~A_{rt}~~	~~is the metal loss parameter~~
~~a~~	~~is a variable provided for reference fluids for Level 1 COF analysis~~
~~b~~	~~is a variable provided for reference fluids for Level 1 COF analysis~~
C_f	is the COF, m^2 (ft^2), ~~or~~ \$ or injuries
C_f^{area}	is the area consequence impact area, m^2 (ft^2)
C_f^{fin}	is the financial consequence of failure, \$
C_f^{inj}	is the injury consequence, injuries
~~CA_f^{flam}~~	~~is the flammable consequence impact area, m^2 (ft^2)~~
~~$CA_{f,n}^{flam}$~~	~~is the flammable consequence impact area for each hole, m^2 (ft^2)~~
~~$D_f(t)$~~	~~is the DF as a function of time, equal to $D_{f-total}$ evaluated at a specific time~~

~~D_f^{thin}~~	~~is the DF for thinning~~
$D_{f\text{-}total}$	is total DF for POF calculation
~~F_{MS}~~	~~is the management systems factor~~
~~FC_f^{fin}~~	~~is the financial consequence, \$~~
~~gff~~	~~is the GFF, failures/year~~
~~gff_n~~	~~is the GFF for each of the n release hole sizes selected for the type of equipment being evaluated, failures/year~~
~~gff_{total}~~	~~is the sum of the individual release hole size generic frequencies, failures/year~~
~~k~~	~~is the release fluid ideal gas specific heat capacity ratio, dimensionless~~
$P_f(t)$	is the POF as a function of time, failures/year
$P_f(t,I_E)$	is the POF as a function of time and inspection effectiveness, failures/year
~~P_s~~	~~is the storage or normal operating pressure, kPa (psi)~~
~~R~~	~~is the universal gas constant = 8314 J/(kg-mol)K [1545 ft-lbf/lb-mol°R]~~
$R(t)$	is the risk as a function of time, m^2/year (ft^2/year), \$/year or injuries/year
$R(t,I_E)$	is the risk as a function of time and inspection effectiveness, m^2/year (ft^2/year) or \$/year
~~t_{min}~~	~~is the minimum required thickness, mm (in.)~~
~~X~~	~~is the release rate or release mass for a Level 1 COF analysis, kg/s [lb/s] or kg [lb]~~
~~ß~~	~~is the Weibull shape parameter~~
~~η~~	~~is the Weibull characteristic life parameter, years~~

4.6 Tables

Table 4.1—Numerical Values Associated with POF and Area-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** (ft^2)
1	$P_f\,(t,I_E) \le$ 3.06E-05	$D_{f\text{-}total} \le 1$	A	$C_f^{area} \le 100$
2	3.06E-05 $< P_f\,(t,I_E) \le$ 3.06E-04	$1 < D_{f\text{-}total} \le 10$	B	$100 < C_f^{area} \le 1{,}000$
3	3.06E-04 $< P_f\,(t,I_E) \le$ 3.06E-03	$10 < D_{f\text{-}total} \le 100$	C	$1{,}000 < C_f^{area} \le 10{,}000$
4	3.06E-03 $< P_f\,(t,I_E) \le$ 3.06E-02	$100 < D_{f\text{-}total} \le 1{,}000$	D	$10{,}000 < C_f^{area} \le 100{,}000$
5	$P_f\,(t,I_E) >$ 3.06E-02	$D_{f\text{-}total} > 1{,}000$	E	$C_f^{area} > 100{,}000$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values in Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms, and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.11.4.

Table 4.1M—Numerical Values Associated with POF and Area-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** (m^2)
1	$P_f\,(t,I_E) \le$ 3.06E-05	$D_{f\text{-}total} \le 1$	A	$C_f^{area} \le 9.29$
2	3.06E-05 $< P_f\,(t,I_E) \le$ 3.06E-04	$1 < D_{f\text{-}total} \le 10$	B	$9.29 < C_f^{area} \le 92.9$
3	3.06E-04 $< P_f\,(t,I_E) \le$ 3.06E-03	$10 < D_{f\text{-}total} \le 100$	C	$92.9 < C_f^{area} \le 929$
4	3.06E-03 $< P_f\,(t,I_E) \le$ 3.06E-02	$100 < D_{f\text{-}total} \le 1000$	D	$929 < C_f^{area} \le 9290$
5	$P_f\,(t,I_E) >$ 3.06E-02	$D_{f\text{-}total} > 1000$	E	$C_f^{area} > 9290$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms, and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.11.4.

Table 4.2—Numerical Values Associated with POF and Financial-based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** ($)
1	$P_f(t, I_E) \le 3.06E\text{-}05$	$D_{f\text{-}total} \le 1$	A	$C_f^{fin} \le 10{,}000$
2	$3.06E\text{-}05 < P_f(t, I_E) \le 3.06E\text{-}04$	$1 < D_{f\text{-}total} \le 10$	B	$10{,}000 < C_f^{fin} \le 100{,}000$
3	$3.06E\text{-}04 < P_f(t, I_E) \le 3.06E\text{-}03$	$10 < D_{f\text{-}total} \le 100$	C	$100{,}000 < C_f^{fin} \le 1{,}000{,}000$
4	$3.06E\text{-}03 < P_f(t, I_E) \le 3.06E\text{-}02$	$100 < D_{f\text{-}total} \le 1000$	D	$1{,}000{,}000 < C_f^{fin} \le 10{,}000{,}000$
5	$P_f(t, I_E) > 3.06E\text{-}02$	$D_{f\text{-}total} > 1000$	E	$C_f^{fin} > 10{,}000{,}000$

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.12.1.

Table 4.3—Numerical Values Associated with POF and Injury-Based COF Categories

Category	Probability Category [1,2,3]		Consequence Category [4]	
	Probability Range	**DF Range**	**Category**	**Range** (injuries)
1	$P_f(t, I_E) \le 3.06E\text{-}05$	$D_{f\text{-}total} \le 1$	A	$C_f^{inj} \le$ ~~0.0058~~3.27E-05
2	$3.06E\text{-}05 < P_f(t, I_E) \le 3.06E\text{-}04$	$1 < D_{f\text{-}total} \le 10$	B	~~0.0058~~3.27E-05 $< C_f^{inj} \le$ 3.27E-04~~0.058~~
3	$3.06E\text{-}04 < P_f(t, I_E) \le 3.06E\text{-}03$	$10 < D_{f\text{-}total} \le 100$	C	3.27E-04~~0.058~~ $< C_f^{inj} \le$ 3.27E-03~~0.58~~
4	$3.06E\text{-}03 < P_f(t, I_E) \le 3.06E\text{-}02$	$100 < D_{f\text{-}total} \le 1000$	D	3.27E-03~~0.58~~ $< C_f^{inj} \le$ 3.27E-02~~05.8~~
5	$P_f(t, I_E) > 3.06E\text{-}02$	$D_{f\text{-}total} > 1000$	E	$C_f^{inj} >$ 3.27E-02~~5.8~~

NOTE 1 POF values are based on a *gff* of 3.06E-05 and an F_{MS} of 1.0. If the suggested *gff* values of Part 2, Table 3.1 are used, the probability range does not apply to AST shell course, AST bottoms and centrifugal compressors.

NOTE 2 In terms of POF, see Part 1, Section 4.1.

NOTE 3 In terms of the total DF, see Part 2, Section 3.4.2.

NOTE 4 In terms of consequence area, see Part 3, Section 4.13.1.

4.7 Figures

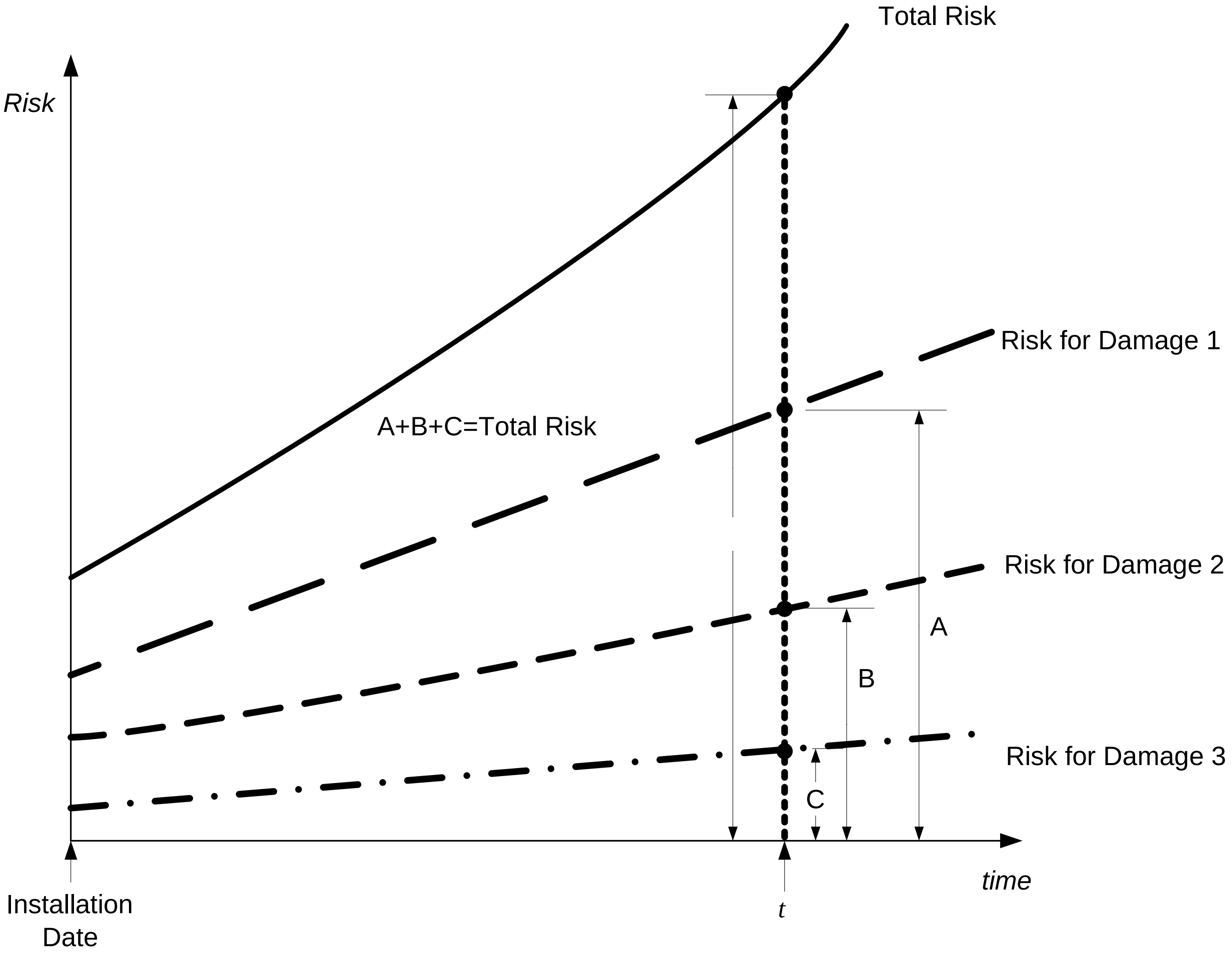
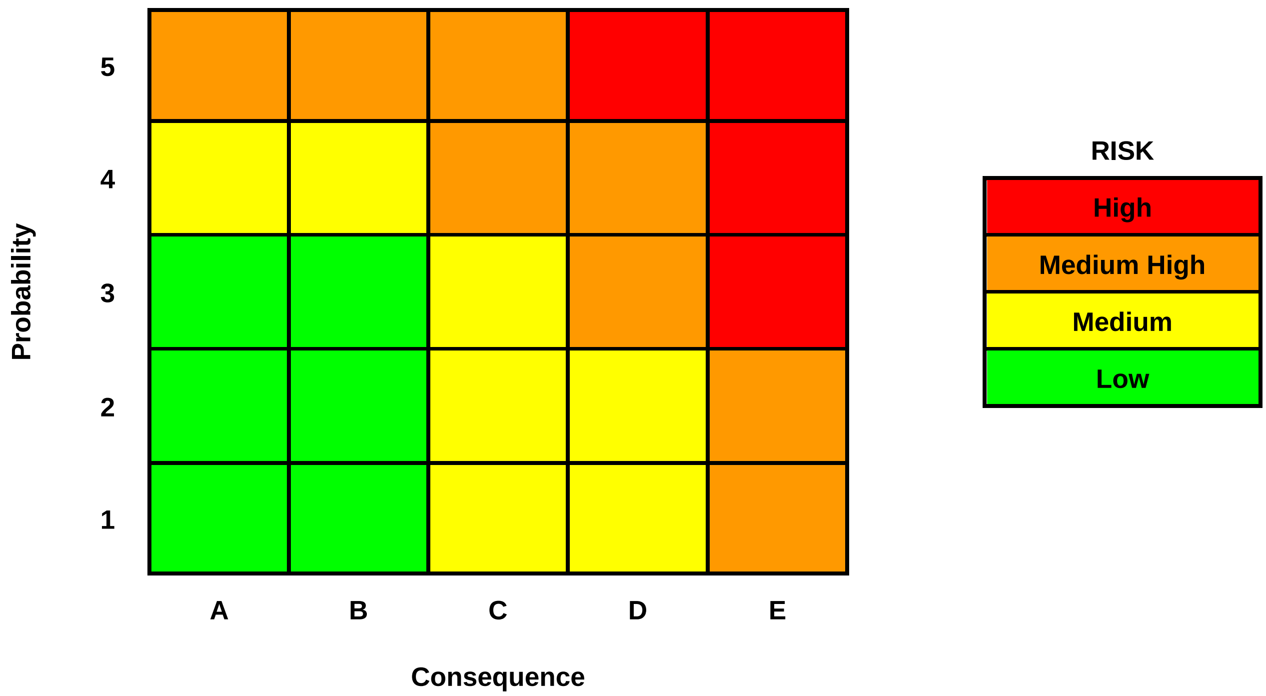
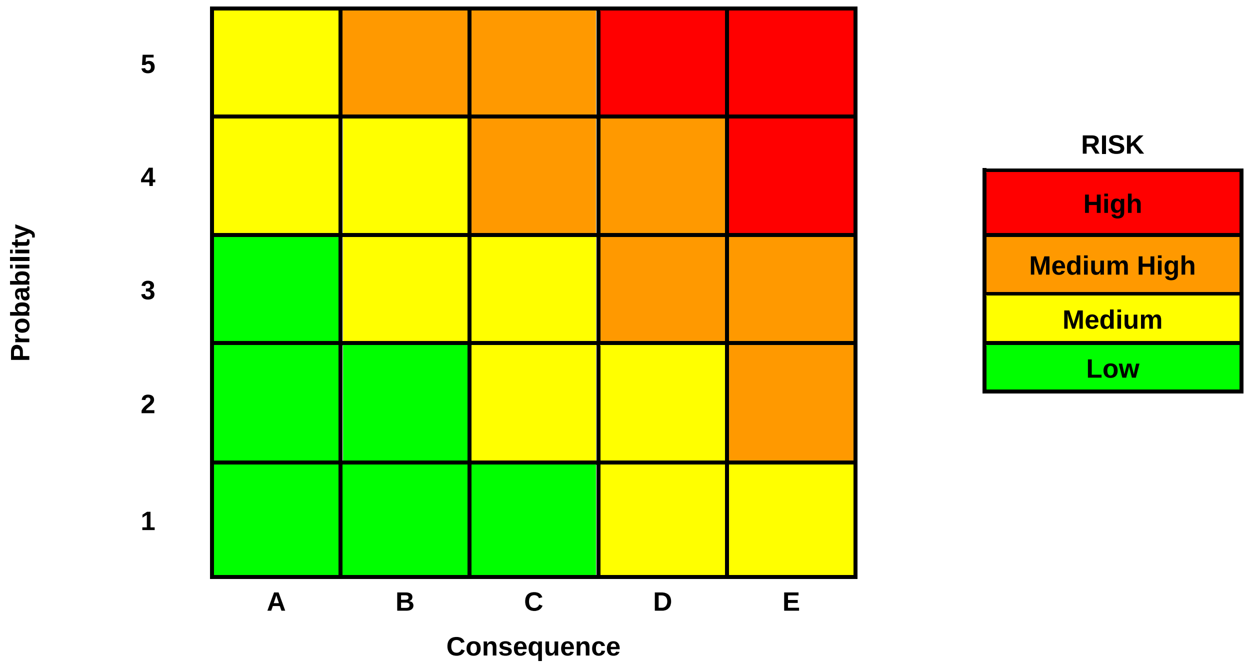


Figure 4.1—Superposition Principle for the Calculation of Risk



NOTE See Table 4.1 and Table 4.2 for ranges in probability and consequence categories.

Figure 4.2—Unbalanced Risk Matrix Example



NOTE See Table 4.1 and Table 4.2 for ranges in probability and consequence categories.

Figure 4.3—Balanced Risk Matrix Example

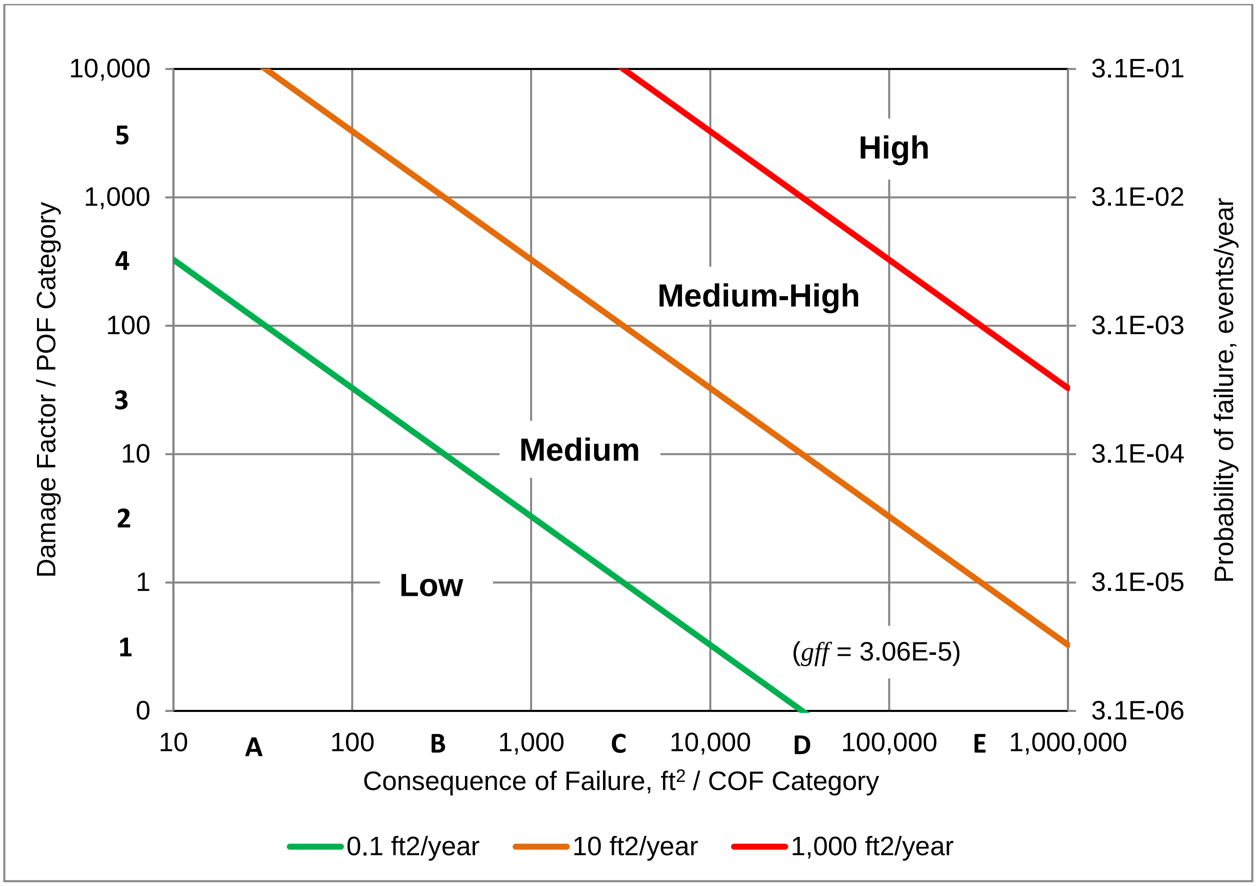


Figure 4.4—Example Iso-risk Plot for Consequence Area

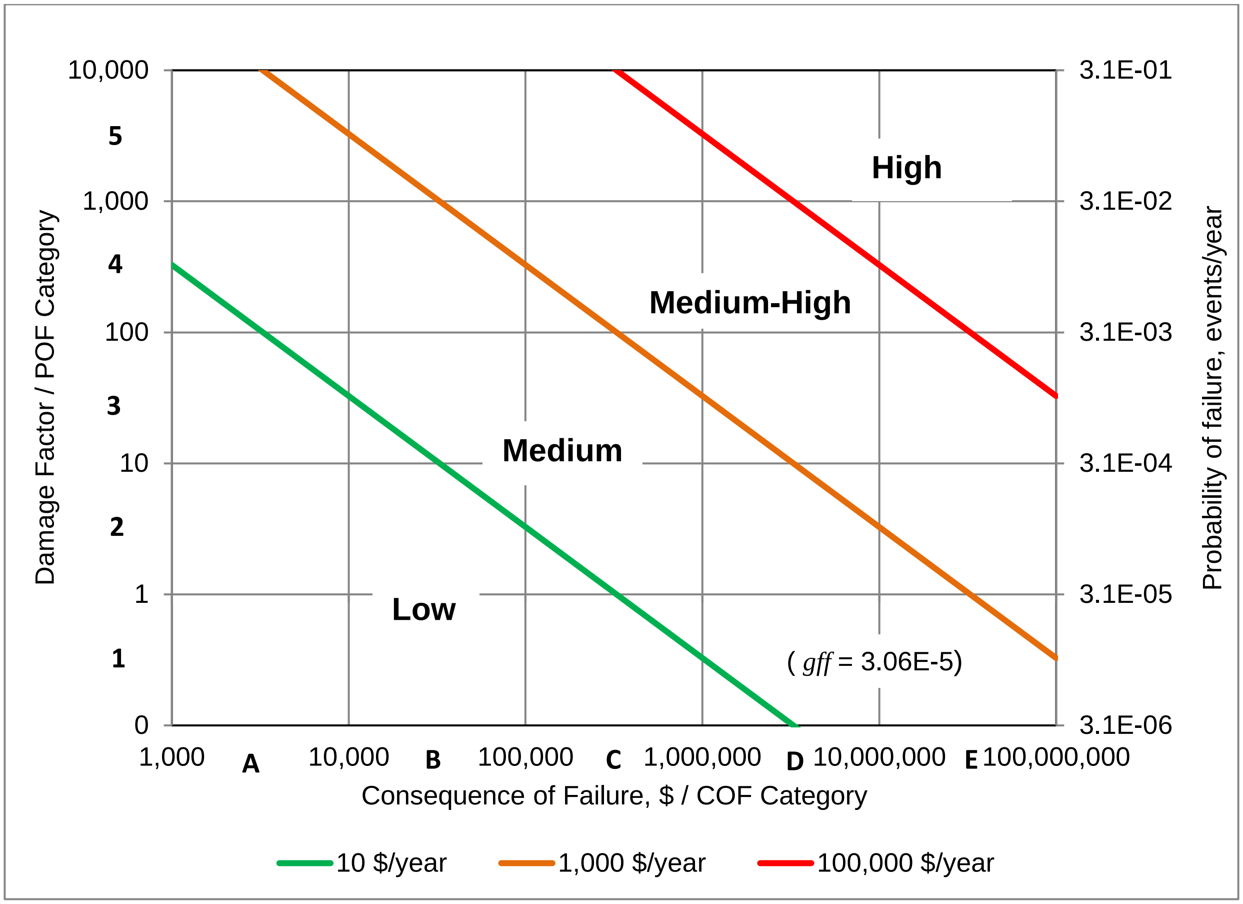
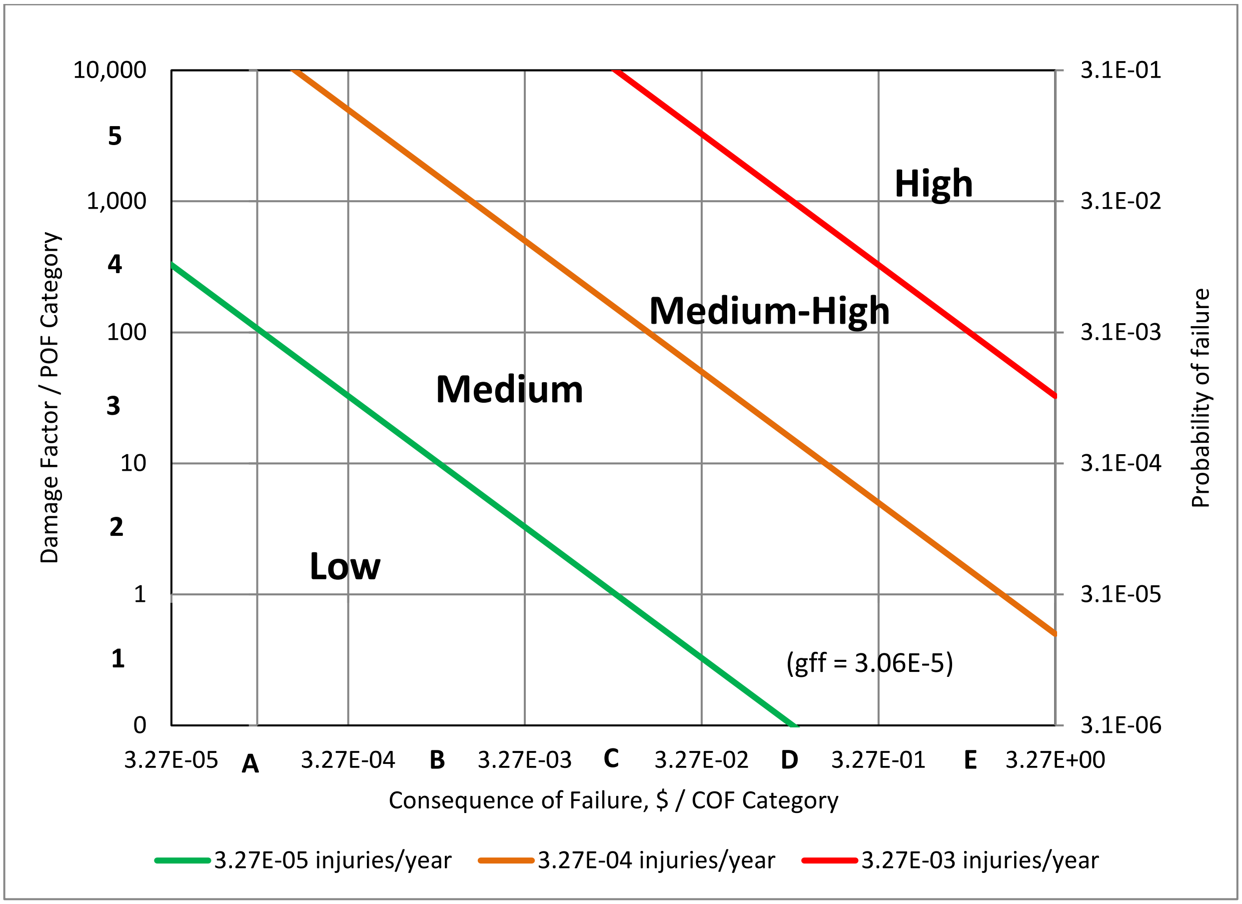


Figure 4.5—Example Iso-risk Plot for Financial Consequence


10,000
5
1,000
4
100
3
10
2
1
1
0
Damage Factor / POF Category
3.1E-01
3.1E-02
3.1E-03
3.1E-04
3.1E-05
3.1E-06
Probability of failure
High
Medium-High
Medium
Low
(gff = 3.06E-5)
3.27E-05
A
3.27E-04
B
3.27E-03
C
3.27E-02
D
3.27E-01
E
3.27E+00
Consequence of Failure, $ / COF Category
3.27E-05 injuries/year
3.27E-04 injuries/year
3.27E-03 injuries/year

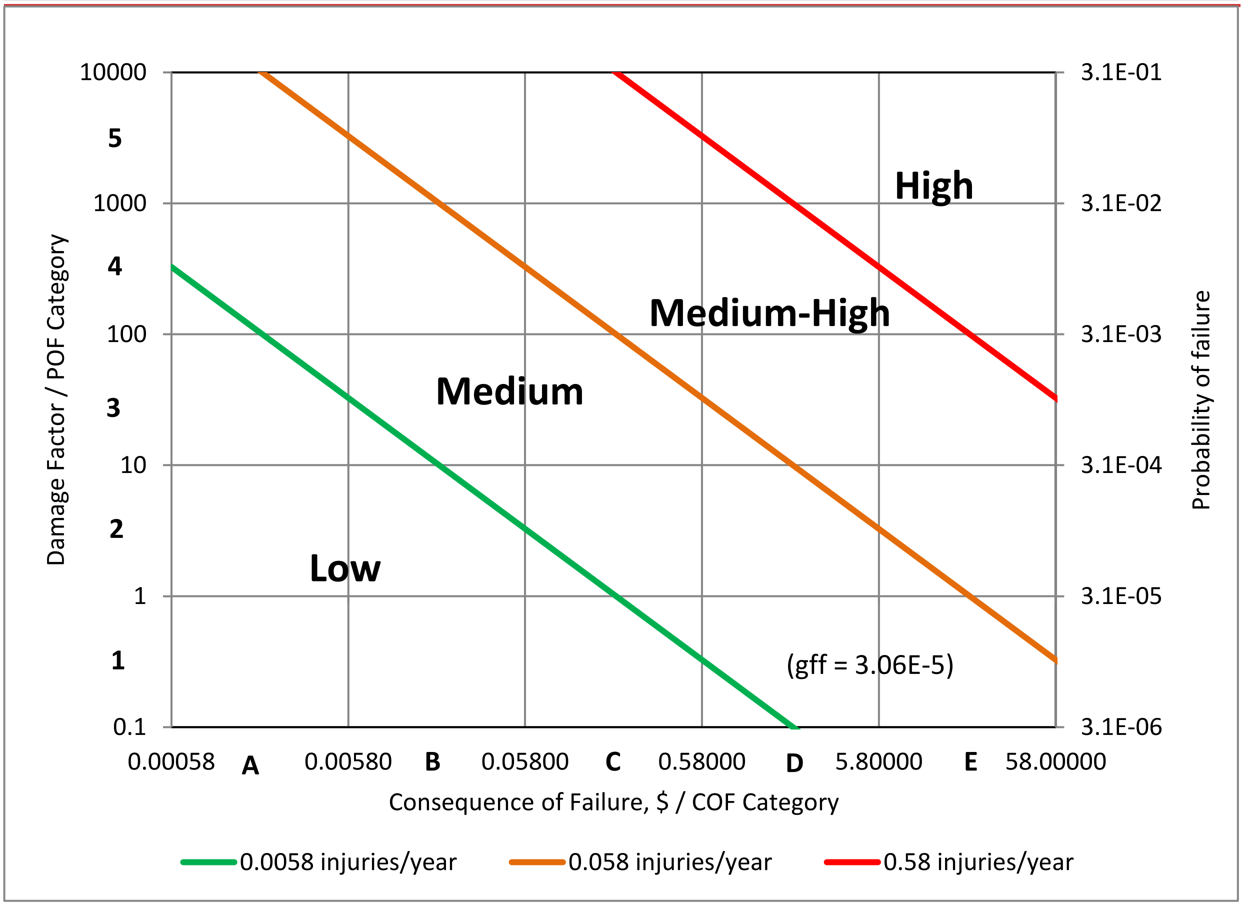

10000
5
1000
4
100
3
10
2
1
1
0.1
Damage Factor / POF Category
3.1E-01
3.1E-02
3.1E-03
3.1E-04
3.1E-05
3.1E-06
Probability of failure
High
Medium-High
Medium
Low
(gff = 3.06E-5)
0.00058
A
0.00580
B
0.05800
C
0.58000
D
5.80000
E
58.00000
Consequence of Failure, $ / COF Category
0.0058 injuries/year
0.058 injuries/year
0.58 injuries/year

Figure 4.6—Example Iso-risk Plot for Injury Consequence

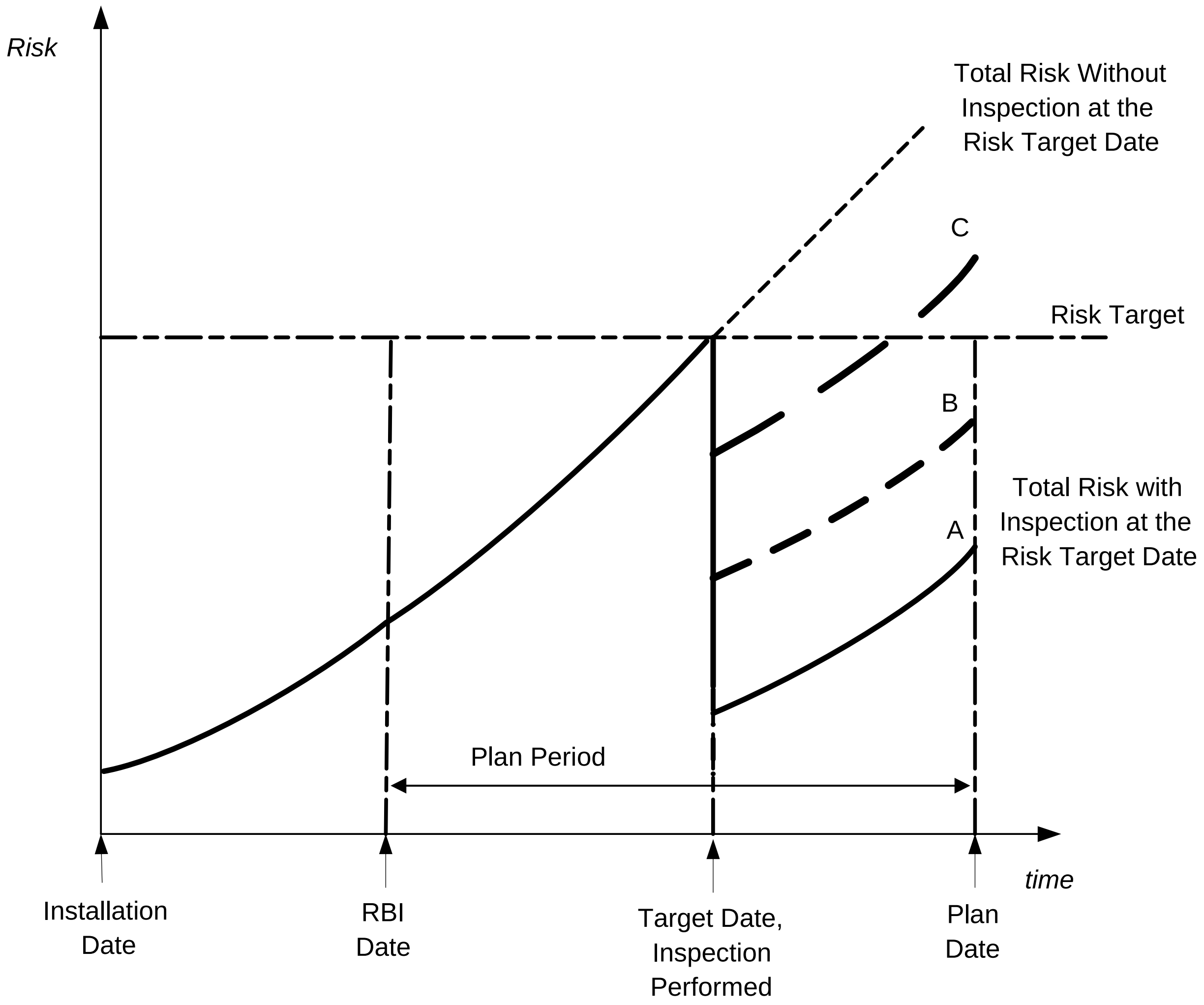


Figure 4.7—Case 1: Inspection Planning when the Risk Target Is Exceeded During the Plan Period

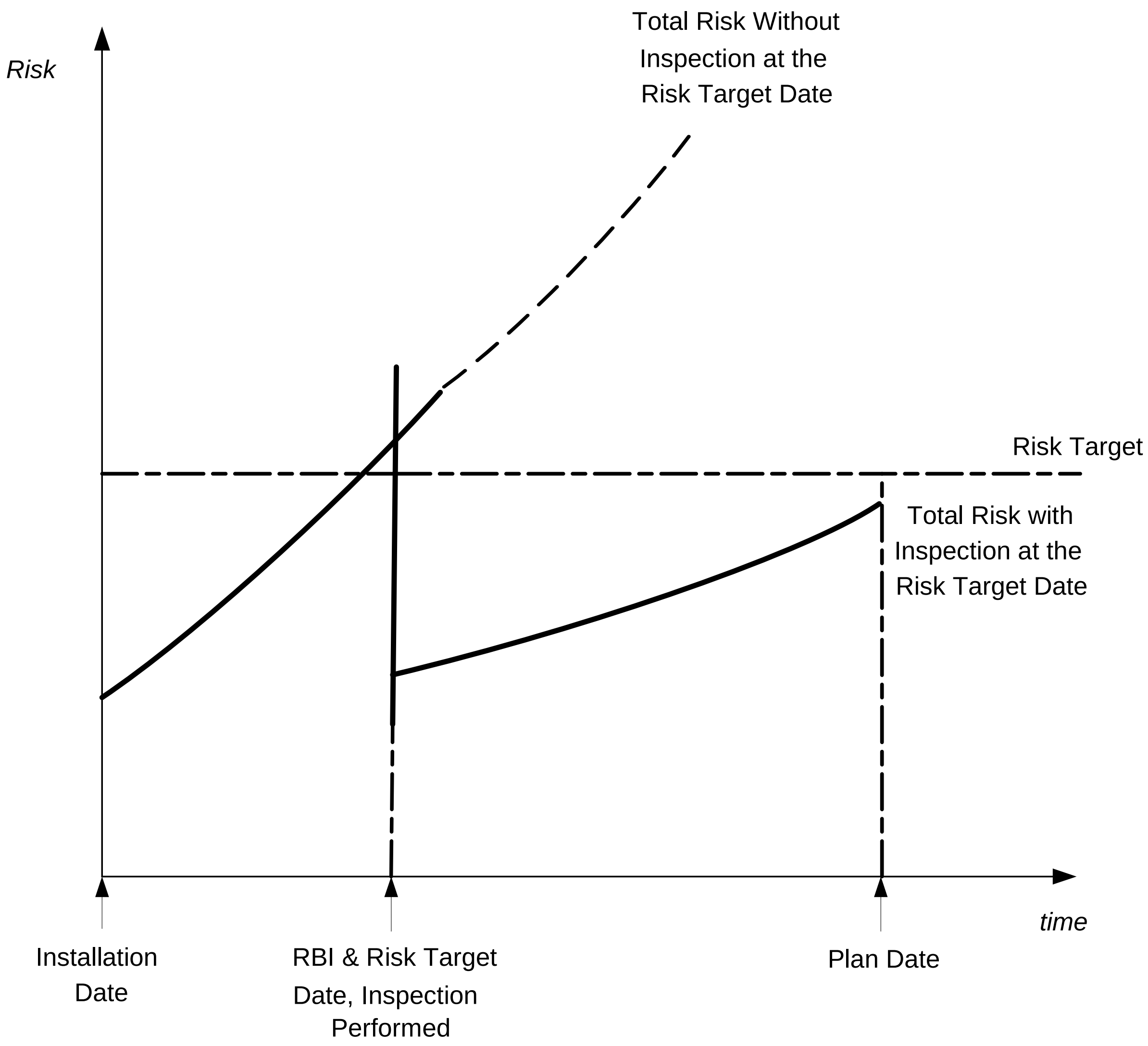


Figure 4.8—Case 2: Inspection Planning when the Risk Target Has Been Exceeded at or Prior to the RBI Date

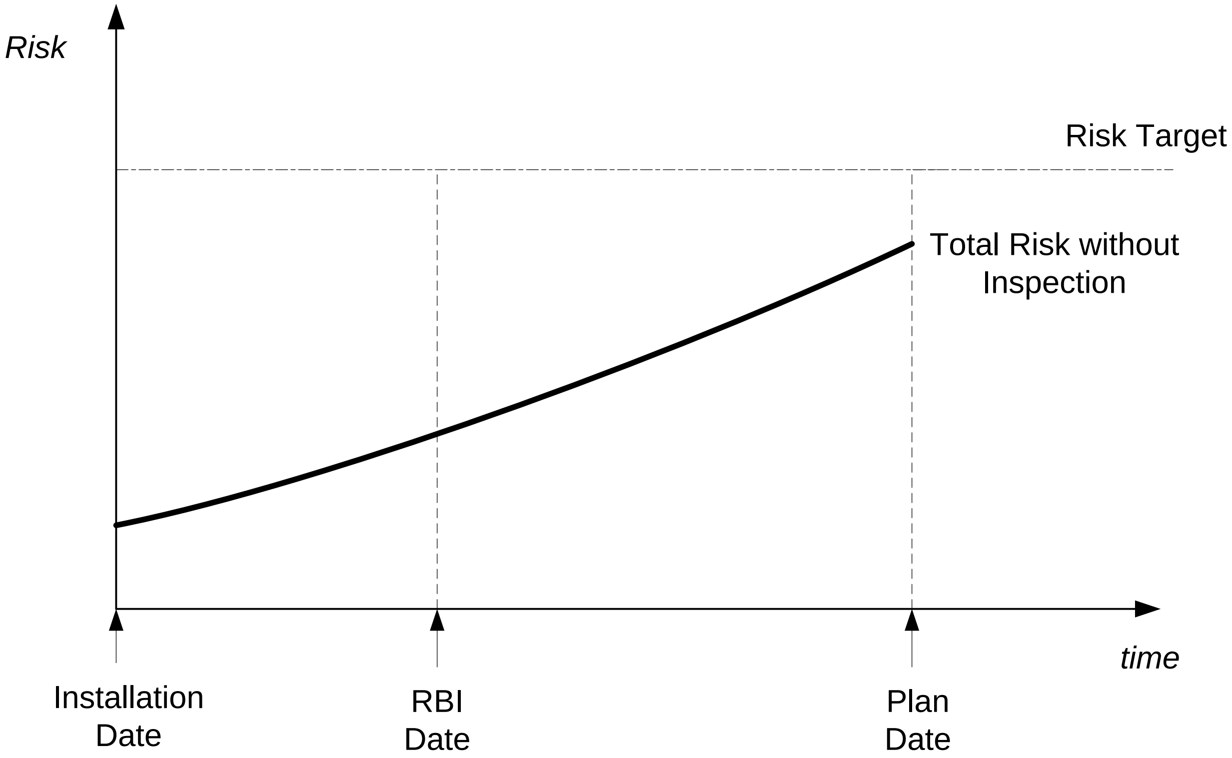


Figure 4.9—Case 3: Inspection Planning when Risk Target Is Not Exceeded During the Plan Period

d) FC includes losses due to business interruption and costs associated with environmental releases. Business interruption consequence is estimated as a function of the flammable and nonflammable consequence area results. Environmental consequence is determined directly from the mass available for release or from the release rate.

3.3 Collateral Damage

Collateral damage such as exposure of electrical, instrumentation, and control equipment to hazardous releases is not considered. As an example, serious delayed consequences can occur when control instrumentation is exposed to releases of chlorine.

3.4 Overview of COF Methodology

3.4.1 General

Two levels of COF methodology are defined as Level 1 and Level 2.

3.4.2 Level 1 Consequence Analysis

The Level 1 consequence analysis can be performed for a defined list of representative fluids. This methodology uses table lookups and graphs that readily can be used to calculate the consequence of releases without the need of specialized modeling software or techniques. A series of consequence modeling analyses were performed for these reference fluids using dispersion modeling software, the results of which have been incorporated into lookup tables. The following assumptions are made in the Level 1 consequence analysis.

a) The fluid phase upon release can be a liquid or a gas, depending on the storage phase and the phase expected to occur upon release to the atmosphere. In general, no consideration is given to the cooling effects of flashing liquid, rainout, jet liquid entrainment, or two-phase releases.

b) Fluid properties for representative fluids containing mixtures are based on average values (e.g. MW, NBP, density, specific heats, AIT).

c) Probabilities of ignition, as well as the probabilities of other release events (VCE, pool fire, jet fire, etc.) have been pre-determined for each of the representative fluids as a function of temperature, fluid AIT, and release type. These probabilities are constants, that is, totally independent of the release rate.

d) The effects of BLEVEs are not included in the assessment.

e) The effects of pressurized nonflammable explosions, such as those possible when nonflammable pressurized gases (e.g. air or nitrogen) are released during a vessel rupture, are not included in the assessment.

f) Meteorological conditions were assumed and used in the dispersion calculations that form the basis for the consequence analysis table lookup (see Annex 3.A).

g) Consequence areas do not consider the release of a toxic product during a combustion reaction (e.g. burning chlorinated hydrocarbons producing phosgene; hydrochloric acid producing chlorine gas; amines producing hydrogen cyanide; sulfur producing sulfur dioxide).

3.4.3 Level 2 Consequence Analysis

The Level 2 consequence analysis is used in cases where the assumptions of the Level 1 consequence analysis are not valid. Examples of where the more rigorous calculations are desired or necessary are as follows.

a) The specific fluid is not represented adequately within the list of reference fluid groups provided, including cases where the fluid is a wide-range boiling mixture or where the fluids toxic consequence is not represented adequately by any of the reference fluid groups.

b) The stored fluid is close to its critical point, in which case the ideal gas assumptions for the vapor release equations are invalid.

c) The effects of two-phase releases, including liquid jet entrainment as well as rainout, need to be included in the assessment.

d) The effects of BLEVEs are to be included in the assessment.

e) The effects of pressurized nonflammable explosions, such as possible when nonflammable pressurized gases (e.g. air or nitrogen) are released during a vessel rupture, are to be included in the assessment.

f) The meteorological assumptions (see Annex 3.A) used in the dispersion calculations (that form the basis for the Level 1 consequence analysis table lookups) do not represent the site data.

Like Level 1 COF, Level 2 consequence areas do not consider the release of a toxic product during a combustion reaction (e.g. burning chlorinated hydrocarbons producing phosgene; hydrochloric acid producing chlorine gas; amines producing hydrogen cyanide; sulfur producing sulfur dioxide).

3.5 COF Methodology

The COF of releasing a hazardous fluid is determined in 12 steps. A description of these steps and a cross-reference to the associated section of this document for the Level 1 and Level 2 consequence analysis are provided in Table 3.1. A flowchart of the methodology is provided in Figure 3.1.

For both the Level 1 and Level 2 consequence analysis, detailed procedures for each of the 12 steps are provided. For the Level 2 consequence analysis, calculations for several of the steps are identical to the Level 1, and references are made to those sections. The special requirements and a step-by-step procedure for ASTs are provided in Section 6.1 through Section 6.6.

3.6 Safety, Financial and Injury-based COF

The COF results are presented in terms of either area, financial loss, or injuries. Financial-based COF is provided for all components, while area-based COF is provided for all components with the exception of storage tank bottoms, PRDs, and heat exchanger bundles (see Table 3.2).

3.7 Use of Atmospheric Dispersion Modeling

Calculation of the consequence areas associated with several event outcomes (flash fires, VCEs) associated with releases of flammable and toxic fluids require the use of hazards analysis software capable of performing atmospheric dispersion analysis (cloud modeling). Assumptions and additional background for the Level 1 dispersion modeling calculations are provided in Annex 3.A. Additional information on the use of cloud dispersion modeling is provided in Section 5.7.5.

3.8 Tables

Table 3.1—Steps in Consequence Analysis

Step	Description	Section in This Part	
		Level 1 Consequence Analysis	Level 2 Consequence Analysis
1	Determine the released fluid and its properties, including the release phase.	4.1	5.1
2	Select a set of release hole sizes to determine the possible range of consequence in the risk calculation.	4.2	
3	Calculate the theoretical release rate.	4.3	5.3
4	Estimate the total amount of fluid available for release.	4.4	
5	Determine the type of release, continuous or instantaneous, to determine the method used for modeling the dispersion and consequence.	4.5	
6	Estimate the impact of detection and isolation systems on release magnitude.	4.6	
7	Determine the release rate and mass for the consequence analysis.	4.7	5.7
8	Calculate flammable/explosive consequence.	4.8	5.8
9	Calculate toxic consequences.	4.9	5.9
10	Calculate nonflammable, nontoxic consequence.	4.10	5.10
11	Determine the final probability weighted component damage and personnel injury consequence areas.	4.11	5.11
12	Calculate C_f^{fin} ~~FC~~.	4.12	
13	Calculate SC_f^{inj} ~~SC~~.	4.13	

Table 3.2—COF Calculation Type Based on Equipment and Component Type

Equipment/Component Type	Consequence Calculation Type		
	Area Based	**Financial Based**	**Safety Based**
Air cooler	Yes	Yes	Yes
Compressor	Yes	Yes	Yes
Heat exchanger (shell, channel)	Yes	Yes	Yes
Heat exchanger bundle	No	Yes	No
Pipe	Yes	Yes	Yes
PRD	No	Yes	No
Pressure vessel (drum, column filter, reactor)	Yes	Yes	Yes
Pump	Yes	Yes	Yes
Tank course	Yes	Yes	Yes
Tank bottom	No	Yes	No

3.9 Figures

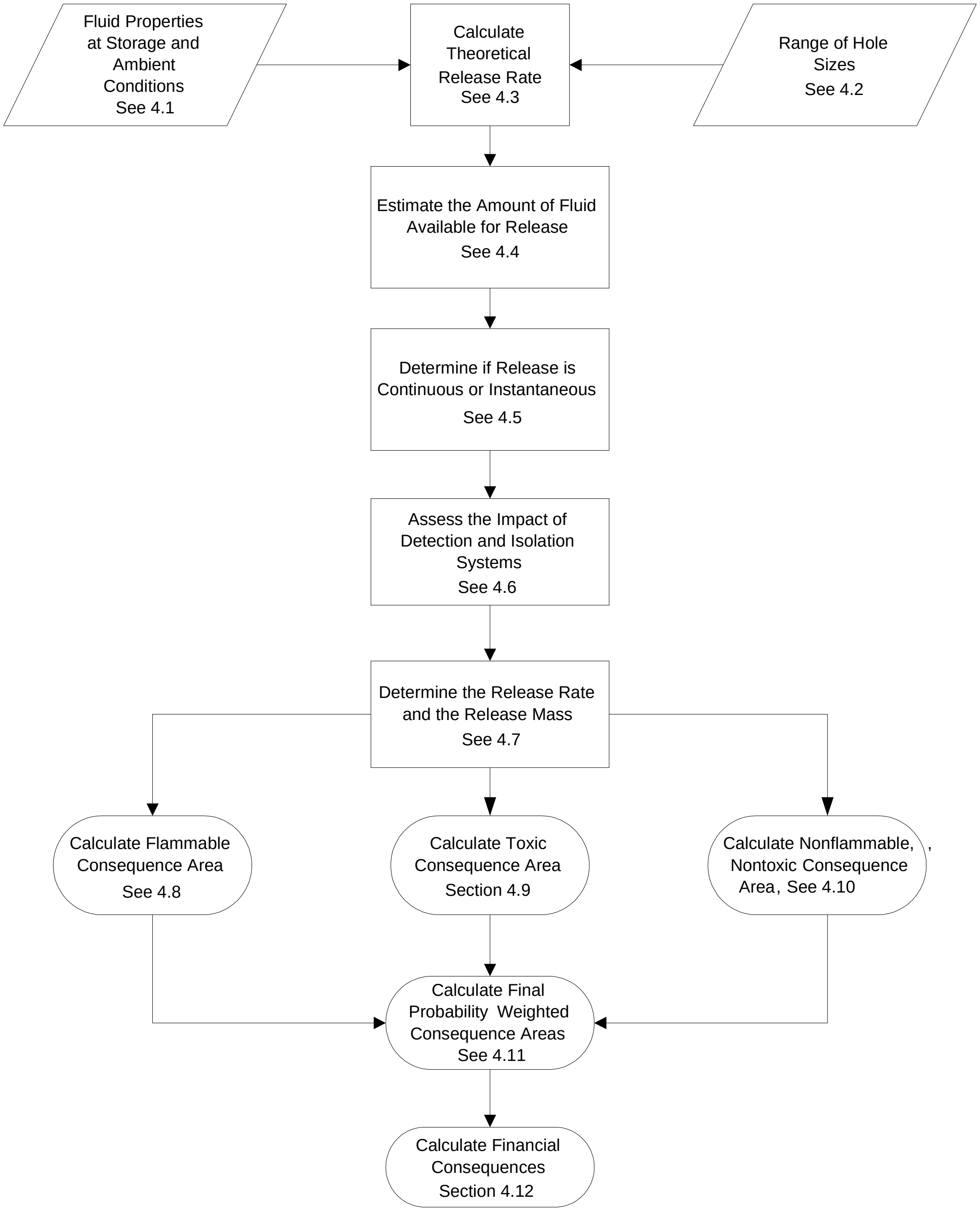


Figure 3.1—Level 1 COF Methodology

a) flammable consequence; see Section 4.8;

b) toxic consequence; see Section 4.9;

c) nonflammable, nontoxic consequence; see Section 4.10.

4.11.2 Final Component Damage Consequence Area

The final component damage consequence area is:

$$CA_{f,cmd} = \max\left[CA_{f,cmd}^{flam},\ CA_{f,cmd}^{tox},\ CA_{f,cmd}^{nfnt}\right] \tag{3.81}$$

Note that since the component damage consequence areas for toxic releases, CA_{cmd}^{tox}, and nonflammable, nontoxic releases, CA_{cmd}^{nfnt}, are both equal to zero, the final component damage consequence area is equal to the consequence area calculated for flammable releases, CA_{cmd}^{flam}.

$$CA_{f,cmd} = CA_{f,cmd}^{flam} \tag{3.82}$$

4.11.3 Final Personnel Injury Consequence Area

The final personnel injury consequence area is:

$$CA_{f,inj} = \max\left[CA_{f,inj}^{flam},\ CA_{f,inj}^{tox},\ CA_{f,inj}^{nfnt}\right] \tag{3.83}$$

4.11.4 Final Consequence Area

The final consequence area is:

$$C_f^{area} = \max\left[CA_{f,cmd},\ CA_{f,inj}\right] \tag{3.84}$$

4.11.5 Calculation of Final Consequence Area

a) STEP 11.1—Calculate the final component damage consequence area, $CA_{f,cmd}$, using Equation (3.82).

b) STEP 11.2—Calculate the final personnel injury consequence area, $CA_{f,inj}$, using Equation (3.83).

c) STEP 11.3—Calculate the final consequence area, C_f^{area}, using Equation (3.84).

4.12 Determine the Financial Consequence

4.12.2 Overview

There are many costs associated with any failure of equipment in a process plant. These include, but are not limited to:

a) cost of equipment repair and replacement;

b) cost of damage to surrounding equipment in affected areas;

c) costs associated with production losses and business interruption as a result of downtime to repair or replace damaged equipment;

d) costs due to potential injuries associated with a failure;

e) environmental cleanup costs.

The approach used is to consider the above costs on both an equipment specific basis and an affected area basis. Thus, any failure (loss of containment) has costs associated with it, even when the release of the hazardous material does not result in damage to other equipment in the unit or serious injury to personnel. Recognizing and using this fact presents a more realistic value of the consequences associated with a failure.

The C_f^{fin} ~~FC~~ of a loss of containment and subsequent release of hazardous materials can be determined by adding up the individual costs discussed above:

$$C_f^{fin} = FC_{f,cmd} + FC_{f,affa} + FC_{f,prod} + FC_{f,inj} + FC_{f,environ} \qquad (3.85)$$

The risk is calculated as the COF (now expressed as cost in dollars) times the POF. For a rigorous and flexible analysis, the consequence (cost) is evaluated at the hole size level. Risk is also evaluated at the release hole size level by using the POF associated with each release hole size. The total risk is calculated as the sum of the risks of each release hole size.

4.12.3 Component Damage Cost

The method chosen for these calculations operates under the presumption that there is a specific cost associated with each possible leak scenario (release hole size) and that these are unique to each component type. This approach was chosen based on the inherent differences in the costs associated with repairing components having small hole damage to that of components having extreme damage as a result of equipment rupture.

A small hole in a piping system can sometimes be repaired with little or no impact on production by use of a temporary clamp until a permanent repair can be scheduled during normal maintenance shutdowns. Larger holes usually do not allow this option, and shutdown plus repair costs are greatly increased.

Example component damage costs, $holecost_n$, for different release hole sizes for each component are shown in Table 4.15. Actual failure cost data for component should be used if available. The sources cited were used to estimate the relative installed costs of the equipment. Since repair or replacement of a component usually does not involve replacement of all supports, foundations, etc., the example repair and replacement costs presented do not reflect actual installed cost.

The example cost estimates shown in Table 4.15 are based on carbon steel prices obtained in 2001. The $holecost_n$ may be multipled by $costfactor$ (user defined) to reflect changed in carbon steel and replacement costs from the 2001 basis and experience. It is suggested that these costs be multiplied by a material cost factor, $matcost$, for other materials. Table 4.16 shows the suggested values for these material cost factors. These factors are based on a variety of sources from manufacturer's data and cost quotations.

The consequence cost to repair or replace the component that has been damaged is a probability weighted average of the individual repair costs determined for each release hole size and is calculated using Equation (3.86). The probability weighting utilizes the generic frequencies of the release hole sizes provided in Part 2, Table 3.1.

$$FC_{f,cmd} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot holecost_n}{gff_{total}} \right) \cdot matcost \cdot costfactor \tag{3.86}$$

4.12.4 Damage Costs to Surrounding Equipment in Affected Area

It is necessary to calculate the component damage costs to other equipment components in the vicinity of the failure, if the failure results in a flammable (or explosive) event. Toxic releases do not result in damage to surrounding equipment. Typically, a constant value of the process unit replacement cost, $equipcost$, is used. In other words, as a starting point, the average cost of other equipment components surrounding any given component is about the same regardless of location within the process unit. This could be refined for individual components by allowing the default value to be overridden with a higher or lower value where appropriate.

The consequence cost to repair or replace surrounding components that have become damaged in the affected area is calculated using the component damage area, CA_{cmd}, calculated in STEP 8.15 using Equation (3.57) in Equation (3.87).

$$FC_{f,affa} = CA_{f,cmd} \cdot equipcost \tag{3.87}$$

4.12.5 Business Interruption Costs

The costs associated with business interruption are determined based on the amount of downtime (and lost production) associated with repairing the damage to the specific piece of equipment that has had loss of containment (due to holes or rupture) as well as the downtime associated with repairing the surrounding equipment in the area of the plant affected by the release (consequence area).

a) For each release hole size, an estimated downtime for each equipment type, $Outage_n$ is presented in Table 4.17. Centrifugal pumps are assumed to have on-line spares, so the assumption is made that there is no downtime associated with the failure of these equipment types. The probability weighting of the downtime required to repair damage for a specific equipment item is given by Equation (3.88). The probability weighting uses the generic frequencies of the release hole sizes provided in Table 3.1 of Part 2.

$$Outage_{cmd} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot Outage_n}{gff_{total}} \right) \cdot Outage_{mult} \tag{3.88}$$

NOTE Downtimes presented in Table 4.17 are the minimum time required to repair equipment damage in the event of a loss of containment. When a loss of containment occurs, such as a nonflammable/nontoxic event, a financial impact results based on the cost to perform a leak repair. If actual downtimes are significantly higher than the time in Table 4.17, the outage multiplier, $Outage_{mult}$, may be used to reflect the increase.

b) If a component has a failure (loss of containment through hole or rupture) resulting in an affected area (consequence area), the cost of downtime for replacement and repair of surrounding equipment in the affected area must be considered. For more details regarding the calculation of surrounding equipment downtime, refer to Dow's Fire and Explosion Index [33]. The downtime associated with repairing the surrounding equipment in the affected area is calculated using Equation (3.89).

$$Outage_{affa} = 10^{1.242+0.585\cdot\log_{10}\left[FC_{affa}\cdot(10)^{-6}\right]} \tag{3.89}$$

c) The cost of the business interruption associated with repairing damaged equipment is equal to the cost associated with lost production due to the shutdown of the facility.

$$FC_{f,prod} = \left(Outage_{cmd} + Outage_{affa}\right)\left(prodcost\right) \tag{3.90}$$

4.12.6 Potential Injury Costs

Another cost to consider when a failure occurs is the potential injury costs. When a business takes injury costs into account in a risk management scheme, then appropriate resources can be spent to prevent these injuries from happening. Just as failure to consider the business cost of a zero affected area event can lead to under-ranking this event with respect to risk, a risk could be present that is not considered in allocating inspection resources if injury costs are not considered.

In the Level 1 consequence analysis, a constant population density, $popdens$, is used as a default for all equipment in the unit (see Section 4.13.3). This default value can be overridden by higher or lower values depending on specific equipment location with respect to controls rooms, walkways, roads, etc. In addition to the population density, the cost per individual, $injcost$, affected must be determined. This value must be sufficiently high to adequately represent typical costs to businesses of an injury up to and including fatal injuries. When assigning this value, consideration should be given to the following:

a) any existing company standards for such calculations,

b) local medical/compensation costs associated with long-term disability,

c) legal/settlement costs, and

d) indirect costs such as increased regulatory scrutiny, loss of reputation, etc.

The costs associated with personnel injury are calculated using Equation (3.91):

$$FC_{inj} = CA_{inj} \cdot popdens \cdot injcost$$

$$FC_{f,prod} = CA_{f,inj} \cdot popdens \cdot injcost \tag{3.91}$$

4.12.7 Environmental Cleanup Costs

Environmental consequence as a result of loss of containment can be significant and should be added to the other costs including fines and other financial penalties. The methods presented here are based on the amount of material spilled to the ground, the number of days to clean up the spill, and the environmental hazards associated with the properties of the fluid released.

The cost of cleanup depends on where the release is likely to be spilled. For example, spills into waterways will be much more costly than spills above ground. In addition, spills that work their way below ground will be more costly than spills above ground. The environmental cost, $envcost$, in \$/bbl, must be provided as an estimate by the analyst.

Fluids that are released as a liquid per Section 4.1.6 are considered to have the potential for environmental costs. Additionally, it is assumed that any liquid with a NBP less than 93 °C (200 °F) will readily evaporate and thus the environmental costs will be negligible. If the release is likely to autoignite, the environmental costs should not be included since the release will probably ignite and burn.

The fraction of the release fluid for remediation is a function of the evaporation rate. Estimates of release fluid evaporation fraction, $frac_{evap}$, as a function of the NBP is provided in Table 4.18. As an alternative, the following equation can be used to estimate $frac_{evap}$:

$$frac_{evap} = \left[\begin{array}{l} -7.1408 + 8.5827(10)^{-3} \cdot ((C_{12} \cdot NBP) + C_{41}) \\ -3.5594(10)^{-6} \cdot \left(\left(C_{12} \cdot NBP \right) + C_{41} \right)^2 \\ + \dfrac{2331.1}{(C_{12} \cdot NBP) + C_{41}} - \dfrac{203545}{\left(\left(C_{12} \cdot NBP \right) + C_{41} \right)^2} \end{array} \right] \tag{3.92}$$

where C_{41} is a conversion factor that is equal to 0 when using the NBP in Fahrenheit (U.S. customary units) and equal to 32 when using Celsius (SI units).

The spill volume of fluid that requires cleanup is calculated using Equation (3.93) for each release hole size using the fluid liquid density, ρ_l (see Table 4.2), and the fraction of release that does not evaporate.

$$vol_n^{env} = \frac{C_{13} \cdot mass_n \left(1 - frac_{evap} \right)}{\rho_l} \tag{3.93}$$

The final spill volume to be cleaned up is a probability weighted average of the spill volumes for each of the release hole sizes. The probability weighting utilizes the generic frequencies of the release hole sizes provided in Part 2, Table 3.1. The environmental cost to clean up the weighted spill volume is calculated using Equation (3.94).

$$FC_{f,environ} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot vol_n^{env}}{gff_{total}} \right) \cdot envcost \tag{3.94}$$

4.12.8 Calculation of FC

a) STEP 12.1—Calculate the cost (consequence in \$) to repair the specific piece of equipment, $FC_{f,cmd}$, using Equation (3.86) with the release hole size damage costs from Table 4.15 and GFFs for the release hole sizes from STEP 2.2. The material cost factor, $matcost$, is obtained from Table 4.16.

b) STEP 12.2—Calculate the cost of damage to surrounding equipment in the affected area, $FC_{f,affa}$, using Equation (3.87) and component damage consequence area, $CA_{f,cmd}$, calculated in STEP 11.1. The equipment cost factor, $equipcost$, is the unit equipment replacement cost in \$/m² (\$/ft²).

c) STEP 12.3—For each release hole size, calculate the cost of business interruption due to the outage days required to repair the damage to equipment.

   1) Calculate the probability weighted repair of the specific piece of equipment using Equation (3.88) and the downtime for each release hole size, $Outage_n$, from Table 4.17.

2) Calculate the downtime required to repair the surrounding equipment in the affected area, $Outage_{affa}$, using Equation (3.89) and the cost of damage to the surrounding equipment in the affected area, $FC_{f,affa}$, calculated in STEP 12.2.

3) Calculate the cost of business interruption, $FC_{f,prod}$, using Equation (3.90). The production costs, $prodcost$, is the cost of lost production on the unit, $/day.

d) STEP 12.4—Calculate the costs associated with personnel injury using Equation (3.91) and the personnel injury consequence area, $CA_{f,inj}$, calculated in STEP 11.2. The unit population density, $popdens$, is the average number of personnel on the unit per m^2 (personnel/ft^2). The personnel injury cost, $injcost$, is the cost incurred by the company as a result serious injury or fatality of personnel.

e) STEP 12.5—Calculate the costs associated with environmental cleanup.

1) Estimate the spill volume from each release hole size, using Equation (3.93), the release mass from STEP 7.3, and the fluid liquid density and evaporation fraction obtained from Table 4.18.

2) Calculate the probability weighted environmental cleanup costs, $FC_{f,environ}$, using Equation (3.94) and the spill volume calculated for each release hole size, vol_n^{env}. The environmental costs, $envcost$, are the environmental cleanup costs, $/bbl.

f) STEP 12.6—Calculate the total C_f^{fin} ~~FC~~ using Equation (3.85), which is the sum of the costs determined in STEPs 12.1 through 12.5.

4.13 Determine Safety Consequence

The final Safety Consequence (~~SC~~ C_f^{inj}) is defined as the product of final personnel injury consequence area, $CA_{f,inj}$, and population density, $popdens$, of the area representing the number of injuries that may occur, as shown in Equation (3.95). The consequence of an event occurring results in a higher risk in a unit with a larger number of personnel than the same event in a unit with a smaller number of personnel present.

$$C_f^{inj} = CA_{f,inj} \cdot popdens \tag{3.95}$$

The $popdens$ of an unit is typically based on the average population density of the process unit, but may be defined as a part of a unit, as preferred by the owner user. The $popdens$ should consider the area of the unit and the typical number of personnel present during each shift and day of the week, including consideration for routine operation and high maintenance or project activity. The $popdens$ is calculated using Equation (3.99).

Determination of the $CA_{f,inj}$ is described in Section 4.11.3 and calculated using Equation (3.83). Flammable Injury COF is calculated using Part 3, Section 4.8.8, Step 8.15, Toxic Injury Area from Part 3, Section 4.9.15, Step 9.6. and NFNT Injury Area from Part 3, Section 4.10.

4.13.2 Determination of Population Density

The average personnel, $Pers_{avg}$, is the average number of personnel present in a unit at any given time. The $Pers_{avg}$ present should consider full time personnel or operators over the 24 hour day for 365 days of a year, plus the additional people are present for a fraction of time, calculated using Equation (3.96).

$$Pers\#_{avg} = 1.0 \cdot \left(Pers\#_n + Present\%_n\right) \cdot \left(Pers\#_{n+1} + Present\%_{n+1}\right) \cdot \left(Pers\#_{n+2} + Present\%_{n+2}\right) .... \tag{3.96}$$

Where $Pers\#_n$ and $Present\%_n$ are the personnel population and percent of time personnel are present, respectively, for each unit staffing activity.

The $popdens$ is calculated using Equation (3.97).

$$popdens = \frac{Pers\#_{avg}}{Area_n^{safety}} \tag{3.97}$$

4.13.3 Calculation of SC

a) Step 13.1 – Calculate the $CA_{f,inj}$ using Equation (3.83).

b) Step 13.2 – Calculate the average personnel, $Pers\#_{avg}$, present in the unit using Equation (3.96).

c) Step 13.3 – Calculate the area the unit covers, $Area_n^{safety}$. The $Area_n^{safety}$ should be defined within the unit boundaries and may include additional areas beyond the unit boundaries that may be impacted. Considering the area within the unit boundaries is acceptable when impacted areas beyond the unit boundaries are sparsely populated. In addition, units in close promimity to heavily populated areas may consider a larger $Area_n^{safety}$.

d) Step 13.4 - Calculate the unit population density, $popdens$, using average population present, $Pers\#_{avg}$, and the $Area_n^{safety}$ using Equation (3.97).

e) Step 13.5 – Calculate the C_f^{inj} using the $CA_{f,inj}$ and $popdens$ using Equation (3.95).

4.14 Nomenclature

The following lists the nomenclature used in Section 4. The coefficients C_1 through C_{41} , which provide the metric and U.S. conversion factors for the equations, are provided in Annex 3.B.

a	is a constant provided for reference fluids for Level 1 consequence analysis
$a_{cmd}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$a_{inj}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area

$a_{cmd}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$a_{inj}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$a_{cmd}^{AINL-CONT}$	is a constant for AINL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$a_{inj}^{AINL-CONT}$	is a constant for AINL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$a_{cmd}^{AINL-INST}$	is a constant for AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$a_{inj}^{AINL-INST}$	is a constant for AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
AIT	is the autoignition temperature of the released fluid, K (°R)
A_n	is the hole area associated with the n^{th} release hole size, mm^2 (in.^{2})
$Area_n^{safety}$	is the area being evaluated for a safety consequence, typically a process unit, m^2 (ft^2)
b	is a variable provided for reference fluids for Level 1 consequence analysis for analysis
$b_{cmd}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AINL-CONT}$	is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AINL-CONT}$	is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AINL-INST}$	is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area

$b_{inj}^{AINL-INST}$	is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
c	is a gas release constant used in HF and H_2S releases for the COF 1 toxic area analysis
C_d	is the release hole coefficient of discharge, unitless
C_p	is the specific heat of the released fluid, J/kg-K (Btu/lb-°R)
C_f	is the final consequence area, m^2 (ft^2)
C_f^{area}	is the safety consequence impact area, m^2 (ft^2)
C_f^{fin}	is the financial consequence, $
C_f^{inj}	is the injury consequence, injuries
$CA_{inj,n}^{acid}$	is the personnel injury consequence area for caustic and acid leaks, associated with the n^{th} release hole size, m^2 (ft^2)
CA^{AIL}	is the flammable consequence area where autoignition is likely to occur, m^2 (ft^2)
$CA_{cmd,n}^{AIL}$	is the continuous/instantaneous blended component damage flammable consequence area that is likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{cmd,n}^{AIL-CONT}$	is the component damage flammable consequence area for continuous releases that is likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{inj,n}^{AIL-CONT}$	is the personnel injury flammable consequence area for continuous releases that is likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{cmd,n}^{AIL-INST}$	is the component damage flammable consequence area for instantaneous releases that is likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{inj,n}^{AIL-INST}$	is the personnel injury flammable consequence area for instantaneous releases that is likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
CA^{AINL}	is the flammable consequence area where autoignition is not likely to occur, m^2 (ft^2)
$CA_{cmd,n}^{AINL}$	is the continuous/instantaneous blended component damage flammable consequence area that is not likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{cmd,n}^{AINL-CONT}$	is the component damage flammable consequence area for continuous releases that is not likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)

$CA_{inj,n}^{AINL-CONT}$	is the personnel injury flammable consequence area for continuous releases that is not likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{cmd,n}^{AINL-INST}$	is the component damage flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{inj,n}^{AINL-INST}$	is the personnel injury flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the n^{th} release hole size, m^2 (ft^2)
$CA^{AIT-blend}$	is the AIT blended flammable consequence area, m^2 (ft^2)
$CA_{f,cmd}$	is the final component damage consequence area, m^2 (ft^2)
$CA_{inj,n}^{CONT}$	is the personnel injury consequence area for continuous releases, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{f,n}^{CONT}$	is the consequence area for a continuous release, m^2 (ft^2)
$CA_{f,cmd}^{flam}$	is the final probability weighted component damage flammable consequence area, m^2 (ft^2)
$CA_{cmd,n}^{flam}$	is the blended component damage flammable consequence area, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{f,inj}^{flam}$	is the final probability weighted personnel injury flammable consequence area, m^2 (ft^2)
$CA_{f,inj,n}^{flam}$	is the blended personnel injury flammable consequence area, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{n}^{IC-blend}$	is the continuous/instantaneous blended flammable consequence area, m^2 (ft^2)
$CA_{f,inj}$	is the final personnel injury consequence area, m^2 (ft^2)
$CA_{inj,n}^{INST}$	is the personnel injury consequence area for instantaneous releases, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{f,n}^{INST}$	is the consequence area for an instantaneous release, m^2 (ft^2)
$CA_{inj,n}^{leak}$	is the personnel injury nonflammable, nontoxic consequence area for steam or acid leaks, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{f,max}$	is the final maximum consequence area, m^2 (ft^2)
$CA_{f,cmd}^{nfnt}$	is the component damage nonflammable, nontoxic consequence area, m^2 (ft^2)

$CA_{f,inj}^{nfnt}$	is the final probability weighted personnel injury consequence area for nonflammable, nontoxic releases such as steam or acids, m^2 (ft^2)
$CA_{inj,n}^{nfnt}$	is the personnel injury nonflammable, nontoxic consequence area, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{inj,n}^{stm}$	is the personnel injury consequence area for steam leaks, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{f,cmd}^{tox}$	is the final probability weighted component damage toxic consequence area, m^2 (ft^2)
$CA_{f,inj}^{tox}$	is the final probability weighted personnel injury toxic consequence area, m^2 (ft^2)
$CA_{inj,n}^{tox-CONT}$	is the personnel injury toxic consequence area for a continuous release, associated with the n^{th} release hole size, m^2 (ft^2)
$CA_{inj,n}^{tox\_INST}$	is the personnel injury toxic consequence area for an instantaneous release, associated with the n^{th} release hole size, m^2 (ft^2)
$costfactor$	is the cost factor reflecting the change in carbon steel and replacement costs from the 2001
d	Is a gas release constant used in HF and H_2S releases for the Level 1 toxic consequence area analysis
d_n	is the diameter of the n^{th} release hole size, mm (in.)
e	Is a gas release constant used in NH_3 and Cl releases for the Level 1 toxic consequence area analysis
$eneff_n$	is the energy efficiency correction factor for instantaneous events exceeding a release mass of 4,536 kg (10,000 lb)
$envcost$	is the environmental cleanup costs, \$/bbl
$equipcost$	is the process unit replacement costs for component, \$/m^2 (\$/ft^2)
f	is a gas release constant used in NH_3 and Cl releases for the Level 1 toxic consequence area analysis
$fact^{AIT}$	is the AIT consequence area blending factor
$fact_{di}$	is the release magnitude adjustment factor, based on the detection and isolations systems present in the unit.
$fact_n^{IC}$	is the continuous/instantaneous consequence area blending factor determined for each release hole size, associated with the n^{th} release hole size

$fact_{mit}$	is the consequence area adjustment factor, based on the mitigation systems present in the unit.
$frac_{evap}$	is the fraction of the released liquid pool that evaporates, needed to estimate the volume of material for environmental cleanup
FC	is the final financial consequence, $
FC_{affa}	is the financial consequence of damage to surrounding equipment on the unit, $
FC_{cmd}	is the financial consequence of component damage, $
$FC_{environ}$	is the financial consequence of environmental cleanup, $
FC_{inj}	is the financial consequence as a result of serious injury to personnel, $
FC_{prod}	is the financial consequence of lost production on the unit, $
g	Is a gas release constant used in acid and caustic releases for the Level 1 area consequence analysis
g_c	is the gravitational constant $=1.0\left(kg-m\right)\big/\left(N-s^2\right)\left[32.2\left(lb_m-ft\right)\big/\left(lb_f-s^2\right)\right]$
gff_n	are the generic failure frequencies for each of the n release hole sizes selected for the type of equipment being evaluated
gff_{total}	is the sum of the individual release hole size generic frequencies
h	is a gas release constant for acid and caustic for the Level 1 area consequence analysis
$holecost_n$	is the equipment repair cost, provided for each of the release hole sizes selected, $
$injcost$	is the cost associated with serious injury or fatality of personnel, $
k	is the release fluid ideal gas specific heat capacity ratio, unitless
$K_{v,n}$	is the liquid flow viscosity correction factor, associated with the n^{th} release hole size, unitless
$ld_{max,n}$	is the maximum leak duration based on isolation and detection systems associated with the n^{th} release hole size, minutes
ld_n	is the actual leak duration of the flammable release based on the available mass and the calculated release rate, associated with the n^{th} release hole size, seconds
ld_n^{tox}	is the leak duration of the toxic release based on the available mass and the calculated release rate, associated with the n^{th} release hole size, seconds

$mass_{add,n}$	is the mass contributed by the surrounding equipment in the inventory group (limited by $W_{\max 8}$), associated 3 minutes release of the nth release hole size, kg (lb)
$mass_n^{AIL-INST}$	is the adjusted or mitigated discharge mass used in the AIL instantaneous consequence calculation associated with the nth release hole size, kg (lb)
$mass_n^{AINL-INST}$	is the adjusted or mitigated discharge mass used in the AINL instantaneous consequence calculation associated with the nth release hole size, kg (lb)
$mass_{avail,n}$	is the available mass for release of each of the release hole sizes, $mass_{add,n}$, and is the sum of the component release mass, $mass_{comp}$, and 3 minutes release, through the associated with the nth release hole size, kg (lb)
$mass_{comp}$	is the component mass for the component or piece of equipment being evaluated, kg (lb)
$mass_{comp,i}$	is the component mass for each of the i components or pieces or equipment that is included in the inventory group, kg (lb)
$mass_{inv}$	is the inventory group mass, kg (lb)
$mass_n$	is the adjusted gas or liquid release rate for detection and isolation systems associated with the nth release hole size, kg (lb)
$mass_n^{tox}$	is the release mass of toxic component used in the toxic consequence calculation associated with the nth release hole size, kg (lb)
$matcost$	is the material cost factor
$mfrac^{tox}$	is the mass fraction of toxic material in the released fluid mixture
MW	is the release fluid molecular weight, kg/kg-mol (lb/lb-mol)
NBP	is the normal boiling point, °C (°F)
$Outage_{affa}$	is the numbers of days of downtime required to repair damage to the surrounding equipment, days
$Outage_{cmd}$	is the probability weighted (on release hole size) numbers of days of downtime required to repair the specific piece of equipment that is being evaluated, days
$Outage_{mult}$	is the equipment outage multiplier that can be used to increase the default outage days for an equipment item, unitless
$Outage_n$	is the number of downtime days to repair damage associated with the nth release hole size, days
$Pers\#_{avg}$	is the average number of people in a defined area at any given time

$Pers\#_n$	is the number of personnel present in a defined area for each unit staffing activity
$Present\%_n$	is the percent of time personnel are present in the defined area for each unit staffing activity, typically developed by reviewing population for a year
$popdens$	is the population density of personnel or employees in the unit, personnel/m^2 (personnel/ft^2)
P_{atm}	is the atmospheric pressure, kPa (psia)
P_s	is the storage or normal operating pressure, kPa (psia)
P_{trans}	is the transition back pressure, kPa (psia). Higher back pressures will result in subsonic vapor flow through the release hole, lower back pressures will cause choked or sonic flow across the release hole
$prodcost$	is the cost of lost production due to downtime to repair equipment, $/day
R	is the universal gas constant = 8.314 J/(kg-mol-K) [1545 ft-lb$_f$/(lb-mol-°R)]
Re_n	is the Reynolds Number for flow through the release, associated with the *n*th release hole size, unitless
$rate_n$	is the adjusted release rate for detection and isolation systems associated with the *n*th release hole size, kg/s (lb/s)
$rate_n^{AIL-CONT}$	is the adjusted or mitigated discharge rate used in the AIL continuous consequence calculation associated with the *n*th release hole size, kg/s (lb/s)
$rate_n^{AINL-CONT}$	is the adjusted or mitigated discharge rate used in the AINL continuous consequence calculation associated with the *n*th release hole size, kg/s (lb/s)
$rate_n^{tox}$	is the release mass rate of toxic component used in the consequence calculation, associated with the *n*th release hole size, kg/s (lb/s)
SC_f	is the safety consequence which is the number of personnel injuries resulting from a release with the potential to cause injuries within a calculated area based on the average number of people in the area at any given time, injuries
t_n	is the time to release 10,000 lb of fluid mass, calculated for each of the *n* release hole sizes selected, seconds
T_s	is the storage or normal operating temperature, K (°R)
vol_n^{env}	is the spill volume to be cleaned up, used to determine environmental cleanup costs, calculated for each of the *n* release hole sizes selected, barrels

$W_{\max 8}$	is the maximum flow rate of additional mass that can be added to the release as contributed from the surrounding equipment in the inventory group, kg/s (lb/s)
W_n	is the gas or liquid release rate associated with the n^{th} release hole size, kg/s (lb/s)
x_i	is the mole fraction of the component and $Property_i$ may be the NBP, MW, or density of the individual components in the fluid mixture
ρ	is the density, kg/m^3 (lb/ft^3)
ρ_{atm}	is the atmospheric air density, kg/m^3 (lb/ft^3)
ρ_l	is the liquid density at storage or normal operating conditions, kg/m^3 (lb/ft^3)
ρ_v	is the vapor density, kg/m^3 (lb/ft^3)

1. Safety Risk Worked Example

1.1 Operating Conditions:

Drum

Area	Area 1 Frac Plant Main Area
COF Area Drum~~Section 7~~	
$CA_{f,inj}^{flam}$	8,866.86 ft^2
$CA_{f,inj}^{tox}$	6,726.43 ft^2
$CA_{f,inj}^{nfnt}$	0.0 ft^2
POF Drum~~Section 6~~	
$DF_{f,total}$	107.596
$P_f(t)$	3.29E^{-03}

1.2 Calculate ~~SC~~ C_f^{inj}

a. Calculate the $CA_{f,inj}$

$$CA_{f,inj} = max\left[CA_{f,inj}^{flam},\ \ CA_{f,inj}^{tox},\ \ CA_{f,inj}^{nfnt}\right]$$
$$CA_{f,inj} = max\left[8866.68, 6726.43, 0\right]$$
$$CA_{f,inj} = 8,866.68\, ft^2$$

b. Calculate the average personnel, $Pers_{avg}$, present in the unit using the personnel staffing in the Table below

Unit Staffing	$Pers\#_n$	**Hours per Week**	**Weeks per Year**	$Present\%_n$	**Total**
Base Load Operators 24/7	10	168	52	~~1.0~~100	10.0
Additional Day Staff	7	50	52	~~0.46~~29.7	~~1.79~~2.08
Routine Maintenance	8	40	46	~~0.39~~21.1	1.68
Annual Program/Project Work	50	60	6	~~0.30~~4.1	2.06
Personnel Average, $Pers_{avg}$					**15.~~53~~82**

$$Pers\#_{avg} = 1.0\cdot\left(Pers\#_n + Present\%_n\right)\cdot\left(Pers\#_{n+1} + Present\%_{n+1}\right)\cdot\left(Pers\#_{n+2} + Present\%_{n+2}\right)\cdot\left(Pers\#_{n+3} + Present\%_{n+3}\right)$$
$$Pers\#_{avg} = 1.0\cdot\left(10+1.0\right)\cdot\left(7+0.297\right)\cdot\left(8+0.211\right)\cdot\left(50+0.041\right)$$
$$Pers\#_{avg} = 15.82\, personnel$$

c. Calculate the area the unit covers, $Area_n^{safety}$

$$Area_n^{safety} = 1,344,390.83\, ft^2$$

Area No., $Area_n$	Density Area Name	$Area_n^{safety}$ (ft²)
Area 1	**Frac Plant Main Area**	1,344,391
~~Area 1~~	~~Around Flares & KO Drums~~	~~1,344,391~~
~~Area 1~~	~~LPG Bullets~~	~~1,344,391~~
Area 3, 4	**Refrigeration Storage & Tanks**	2,420,782
Area 9, 12	**Jetty**	542,501
	Jetty End	13,455
Area 7	**Fire Water**	125,938
Area 8	**Water Treatment**	491,157
Area 5	**Ballast Water**	1,004,768

d. Calculate the unit population density, $popdens$, using average population present, $Pers\#_{avg}$, and the $Area_n^{safety}$

$$popdens = \frac{Pers\#_{avg}}{Area_n^{safety}}$$

$$popdens = \frac{15.82}{1,344,390.83}$$

$$popdens = 1.17E^{-05}\, personnel / ft^2$$

e. Calculate the C_f^{inj} $(injuries)$ using the $CA_{f,inj}$ $\left(ft^2\right)$ and $popdens$ $\left(\frac{people}{ft^2}\right)$

$$C_{f,inj} = CA_{f,inj} \cdot popdens$$

$$C_{f,inj} = 8,866.86 \cdot 1.17E^{-05}$$

$$C_{f,inj} = 0.104\ injuries$$

f. Calculate the $R(t)$ using the C_f^{inj} ~~SC_f~~ and $P_f(t)$ using Part 1, Section 4.3.1

$$R(t) = P_f(t) \cdot C_f^{inj}$$

$$R(t) = 3.29E^{-03} \cdot 0104$$

$$R(t) = 3.42E^{-04} injuries / year$$