Part 3—Consequence of Failure Methodology

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Risk-based Inspection Methodology
Part 3—Consequence of Failure Methodology

1 Scope

The calculation of the consequence of a leak or rupture of a component is covered in this document. This document is Part 3 of a five-part volume set presenting the API 581 RBI methodology. The consequence calculated is not intended to be used in a rigorous consequence analysis of a component, such as might be employed during unit design, equipment siting, and for other safety purposes. However, the methods provided are consistent with these approaches.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Standard 520, *Sizing, Selection, and Installation of Pressure–relieving Devices, Part 1—Sizing and Selection*

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 1—Introduction to Risk-Based Inspection Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 4—Inspection Planning Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 5—Special Equipment*

3 General

3.1 Overview

The COF methodology is performed to aid in establishing a ranking of equipment items on the basis of risk. The consequence measures presented in this part are intended to be used for establishing priorities for inspection programs. Methodologies for two levels of analysis are provided. A Level 1 COF methodology is detailed in Section 4 for a defined list of hazardous fluids. The Level 2 COF methodology is provided in Section 5 and is intended as a more rigorous approach that can be applied to a wider range of hazardous fluids. A storage tank COF methodology is provided in Part 5, Section 4.

3.2 Consequence Categories

The major consequence categories are analyzed using different techniques, as follows.

a) Flammable and explosive consequence is calculated using event trees to determine the probabilities of various outcomes (e.g. pool fires, flash fires, VCEs) to determine the magnitude of the consequence. Consequence areas can be determined based on serious personnel injuries and component damage from thermal radiation and explosions. Financial losses are determined based on the area affected by the release.

b) Toxic consequence is calculated to determine the magnitude of the consequence area as a result of overexposure of personnel to toxic concentrations within a vapor cloud. Where fluids are flammable and toxic, the toxic event probability assumes that if the release is ignited, the toxic consequence is negligible (i.e. toxics are consumed in the fire). Financial losses are determined based on the area affected by the release.

c) Nonflammable/nontoxic release consequences from chemical splashes and high-temperature steam burns are determined based on serious injuries to personnel. Physical explosions and BLEVEs can also cause serious personnel injuries and component damage.

d) Financial consequence 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 are 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 with the results incorporated into lookup tables. The following assumptions are made in the Level 1 consequence analysis.

a) The release fluid phase is a liquid or a gas, depending on the storage phase and the expected phase after release to the atmosphere. In general, cooling effects of flashing liquid, rainout, jet liquid entrainment, or two-phase releases are not considered.

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

c) Probability of ignition as well as the probability of other release events (VCE, pool fire, jet fire, etc.) were predetermined for each of the representative fluids as a function of temperature, fluid AIT, and release type. These probabilities are constants and independent of the release rate.

d) BLEVEs were not included in the Level 1 assessment.

e) Pressurized nonflammable explosions during a vessel rupture, such as nonflammable pressurized air or nitrogen, were not included in the Level 1 assessment.

f) Meteorological conditions were assumed in the dispersion calculations (see Annex 3.A).

g) Toxic products produced during a combustion reaction (e.g. burning chlorinated hydrocarbons producing phosgene, HCl producing chlorine gas, amines producing hydrogen cyanide, sulfur producing sulfur dioxide) were not considered in the Level 1 assessment.

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 may be 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 need 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, need 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) do not represent the site data.

Level 2 consequence areas do not consider the release of a toxic product during a combustion reaction (e.g. burning chlorinated hydrocarbons producing phosgene, HCl 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 flow chart of the methodology is provided in Figure 3.1.

Detailed procedures for each of the 12 steps are provided for both the Level 1 and Level 2 consequence analysis. Level 2 consequence analysis calculations for several of the 12 steps are identical to the Level 1 and references are made to those sections, where appropriate. The requirements and a step-by-step procedure for storage tanks are provided in Part 5, Section 4.

3.6 Safety-, Financial-, and Injury-based COF

COF results are presented in terms of either safety, financial loss, or injuries. Financial-based COF is provided for all components. 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 Level 2 COF 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}.	4.12	
13	Calculate C_f^{inj}.	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

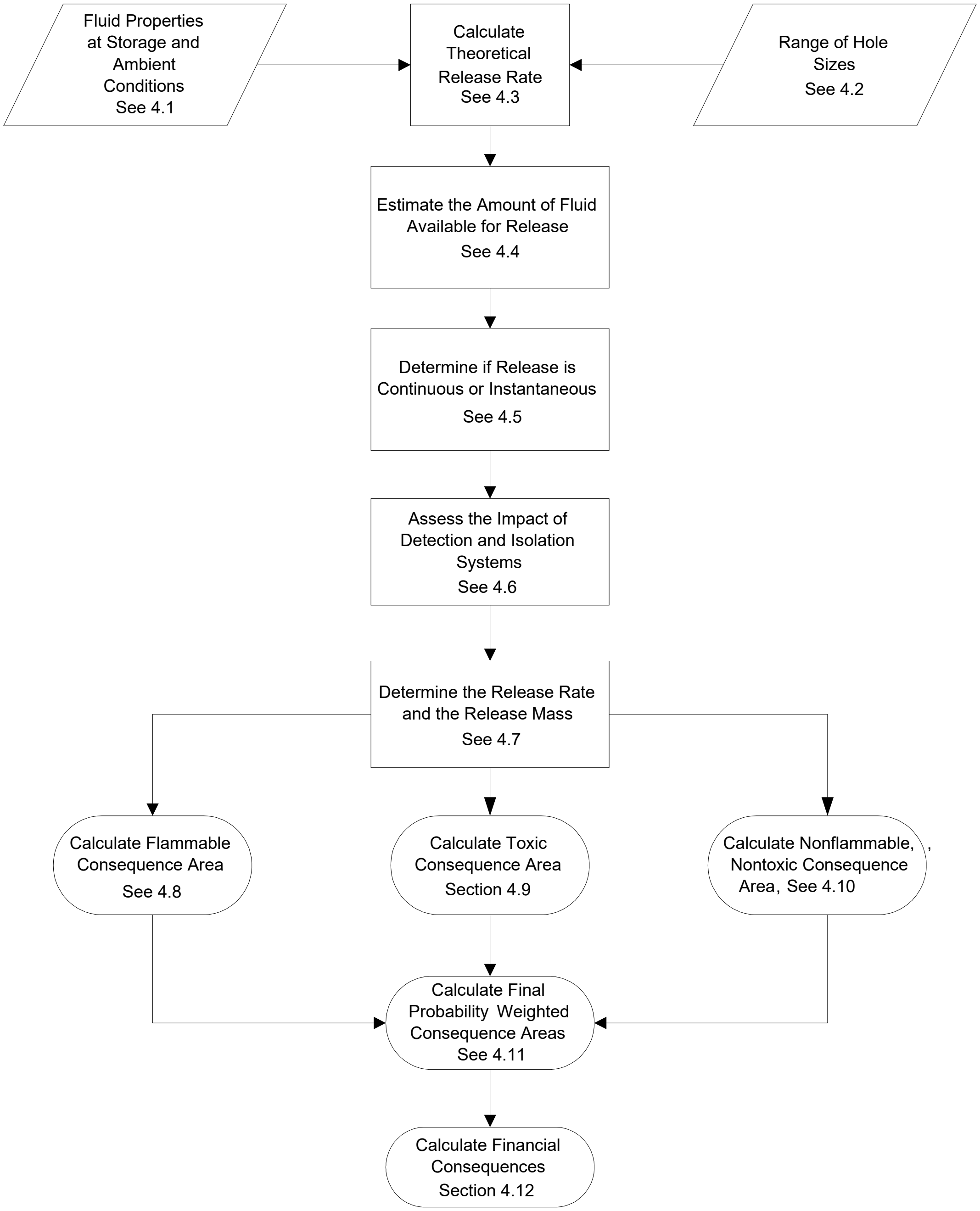


Figure 3.1—Level 1 COF Methodology

4 COF—Level 1

4.1 Determine the Representative Fluid and Associated Properties

4.1.1 Representative Fluids

In the Level 1 consequence analysis, a representative fluid that most closely matches the fluid contained in the pressurized system being evaluated is selected from the representative fluids shown in Table 4.1. Because very few refinery and chemical plant streams are pure materials, the selection of a representative fluid almost always involves making some assumptions. Annex 3.A provides guidance on selecting a representative fluid when an obvious match in Table 4.1 cannot be found or when the fluid is a mixture with or without toxic components.

4.1.2 Fluid Properties

The required fluid properties estimated for each of the representative fluids as provided in Table 4.2 are dependent on the stored phase of the fluid below.

a) Stored liquid:

   1) NBP,

   2) density, ρ_l; and

   3) AIT.

b) Stored vapor or gas:

   1) NBP;

   2) MW;

   3) ideal gas specific heat capacity ratio, k;

   4) constant pressure specific heat, C_p; and

   5) AIT.

The properties of fluids (or individual components of mixtures) typically can be found in standard chemical reference books. The NBP is used in determining the phase of the fluid when released to the atmosphere. The MW or density is used to determine the release rate of a liquid or gas, respectively.

4.1.3 Choice of Representative Fluids for Acids and Caustic Fluids

The appropriate choice of reference fluid for acids and caustics is acid/caustic. Acid/caustic should be used when the release fluid is nonflammable and nontoxic but presents a personnel hazard when contacted during the release. Acid/caustic is modeled as a liquid spray; see Section 4.10.3.

4.1.4 Estimation of Ideal Gas Specific Heat Capacity Ratio

If the value of the ideal gas specific heat capacity ratio is unknown, an estimate can be made provided a value of the constant pressure specific heat capacity, C_p, is available, using Equation (3.1).

$$k = \frac{C_p}{C_p - R} \tag{3.1}$$

The constant specific heat capacity, C_p, may be calculated using equations provided in Table 4.2.

4.1.5 Flammable Fluid Types

The initial consequence analysis results were determined for instantaneous or continuous releases using the equations provided in lookup tables. The results were later modified to smooth transitions between instantaneous to continuous releases as well as smoothing the impact or releases as the operating temperature approaches the AIT (see Section 4.8.5 and Section 4.8.6).

a) Type 0 Fluids—Consequence area equations were not smoothed during development for the initial set of reference fluids. Blending using adjustment factors through the transitions are applied to the consequence area calculation in these Type 0 fluids shown in Table 4.1.

b) Type 1 Fluids—Instantaneous to continuous blending was performed during development of Type 1 reference fluids and the resulting consequence area equations accounted for the adjustments. As a result, instantaneous/continuous blending factors are not applied to Type 1 fluids.

4.1.6 Release Phase

The dispersion characteristics of a fluid and the probability of consequence outcomes (events) after release are dependent on the phase (i.e. gas, liquid, or two-phase) of the fluid after it is released to the atmosphere. Releases from pressurized units can be two-phase releases, especially if the fluid is viscous or has a tendency to foam. Released fluids operating under pressure above their boiling points will flash and produce a two-phase release. Guidelines for determining the phase of the released fluid when using the Level 1 consequence analysis are provided in Table 4.3 if more sophisticated methods are not available. Consultation with process or operations personnel is appropriate in this determination. For steam, the release phase is gas. For the representative fluid, acid/caustic, the release phase is always liquid (see Section 4.1.3).

Where more rigorous calculations are desired in order to include the effect of two-phase flashing releases as described in Section 5.3.4, a Level 2 consequence analysis can be performed.

4.1.7 Calculation of Release Phase

a) Step 1.1—Select a representative fluid group from Table 4.1.

b) Step 1.2—Determine the stored fluid phase: liquid or gas. If stored fluid is two-phase, use the conservative assumption of liquid. Alternatively, a Level 2 consequence analysis can be performed.

c) Step 1.3—Determine the stored fluid properties.

   1) For a stored liquid:

      — stored liquid density, ρ_l [lb/ft^3 (kg/m^3)], estimated from Table 4.2;

      — AIT [°R (K)], estimated from Table 4.2.

   2) For a stored gas:

      — MW [lb/lb-mol (kg/kg-mol)] can be estimated from Table 4.2;

      — ideal gas specific heat ratio, k, can be estimated using Equation (3.1) and the C_p values as determined using Table 4.2;

      — AIT [°R (K)] can be estimated from Table 4.2.

d) Step 1.4—Determine the steady state phase of the fluid after release to the atmosphere using Table 4.3 and the phase of the fluid stored in the equipment as determined in Step 1.2.

4.2 Release Hole Size Selection

4.2.1 General

A discrete set of release events or release hole sizes are used since it would be impractical to perform the consequence analysis for a continuous spectrum of release hole sizes. The release hole sizes allow for a manageable analysis, reflects the range of possible outcomes, and is consistent with quantitative risk assessment practices.

The release hole sizes shown in Table 4.4 are based on the component type and geometry as described in Annex 3.A. The maximum release hole size is based on a 16 in. diameter as a practical limit for a catastrophic component failure since failure do not involve disintegration of the equipment.

4.2.2 Calculation of Release Hole Sizes

The following steps are repeated for each release hole size.

a) Step 2.1—Based on the component type and Table 4.4, determine the release hole size diameters, d_n. If $D < d_n$, $d_n = D$.

b) Step 2.2—Determine the generic failure frequency, gff_n, for the n^{th} release hole size from Part 2, Table 3.1, and the total gff_n from the table or from Equation (3.2).

$$gff_{\text{total}} = \sum_{n=1}^{4} gff_n \tag{3.2}$$

4.3 Release Rate Calculation

4.3.1 Overview

Release rates depend upon the physical properties of the material, the initial phase, the process operating conditions, and the assigned release hole sizes. The release rate equation is selected based on the phase of the material inside the component and the discharge regime (sonic or subsonic) as the material is released.

The initial phase of the hazardous material is the phase of the stored fluid in process conditions (i.e. flashing and aerosolization are not included). For two-phase systems (condensers, phase separators, evaporators, reboilers, etc.), choosing liquid as the initial state inside the equipment is conservative and may be preferred. An exception may be for two-phase piping systems where an upstream spill inventory should be considered. If a majority of the upstream material can be released as gas, then a gas phase should be modeled. The results should be checked accordingly for conservatism. Components containing two phases should have a closely approximated potential spill inventory to prevent overly conservative results. The release rate equations are provided in the following sections. The initial phase within the equipment can be determined using a fluid property solver that eliminates assumptions on the release rate calculations.

4.3.2 Liquid Release Rate Calculation

Discharges of liquids through a sharp-edged orifice is discussed in the work by Crowl and Louvar [1] and may be calculated using Equation (3.3).

$$W_n = C_d \cdot K_{v,n} \cdot \rho_l \cdot \frac{A_n}{C_1} \sqrt{\frac{2 \cdot g_c \cdot (P_s - P_{atm})}{\rho_l}} \tag{3.3}$$

In Equation (3.3), the discharge coefficient, C_d, for fully turbulent liquid flow from sharp-edged orifices is in the range of $0.60 \le C_d \le 0.65$. A value of C_d = 0.61 is recommended [17]. Equation (3.3) is used for both flashing and non-flashing liquids.

The viscosity correction factor, $K_{v,n}$, can be determined from Figure 4.1 or approximated using Equation (3.4), both of which have been reprinted from API 520, Part 1. As a conservative assumption, a value of 1.0 may be used.

$$K_{v,n} = \left(0.9935 + \frac{2.878}{Re_n^{0.5}} + \frac{342.75}{Re_n^{1.5}}\right)^{-1.0} \tag{3.4}$$

4.3.3 Vapor Release Rate Equations

There are two regimes for flow of gases or vapors through an orifice: sonic (or choked) for higher internal pressures and subsonic flow for lower pressures [15 psig (103.4 kPa) or less]. Because most process equipment operate above 15 psig (103.4 kPa), sonic (choked) flow releases are the most common in the process industry [1].

Vapor release rates are calculated in a two-step process. In the first step, the flow regime is determined, and in the second step the release rate is calculated using the equation for the specific flow regime. The transition pressure at which the flow regime changes from sonic to subsonic is defined by Equation (3.5).

$$P_{trans} = P_{atm}\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \tag{3.5}$$

The two equations used to calculate vapor flow rate are shown below.

a) If the storage pressure, P_s, within the equipment item is greater than the transition pressure, P_{trans}, calculated using Equation (3.5), then the release rate is calculated using Equation (3.6). This equation is based on discharges of gases and vapors at sonic velocity through an orifice; see Crowl and Louvar [1].

$$W_n = \frac{C_d}{C_2} \cdot A_n \cdot P_s \sqrt{\left(\frac{k \cdot MW \cdot g_c}{R \cdot T_s}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{3.6}$$

b) If the storage pressure is less than or equal to P_{trans}, calculated using Equation (3.5), then the release rate is calculated using Equation (3.7). This equation is based on the discharge of a gas or vapor at subsonic velocity through an orifice; see Crowl and Louvar [1].

$$W_n = \frac{C_d}{C_2} \cdot A_n \cdot P_s \sqrt{\left(\frac{MW \cdot g_c}{R \cdot T_s}\right)\left(\frac{2 \cdot k}{k-1}\right)\left(\frac{P_{atm}}{P_s}\right)^{\frac{2}{k}}\left(1 - \left(\frac{P_{atm}}{P_s}\right)^{\frac{k-1}{k}}\right)} \tag{3.7}$$

c) In Equation (3.6) and Equation (3.7), the discharge coefficient, C_d, for fully turbulent gas or vapor flow from sharp-edged orifices is typically in the range of $0.61 \le C_d \le 1.0$. Crowl and Louvar [1] indicate that a discharge coefficient of C_d = 0.61 is suitable for subsonic gas/vapor releases having a Reynolds number of greater than 30,000. They recommend a conservative discharge coefficient of C_d = 1.0 for sonic gas/vapor releases or for situations where the discharge coefficient is uncertain. The conservative value of C_d = 1.0 is recommended for both sonic and subsonic gas/vapor releases.

4.3.4 Calculation of Release Rate

a) Step 3.1—Select the appropriate release rate equation as described above using the stored fluid phase determined in Step 1.2.

b) Step 3.2—For each release hole size, calculate the release hole size area, A_n, using Equation (3.8) based on d_n.

$$A_n = \frac{\pi d_n^2}{4} \tag{3.8}$$

NOTE If $D < d_n$, then set $d_n = D$.

c) Step 3.3—For liquid releases, for each release hole size, calculate the viscosity correction factor, $K_{v,n}$, using Figure 4.1 or Equation (3.4), as defined in Section 4.3.2.

d) Step 3.4—For each release hole size, calculate the release rate, W_n, for each release area, A_n, determined in Step 3.2 using Equations (3.3), (3.6), or (3.7).

4.4 Estimate the Fluid Inventory Available for Release

4.4.1 Overview

The leaking component inventory is combined with inventory from other associated components that contribute fluid mass. Additional background on the development of the inventory group concept is provided in Annex 3.A.

4.4.2 Maximum Mass Available for Release (Available Mass)

The available mass for release is estimated for each release hole size as the lesser of the following two quantities.

a) Inventory Group Mass—The component being evaluated is part of a larger group of components that can be expected to provide fluid inventory to the release. These equipment items together form an inventory group. Additional guidance for creating logical inventory groups is provided in Annex 3.A. The inventory group calculation is used as an upper limit on the mass of fluid available for a release and does not indicate that this amount of fluid would be released in all leak scenarios. The inventory group mass is calculated using Equation (3.9).

$$mass_{\text{inv}} = \sum_{i=1}^{N} mass_{\text{comp},i} \tag{3.9}$$

b) Component Mass—It is assumed that for large leaks, operator intervention will occur within 3 minutes, thereby limiting the amount of released material (see Annex 3.A for additional background). Therefore, the amount of available mass for the release is limited to the mass of the component plus an additional mass, $mass_{\text{add},n}$, that is calculated based on 3 minutes of leakage from the component's inventory group. This $mass_{\text{add},n}$ is calculated assuming the same flow rate from the leaking component but is limited to an 8 in. (203 mm) release hole size. The $mass_{\text{add},n}$ is calculated for each release hole size using Equation (3.10).

$$mass_{\text{add},n} = 180 \cdot \min\left[W_n,\ W_{\text{max8}}\right] \tag{3.10}$$

In Equation (3.10), the maximum flow rate, W_{max8}, to be added to the release from the surrounding components, W_{max8} [limited by an 8 in. (203 mm) diameter leak], is calculated using Equations (3.3), (3.6), or (3.7), as applicable, with the hole area, $W_n = 50.3$ in.^{2} (32,450 mm^2).

The maximum mass available, $mass_{\text{avail},n}$, for release is calculated using Equation (3.11).

$$mass_{\text{avail},n} = \min\left[\left\{mass_{\text{comp}} + mass_{\text{add},n}\right\},\ mass_{\text{inv}}\right] \tag{3.11}$$

Plant detection, isolation, and mitigation techniques, as described in Section 4.6, will limit the duration of the release such that the actual mass released to atmosphere can be significantly less than the available mass as determined above.

Further guidance on the basis of the above methodology for calculating the available mass and the inventory grouping is provided in Annex 3.A.

4.4.3 Calculation of Inventory Mass

a) Step 4.1—Group components and equipment items into inventory groups (see Annex 3.A).

b) Step 4.2—Calculate the fluid mass, $mass_{\text{comp}}$, in the component being evaluated.

c) Step 4.3—Calculate the fluid mass in each of the other components that is included in the inventory group, $mass_{\text{comp},i}$.

d) Step 4.4—Calculate the fluid mass in the inventory group, $mass_{\text{inv}}$, using Equation (3.9).

e) Step 4.5—Calculate the flow rate from an 8 in. (203 mm) diameter hole, W_{max8}, using Equations (3.3), (3.6), or (3.7), as applicable, with $A_n = A_8 = 50.3 \text{ in.}^2 \left(32{,}450 \text{ mm}^2\right)$. This is the maximum flow rate that can be added to the equipment fluid mass from the surrounding equipment in the inventory group.

f) Step 4.6—For each release hole size, calculate the added fluid mass, $mass_{\text{add},n}$, resulting from 3 minutes of flow from the inventory group using Equation (3.10), where W_n is the leakage rate for the release hole size being evaluated and W_{max8} is from Step 4.5.

g) Step 4.7—For each release hole size, calculate the available mass, $mass_{\text{avail},n}$, for release using Equation (3.11).

4.5 Determine the Release Type (Continuous or Instantaneous)

4.5.1 Release Type—Instantaneous or Continuous

The release is modeled as one of two following types.

a) Instantaneous Release—An instantaneous or puff release is one that occurs so rapidly that the fluid disperses as a single large cloud or pool.

b) Continuous Release—A continuous or plume release is one that occurs over a longer period of time, allowing the fluid to disperse in the shape of an elongated ellipse (depending on weather conditions).

The transition point between continuous and instantaneous release types is 55.6 lb/s (25.22 kg/s) or $\dfrac{10{,}000 \text{ lb}}{180 \text{ s}} = 55.6 \text{ lb/s}$. Further guidance on the background and importance of selecting the proper type of release is provided in Annex 3.A.

4.5.2 Calculation of Release Type

a) Step 5.1—For each release hole size, determine if the release type is instantaneous or continuous. The following guidance should be followed to assign continuous and instantaneous releases (see Figure 4.2).

   1) Small release hole size of $<$ 0.25 in. (6.35 mm) are continuous.

   2) Medium, large, and rupture release hole size cases when $>$ 10,000 lb (4,536 kg) mass is released in $<$ 3 minutes is instantaneous.

   3) Release rates , W_n, of $>$ 55.6 lb/s (25.22 kg/s) are instantaneous.

   4) All other releases are considered as continuous.

4.6 Estimate the Impact of Detection and Isolation Systems on Release Magnitude

4.6.1 Overview

Refining and petrochemical plants typically have a variety of detection, isolation, and mitigation systems that are designed to reduce the effects of a release of hazardous materials. These systems affect a release in different ways. Some systems reduce magnitude and duration of the release by detecting and isolating the leak. Other systems reduce the consequence area by minimizing the chances for ignition or limiting the spread of material. A methodology for quantifying the effectiveness of detection, isolation, and mitigation systems is included in the COF calculation.

Detection, isolation, and mitigation systems for RBI analysis affects the release in the following two ways.

a) Detection and Isolation Systems—These systems are designed to detect and isolate a leak and tend to reduce the magnitude and duration of the release (see Section 4.6.2).

b) Mitigation Systems—These systems are designed to mitigate or reduce the consequence of a release (see Section 4.8.3).

4.6.2 Assessing Detection and Isolation Systems

Detection and isolation systems that are present in the unit can have a significant impact on the magnitude and duration of the hazardous fluid release. Guidance for assigning a qualitative letter rating (A, B, or C) to the unit's detection and isolation systems is provided in Table 4.5. Detection System A is usually found in specialty chemical applications and is not often used in refineries.

The information presented in Table 4.5 is used when evaluating the consequence of continuous releases; see Section 4.7.1.

4.6.3 Impact on Release Magnitude

Detection and isolation systems can reduce the magnitude of the release. For the release of both flammable and toxic materials, isolation valves serve to reduce the release rate or mass by a specified amount, depending on the quality of these systems. The recommended reduction values are presented in Table 4.6.

4.6.4 Impact on Release Duration

Detection and isolation systems can reduce the duration of the release. This is important when calculating the consequence of toxic releases because toxic consequences are a function of concentration and exposure duration. The duration is used as direct input to the estimation of flammable and toxic consequences.

The quality ratings of the detection and isolation systems have been translated into an estimate of leak duration. Total leak duration, $ld_{\max,n}$, presented in Table 4.7, is the sum of the following:

a) time to detect the leak,

b) time to analyze the incident and decide upon corrective action, and

c) time to complete appropriate corrective actions.

NOTE There is no total leak duration provided in Table 4.7 for the rupture case [largest release hole size, if greater than 4 in. (102 mm) diameter].

4.6.5 Releases to the Environment

Environmental consequence is mitigated in two ways: physical barriers act to contain leaks on site, and detection and isolation systems limit the duration of the leak. In API 581, the volume contained on site is accounted for directly in the spill calculation. Detection and isolation systems serve to reduce the duration of the leak and, thus, the final spill volume.

4.6.6 Calculation for Detection and Isolation

a) Step 6.1—Determine the detection and isolation systems present in the unit.

b) Step 6.2—Using Table 4.5, select the appropriate classification (A, B, C) for the detection system.

c) Step 6.3—Using Table 4.5, select the appropriate classification (A, B, C) for the isolation system.

d) Step 6.4—Using Table 4.6 and the classifications determined in Steps 6.2 and 6.3, determine the release reduction factor, $fact_{\text{di}}$.

e) Step 6.5—Using Table 4.7 and the classifications determined in Steps 6.2 and 6.3, determine the maximum leak duration for each of the selected release hole sizes, $ld_{\max,n}$.

4.7 Determine the Release Rate and Mass for COF

4.7.1 Continuous Release Rate

For continuous releases, the release is modeled as a steady state plume; therefore, the release rate (units are lb/s) is used as the input to the consequence analysis. The release rate that is used in the analysis is the theoretical release as discussed in Section 4.3, adjusted for the presence of unit detection and isolations as discussed in Section 4.6 [see Equation (3.12)].

$$rate_n = W_n \cdot (1 - fact_{\text{di}}) \tag{3.12}$$

4.7.2 Instantaneous Release Mass

For transient instantaneous puff releases, the release mass is required to perform the analysis. The available release mass, $mass_{\text{avail},n}$, as determined in Section 4.4.2 for each release hole size, $mass_{\text{avail},n}$, is used to determine an upper bound release mass, $mass_n$, as shown in Equation (3.13).

$$mass_n = \min\left[\{rate_n \cdot ld_n\},\ mass_{\text{avail},n}\right] \tag{3.13}$$

In this equation, the leak duration, ld_n, cannot exceed the maximum duration $ld_{\text{max},n}$, established in Section 4.6.4 based on the detection and isolation systems present. Equation (3.14) can be used to calculate the actual duration of the release, ld_n.

$$ld_n = \min\left[\left\{\frac{mass_{\text{avail},n}}{rate_n}\right\},\ \left\{60 \cdot ld_{\text{max},n}\right\}\right] \tag{3.14}$$

4.7.3 Calculation of Release Rate and Mass

a) Step 7.1—For each release hole size, calculate the adjusted release rate, $rate_n$, using Equation (3.12), where the theoretical release rate, W_n, is from Step 3.2.

   NOTE 1 The release reduction factor, $fact_{\text{di}}$, determined in Step 6.4 accounts for any detection and isolation systems that are present.

b) Step 7.2—For each release hole size, calculate the leak duration, ld_n, of the release using Equation (3.14), based on the available mass, $mass_{\text{avail},n}$, from Step 4.6 and the adjusted release rate, $rate_n$, from Step 7.1.

   NOTE 2 The leak duration cannot exceed the maximum duration, $ld_{\text{max},n}$, determined in Step 6.5.

c) Step 7.3—For each release hole size, calculate the upper bound release mass, $mass_n$, using Equation (3.13) based on the release rate, $rate_n$, from Step 3.2, the leak duration, ld_n, from Step 7.2, and the available mass, $mass_{\text{avail},n}$, from Step 4.6.

4.8 Determine Flammable and Explosive Consequence

4.8.1 Overview

Equations to calculate flammable and explosive consequence have been developed for the representative fluids presented in Table 4.1. Consequence areas are estimated from a set of equations using release rate (for continuous releases) or release mass (for instantaneous releases) as input. Technical background information pertaining to the development of the empirical equations for the flammable consequence areas is provided in Annex 3.A. An assumption is made that the probability of ignition for a continuous release is constant and is a function of the material released and whether or not the fluid is at or above its AIT. The probability does not increase as a function of release rate. For an instantaneous release, the probability of ignition increases. The probability of ignition and other event tree probabilities for the Level 1 COF are documented in Annex 3.A. An instantaneous release is defined as any release larger than 10,000 lb (4,536 kg) in 3 minutes, which is equivalent to a release rate of 55.6 lb/s (25.2 kg/s). A continuous release of 55.6 lb/s (25.5 kg/s) would have a lower consequence than an instantaneous release at 55.6 lb/s (25.2 kg/s) of the same material. Therefore, the Level 1 COF blends the continuous and instantaneous releases results (see Section 4.8.7).

4.8.2 Consequence Area Equations

4.8.2.1 Generic Equations

The following equations are used to determine the flammable consequence areas for component damage and personnel injury. The background for development of these generic equations is provided in Annex 3.A.

a) Continuous Release—For a continuous release, Equation (3.15) is used. Coefficients for this equation for component damage areas and personnel injury areas are provided in Table 4.8 and Table 4.9, respectively.

$$CA_{\text{f},n}^{\text{CONT}} = a\left(rate_n\right)^b \tag{3.15}$$

b) Instantaneous Release—For an instantaneous release, Equation (3.16) is used. Coefficients for this equation for component damage areas and personnel injury areas are provided in Table 4.8 and Table 4.9, respectively.

$$CA_{\mathrm{f},n}^{\mathrm{INST}} = a\left(mass_n\right)^b \tag{3.16}$$

4.8.2.2 Development of Generic Equations

Equation (3.15) and Equation (3.16) were used to calculate overall consequence areas following a three-step process.

a) An event tree analysis was performed by listing possible events or outcomes and providing estimates for the probabilities of each event. The two main factors that define the paths on the event tree for the release of flammable material are the probability of ignition and the timing of ignition. The event trees used are provided in Figure 4.3 where event probabilities were set as a function of release type (continuous or instantaneous) and temperature (proximity to the AIT). These probabilities are provided in Annex 3.A.

b) The consequence areas as a result of each event were calculated using appropriate analysis techniques, including cloud dispersion modeling. Additional background on the methods used for these calculations are provided in Annex 3.A.

c) The consequence areas of each individual event were combined into a single probability weighted empirical equation representing the overall consequence area of the event tree (see Annex 3.A).

4.8.2.3 Threshold Limits

Threshold limits for thermal radiation and overpressure, sometimes referred to as impact criteria, were used to calculate the consequence areas for a particular event outcome (pool fire, VCE, etc.).

a) Component damage criteria:

   1) explosion overpressure—5 psig (34.5 kPa);

   2) thermal radiation—12,000 Btu/(hr-ft^2) [37.8 kW/m^2] (jet fire, pool fire, and fireball); and

   3) flash fire—25 % of the area within the lower flammability limits (LFLs) of the cloud when ignited.

b) Personnel injury criteria:

   1) explosion overpressure—34.5 kPa (5 psig);

   2) thermal radiation—4000 Btu/(hr-ft^2) [12.6 kW/m^2] (jet fire, fireball, and pool fire); and

   3) flash fire—the LFL limits of the cloud when ignited.

The predicted results using the above threshold limits were intended to produce a relative risk ranking that, while being considered to be reasonably accurate, are not the highest levels of consequence that could be estimated for a given accident sequence. As are most effects data, the component damage and personnel injury criteria listed above are subject to intensive scientific debate, and values other than those used in this methodology could be suggested.

4.8.3 Adjustment of Consequence Areas to Account for Mitigation Systems

4.8.3.1 Evaluating Post-leak Mitigation of Consequence

Evaluating post-leak response is an important step in consequence analysis. In this step, the various mitigation systems in place are evaluated for their effectiveness in limiting the consequence areas. Toxic releases are typically characterized as a prolonged buildup, then reduction, in cloud concentration, with accumulated exposure throughout. Flammable events are more often releases that are either ignited quickly or the material is quickly dispersed below its LFL. For these reasons, different approaches are necessary for evaluating the post-leak response based on the type of consequence. Mitigation systems and their effect on flammable release events are presented in this section.

4.8.3.2 Effects of Mitigation Measures on Flammable Consequence Magnitudes

The adjustments to the magnitude of the consequence for flammable releases based on unit mitigation systems are provided in Table 4.10. These values are based on engineering judgment, using experience in evaluating mitigation measures in quantitative risk analyses. The consequence area reduction factor, $fact_{\text{mit}}$, to account for the presence of mitigation systems is provided in Table 4.10.

4.8.4 Adjustment of Consequence Areas for Energy Efficiencies

Comparison of calculated consequence with those of actual historical releases indicates that there is a need to correct large instantaneous releases for energy efficiency. This correction is made for instantaneous events exceeding a release mass of 10,000 lb (4,536 kg) by dividing the calculated consequence areas by the adjustment factor, $eneff_n$, given by Equation (3.17).

$$eneff_n = 4 \cdot log_{10}\left[C_{4\text{A}} \cdot mass_n\right] - 15 \tag{3.17}$$

NOTE The adjustment defined by Equation (3.17) is not applied to continuous releases.

4.8.5 Blending of Results Based on Release Type

The Level 1 consequence area calculations yield significantly different results, depending on whether the continuous area equations are used or the instantaneous area equations are used. The blending factor is determined as follows based on the release type.

a) For Continuous Releases—A blending factor is calculated to smooth the results for releases near the continuous to instantaneous transition [10,000 lb (4,536 kg) released in less than 3 minutes or a release rate of 55.6 lb/s (25.2 kg/s)] using Equation (3.18).

$$fact_n^{\text{IC}} = \min\left[\left\{\frac{rate_n}{C_5}\right\},\ 1.0\right] \tag{3.18}$$

When instantaneous equation constants are not provided in Table 4.8 and Table 4.9 for the reference fluid, the blending factor is defined in Equation (3.19).

$$fact_n^{\text{IC}} = 0.0 \tag{3.19}$$

b) For Instantaneous Releases—Blending is not required for instantaneous releases 10,000 lb (4,536 kg) released in less than 3 minutes or a release rate of 55.6 lb/s (25.2 kg/s)]. The blending factor, $fact_n^{\text{IC}}$, for an instantaneous release is defined in Equation (3.20).

$$fact_n^{\text{IC}} = 1.0 \tag{3.20}$$

The blended release area is calculated using Equation (3.21).

NOTE This area is proportionate to the proximity of the actual release rate, $rate_n$, is to the continuous/instantaneous transition rate of 55.6 lb/s (25.2 kg/s).

$$CA_n^{\text{IC-blend}} = CA_n^{\text{INST}} \cdot fact_n^{\text{IC}} + CA_n^{\text{CONT}} \left(1 - fact_n^{\text{IC}}\right) \tag{3.21}$$

4.8.6 Blending of Results Based on AIT

Consequence area calculations yield significantly different results depending on whether the autoignition not likely consequence equations are used or the autoignition likely consequence area equations are used. The consequence areas are blended using Equation (3.22).

$$CA^{\text{AIT-blend}} = CA^{\text{AIL}} fact^{\text{AIT}} + CA^{\text{AINL}} \left(1 - fact^{\text{AIT}}\right) \tag{3.22}$$

The AIT blending factor, $fact^{\text{AIT}}$, is determined using the following equations.

$$fact^{\text{AIT}} = 0 \qquad \text{for } T_s + C_6 \le AIT \tag{3.23}$$

$$fact^{\text{AIT}} = \frac{\left(T_s - AIT + C_6\right)}{2 \cdot C_6} \qquad \text{for } T_s + C_6 > AIT > T_s - C_6 \tag{3.24}$$

$$fact^{\text{AIT}} = 1 \qquad \text{for } T_s - C_6 \ge AIT \tag{3.25}$$

NOTE T_s is in °R (°K).

4.8.7 Determination of Final Flammable Consequence Areas

The final flammable consequence areas are determined as a probability weighted average of the individual (blended) flammable areas calculated for each release hole size. This is performed for both the component damage and the personnel injury consequence areas. The probability weighting utilizes the generic frequencies of the release hole sizes selected per Section 4.2.

The equation for probability weighting of the component damage consequence areas is given by Equation (3.26).

$$CA_{\text{f,cmd}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{cmd},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.26}$$

The equation for probability weighting of the personnel injury consequence areas is given by Equation (3.27).

$$CA_{\text{f,inj}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{inj},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.27}$$

In Equation (3.28) and Equation (3.29), the gff_n for each release hole size and gff_{total} are provided in Part 2, Table 3.1.

4.8.8 Calculation of Consequence Area

a) Step 8.1—Select the consequence area mitigation reduction factor, $fact_{\text{mit}}$, from Table 4.10.

b) Step 8.2—For each release hole size, calculate the energy efficiency correction factor, $eneff_n$, using Equation (3.17).

c) Step 8.3—Determine the fluid type, either Type 0 or Type 1, from Table 4.1.

d) Step 8.4—For each release hole size, calculate the component damage consequence areas for autoignition not likely, continuous release (AINL-CONT), $CA^{\text{AINL-CONT}}_{\text{cmd},n}$.

   1) Determine the appropriate constants a and b from the Table 4.8. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a^{\text{AINL-CONT}}_{\text{cmd}} \tag{3.28}$$

$$b = b^{\text{AINL-CONT}}_{\text{cmd}} \tag{3.29}$$

   2) Use Equation (3.30) to calculate the consequence area.

$$CA^{\text{AINL-CONT}}_{\text{cmd},n} = a\left(rate_n\right)^b \cdot \left(1 - fact_{\text{mit}}\right) \tag{3.30}$$

e) Step 8.5—For each release hole size, calculate the component damage consequence areas for autoignition likely, continuous release (AIL-CONT), $CA^{\text{AIL-CONT}}_{\text{cmd},n}$.

   1) Determine the appropriate constants, a and b, from the Table 4.8. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a^{\text{AIL-CONT}}_{\text{cmd}} \tag{3.31}$$

$$b = b^{\text{AIL-CONT}}_{\text{cmd}} \tag{3.32}$$

   2) Use Equation (3.33) to calculate the consequence area.

$$CA^{\text{AIL-CONT}}_{\text{cmd},n} = a\left(rate_n\right)^b \cdot \left(1 - fact_{\text{mit}}\right) \tag{3.33}$$

f) Step 8.6—For each release hole size, calculate the component damage consequence areas for autoignition not likely, instantaneous release (AINL-INST), $CA^{\text{AINL-INST}}_{\text{cmd},n}$.

   1) Determine the appropriate constants, a and b, from the Table 4.8. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a^{\text{AINL-INST}}_{\text{cmd}} \tag{3.34}$$

$$b = b^{\text{AINL-INST}}_{\text{cmd}} \tag{3.35}$$

   2) Use Equation (3.36) for the consequence area.

$$CA_{\text{cmd},n}^{\text{AINL-INST}} = a\left(mass_n\right)^b \cdot \left(\frac{1 - fact_{\text{mit}}}{eneff_n}\right) \tag{3.36}$$

g) Step 8.7—For each release hole size, calculate the component damage consequence areas for autoignition likely, instantaneous release (AIL-INST), $CA_{\text{cmd},n}^{\text{AIL-INST}}$.

1) Determine the appropriate constants, a and b, from the Table 4.8. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a_{\text{cmd}}^{\text{AIL-INST}} \tag{3.37}$$

$$b = b_{\text{cmd}}^{\text{AIL-INST}} \tag{3.38}$$

2) Use Equation (3.39) to calculate the consequence area.

$$CA_{\text{cmd},n}^{\text{AIL-INST}} = a\left(mass_n\right)^b \cdot \left(\frac{1 - fact_{\text{mit}}}{eneff_n}\right) \tag{3.39}$$

h) Step 8.8—For each release hole size, calculate the personnel injury consequence areas for autoignition not likely, continuous release (AINL-CONT), $CA_{\text{inj},n}^{\text{AINL-CONT}}$.

1) Determine the appropriate constants, a and b, from the Table 4.9. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a_{\text{inj}}^{\text{AINL-CONT}} \tag{3.40}$$

$$b = b_{\text{inj}}^{\text{AINL-CONT}} \tag{3.41}$$

2) Calculate the consequence area using Equation (3.42).

$$CA_{\text{inj},n}^{\text{AINL-CONT}} = \left[a \cdot \left(rate_n\right)^b\right] \cdot \left(1 - fact_{\text{mit}}\right) \tag{3.42}$$

i) Step 8.9—For each release hole size, calculate the personnel injury consequence areas for autoignition likely, continuous release (AIL-CONT), $CA_{\text{inj},n}^{\text{AIL-CONT}}$.

1) Determine the appropriate constants, a and b, from the Table 4.9. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a_{\text{inj}}^{\text{AIL-CONT}} \tag{3.43}$$

$$b = b_{\text{inj}}^{\text{AIL-CONT}} \tag{3.44}$$

2) Calculate the consequence area using Equation (3.45).

$$CA_{\text{inj},n}^{\text{AIL-CONT}} = \left[a \cdot \left(rate_n\right)^b\right] \cdot \left(1 - fact_{\text{mit}}\right) \tag{3.45}$$

j) Step 8.10—For each release hole size, calculate the personnel injury consequence areas for autoignition not likely, instantaneous release (AINL-INST), $CA_{\text{inj},n}^{\text{AINL-INST}}$.

1) Determine the appropriate constants, a and b, from the Table 4.9. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a_{\text{inj}}^{\text{AINL-INST}} \tag{3.46}$$

$$b = b_{\text{inj}}^{\text{AINL-INST}} \tag{3.47}$$

2) Calculate the consequence area using Equation (3.48).

$$CA_{\text{inj},n}^{\text{AINL-INST}} = \left[a \cdot \left(mass_n\right)^b\right] \cdot \left(\frac{1 - fact_{\text{mit}}}{eneff_n}\right) \tag{3.48}$$

k) Step 8.11—For each release hole size, calculate the personnel injury consequence areas for autoignition likely, instantaneous release (AIL-INST), $CA_{\text{inj},n}^{\text{AIL-INST}}$.

1) Determine the appropriate constants, a and b, from the Table 4.9. The release phase as determined in Step 1.4 will be needed to assure selection of the correct constants.

$$a = a_{\text{inj}}^{\text{AIL-INST}} \tag{3.49}$$

$$b = b_{\text{inj}}^{\text{AIL-INST}} \tag{3.50}$$

2) Calculate the consequence area using Equation (3.51).

$$CA_{\text{inj},n}^{\text{AIL-INST}} = \left[a \cdot \left(mass_n\right)^b\right] \cdot \left(\frac{1 - fact_{\text{mit}}}{eneff_n}\right) \tag{3.51}$$

l) Step 8.12—For each release hole size, calculate the instantaneous/continuous blending factor, $fact_n^{\text{IC}}$, using Equations (3.18), (3.19), or (3.20), as applicable. Instantaneous/continuous blending is not required for Type 1 fluids. For Type 1 fluids, use the component damage and personnel injury areas based on release type.

m) Step 8.13—Calculate the AIT blending factor, $fact^{\text{AIT}}$, using Equations (3.23), (3.24), or (3.25), as applicable.

n) Step 8.14—For Type 0 fluids, calculate the continuous/instantaneous blended consequence areas for Type 0 fluid components using Equations (3.52) through (3.55) based on the consequence areas calculated in Steps 8.4, 8.5, 8.6, 8.7, 8.8, 8.9, 8.10, and 8.11, and the continuous/instantaneous blending factor, $fact_n^{\text{IC}}$, from Step 8.12. Instantaneous/continuous blending is not required for Type 1 fluids. For Type 1 fluids, use the component damage and personnel injury areas based on release type from Steps 8.4 to 8.11.

$$CA_{\text{cmd},n}^{\text{AIL}} = CA_{\text{cmd},n}^{\text{AIL-INST}} \cdot fact_n^{\text{IC}} + CA_{\text{cmd},n}^{\text{AIL-CONT}} \cdot \left(1 - fact_n^{\text{IC}}\right) \tag{3.52}$$

$$CA_{\text{inj},n}^{\text{AIL}} = CA_{\text{inj},n}^{\text{AIL-INST}} \cdot fact_n^{\text{IC}} + CA_{\text{inj},n}^{\text{AIL-CONT}} \cdot \left(1 - fact_n^{\text{IC}}\right) \tag{3.53}$$

$$CA_{\text{cmd},n}^{\text{AINL}} = CA_{\text{cmd},n}^{\text{AINL-INST}} \cdot fact_n^{\text{IC}} + CA_{\text{cmd},n}^{\text{AINL-CONT}} \cdot \left(1 - fact_n^{\text{IC}}\right) \tag{3.54}$$

$$CA_{\text{inj},n}^{\text{AINL}} = CA_{\text{inj},n}^{\text{AINL-INST}} \cdot fact_n^{\text{IC}} + CA_{\text{inj},n}^{\text{AINL-CONT}} \cdot \left(1 - fact_n^{\text{IC}}\right) \tag{3.55}$$

o) Step 8.15—Calculate the AIT blended consequence areas for all components using Equations (3.56) and (3.57) based on the consequence areas determined in Step 8.14 and the AIT blending factors, $fact^{\text{AIT}}$ calculated in Step 8.13. The resulting consequence areas are the component damage and personnel injury flammable consequence areas, $CA_{\text{cmd},n}^{\text{flam}}$ and $CA_{\text{inj},n}^{\text{flam}}$, for each release hole sizes selected in Step 2.2.

$$CA_{\text{cmd},n}^{\text{flam}} = CA_{\text{cmd},n}^{\text{AIL}} \cdot fact^{\text{AIT}} + CA_{\text{cmd},n}^{\text{AINL}} \cdot \left(1 - fact^{\text{AIT}}\right) \tag{3.56}$$

$$CA_{\text{inj},n}^{\text{flam}} = CA_{\text{inj},n}^{\text{AIL}} \cdot fact^{\text{AIT}} + CA_{\text{inj},n}^{\text{AINL}} \cdot \left(1 - fact^{\text{AIT}}\right) \tag{3.57}$$

p) Step 8.16—Determine the final consequence areas (probability weighted on release hole size) for component damage and personnel injury using Equation (3.58) and Equation (3.59) based on the consequence areas from Step 8.15.

$$CA_{\text{f,cmd}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{cmd},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.58}$$

$$CA_{\text{f,inj}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{inj},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.59}$$

4.9 Determine Toxic Consequence

4.9.1 General

Toxic fluids are similar to flammables in that not all toxic releases result in a single type of effect. By themselves, HF, ammonia, and chlorine pose only a toxic hazard. On the other hand, some toxic materials such as hydrogen sulfide (H_2S) are both toxic and flammable. However, any toxic material, when mixed with hydrocarbons, can pose flammable and toxic hazards.

The toxic consequence is calculated using a hazards analysis in conjunction with atmospheric dispersion models similar to the flammable procedure described in Section 4.8.

4.9.2 Common Refining Toxic Materials

The procedure for determination of toxic consequence of four toxic materials that typically contribute to toxic risks for a refinery—hydrogen fluoride (HF), hydrogen sulfide (H_2S), ammonia (NH_3), and chlorine (Cl)—is provided in Section 4.9.6 and Section 4.9.7.

4.9.3 Common Chemical Industry Toxic Materials

The determination of toxic consequence includes 10 additional toxic chemicals commonly used in the chemical industry as described in Section 4.9.8. Level 1 toxic consequence analysis uses probit data for determining the consequence areas (see Table 4.14).

4.9.4 Representative Fluids for Toxic Mixtures

Modeling of releases where the toxic component is part of a mixture is a special case for the Level 1 consequence analysis. For these cases, the analysis requires the selection of a representative fluid from Table 4.1 for the purpose of determining the release rate that is used in the consequence assessment. The representative fluid should be selected based upon the average boiling point, density, and MW of the mixture; see Section 4.1.2. A Level 2 consequence analysis per Section 5 rigorously calculates the fluid composition and release mixture.

4.9.5 Determination of the Toxic Release Rate and Mass

The toxic release rate or mass to be used in the toxic consequence analysis is determined based on the mass fraction of the toxic component, $mfrac^{\text{tox}}$, that is present in the release fluid.

$$rate_n^{\text{tox}} = mfrac^{\text{tox}} \cdot W_n \tag{3.60}$$

$$mass_n^{\text{tox}} = mfrac^{\text{tox}} \cdot mass_n \tag{3.61}$$

For pure toxic fluids ($frac^{\text{tox}} = 1.0$), the toxic release rate, $rate_n^{\text{tox}}$, is equal to the release rate, W_n , as calculated in Section 4.3, and the toxic release mass, $mass_n^{\text{tox}}$, is equal to the release mass, $mass_n$, as calculated in Section 4.7. For mixtures, the toxic release rate and release mass are modified based on the percentage of the toxic component in the mixture and the storage phase (liquid or vapor) of the mixture.

NOTE The magnitude reduction factor, $fact_{\text{di}}$, to account for detection and isolation systems is not applied to toxic releases (see Section 4.6).

4.9.6 Estimation of Toxic Consequence Area for HF and H_2S

a) The background for the development of the toxic consequence equations for HF and H_2S is provided in Annex 3.A. For determination of the toxic consequence areas, the assumption was made that the release phase would always be a gas or vapor.

b) The toxic consequence areas for continuous releases of HF or H_2S as a function of the release rate may be calculated using Equation (3.62).

$$CA_{\text{inj},n}^{\text{tox-CONT}} = C_8 \cdot 10^{\left(c \cdot \log_{10}\left[C_{4\text{B}} \cdot rate_n^{\text{tox}}\right] + d\right)}$$

$$CA_{\text{inj},n}^{\text{tox-CONT}} = C_8 \cdot \left(\left[C_{4\text{B}} \cdot rate_n^{\text{tox}}\right] \wedge c \cdot 10 \wedge d\right) \tag{3.62}$$

NOTE 1 For continuous releases, the toxic release rate, $rate_n^{\text{tox}}$, is used as the input to Equation (3.62). The constants, c and d, to be used in Equation (3.62) are provided in Table 4.11 as a function of release duration. Interpolation between curves using the actual duration (defined in Section 4.9.10) is acceptable.

c) The toxic consequence areas for instantaneous releases of HF or H_2S as a function of the release rate may be calculated using Equation (3.63).

$$CA_{\text{inj},n}^{\text{tox-INST}} = C_8 \cdot 10^{\left(c \cdot \log_{10}\left[C_{4\text{B}} \cdot mass_n^{\text{tox}}\right] + d\right)}$$

$$CA_{\text{inj},n}^{\text{tox-INST}} = C_8 \cdot \left(\left[C_{4B} \cdot mass_n^{\text{tox}} \right] \wedge c \cdot 10 \wedge d \right) \quad (3.63)$$

NOTE 2 For instantaneous releases, the toxic release mass, $mass_n^{\text{tox}}$, is used as the input to Equation (3.63). The constants, c and d, to be used in Equation (3.63) are provided in Table 4.11.

4.9.7 Estimation of Toxic Consequence Area for Ammonia and Chlorine

a) The background for the development of the toxic consequence equations for ammonia and chlorine are provided in Annex 3.A. For determination of the consequence areas, the assumption was made that the release phase would always be a gas or vapor.

b) The toxic consequence areas for continuous releases of ammonia or chlorine as a function of the release rate may be calculated using Equation (3.64).

$$CA_{\text{inj},n}^{\text{tox-CONT}} = e \left(rate_n^{\text{tox}} \right)^f \quad (3.64)$$

NOTE 1 For continuous releases, the toxic release rate, $rate_n^{\text{tox}}$, is used as the input to Equation (3.64). The constants e and f for Equation (3.64) are provided in Table 4.12 as a function of release duration. Interpolation between curves using the actual duration is acceptable.

c) The toxic consequence areas for instantaneous releases of ammonia or chlorine as a function of the release rate may be calculated using Equation (3.65).

$$CA_{\text{inj},n}^{\text{tox-INST}} = e \left(mass_n^{\text{tox}} \right)^f \quad (3.65)$$

NOTE 2 For instantaneous releases, the toxic release mass, $mass_n^{\text{tox}}$, is used as the input to Equation (3.65). The constants e and f for Equation (3.65) are provided in Table 4.12.

4.9.8 Estimation of Toxic Consequence Area for Additional Common Chemicals

a) The background for the development of the toxic consequence equations for 10 additional common chemicals shown below is provided in Annex 3.A. For determination of the consequence areas, the assumption was made that the release phase could either be a vapor, liquid, or powder. Additionally, the consequence equations were developed for continuous release equations only.

1) Aluminum Chloride ($AlCl_3$)—Powder.

2) Carbon Monoxide (CO)—Gas only.

3) Hydrogen Chloride (HCl)—Gas only.

4) Nitric Acid—Gas or liquid.

5) Nitrogen Dioxide (NO_2)—Gas or liquid.

6) Phosgene—Gas or liquid.

7) Toluene Diisocyanate (TDI)—Liquid only.

8) Ethylene Glycol Monoethyl Ether (EE)—Gas or liquid.

9) Ethylene Oxide (EO)—Gas only.

10) Propylene Oxide (PO)—Gas or liquid.

b) Procedures for these chemicals have been developed in much the same manner as that for ammonia and chlorine and are further described in Annex 3.A.

c) The toxic consequence area can be approximated as a function of duration (except for $AlCl_3$) using Equation (3.64) and the constants e and f provided in Table 4.13.

4.9.9 Material Concentration Cut-off

As a general rule, it is not necessary to evaluate a toxic release if the concentration of the stored fluid within the component or equipment item is at or below the immediately dangerous to life or health (IDLH) value. For HF, this is 30 ppm, for H_2S this is 100 ppm, for NH_3 this is 300 ppm, and for Cl this is 10 ppm. Other IDLH values are provided in Table 4.14.

4.9.10 Release Duration

The potential toxic consequence is estimated using both the release duration and release rate, whereas the flammable impact relies on just the magnitude of the release, i.e. rate or mass. The duration of a release depends on the following:

a) the inventory in the equipment item and connected systems,

b) time to detect and isolate the leak,

c) any response measures that may be taken.

The maximum release duration is set at 1 hour, for the following two reasons.

a) It is expected that the plant's emergency response personnel will employ a shutdown procedure and initiate a combination of mitigation measures to limit the duration of a release.

b) It is expected that personnel will either be moved out of the area or be evacuated by emergency responders within 1 hour of the initial exposure.

The release duration can be estimated as the inventory in the system divided by the initial release rate. While the calculated duration may exceed 1 hour, there may be systems in place that will significantly shorten this time, such as isolation valves and rapid-acting leak detection systems. Times should be determined on a case-by-case basis. The leak duration, ld_n^{tox}, should be calculated for each release hole size as the minimum of:

a) 1 hour,

b) release mass (mass available) divided by release rate (see Section 4.7), and

c) maximum leak duration, $ld_{\max,n}$ listed in Table 4.7.

$$ld_n^{\text{tox}} = \min\left(3600,\ \left\{\frac{mass_n}{W_n}\right\},\ \left\{60 \cdot ld_{\max,n}\right\}\right) \tag{3.66}$$

4.9.11 Toxic Outcome Probabilities

In the event the release involves both toxic and flammable outcomes, it is assumed that either the flammable outcome consumes the toxic material or that the toxic materials disperse and flammable materials have insignificant consequences. In this case, the probability for the toxic event is the remaining non-ignition frequency for the event (i.e. the probability of safe dispersion).

4.9.12 Consequence of Releases Containing Multiple Toxic Chemicals

Consequence results for releases of multicomponent toxic chemicals are uncommon but determined by calculating the consequence area for each of the individual toxic components within the mixture. The overall toxic consequence area is the largest of the individual toxic areas.

4.9.13 Effects of Mitigation Measures on Toxic Releases

To this point, isolation and detection capabilities have been taken into account in calculating the quantity of material that may be released during a loss-of-containment event (see Section 4.7.1). However, there may be additional systems in place, such as water sprays, that can mitigate a release once the material has reached the atmosphere.

The effectiveness of mitigating systems are accounted for by reducing the release rate and duration for continuous releases or by reducing the release mass for instantaneous releases. The RBI analyst will need to provide their own reduction factors, based on the effectiveness of their particular spray-system design or passive mitigation technology.

Where mitigation is a major issue, specialists should be consulted to get an accurate input. As an example, it is possible to mitigate HF releases with a water spray. However, the fraction of HF that is removed by a water spray may vary from near 0 % to near 100 % depending on the size of the release, the droplet size, flow rate and orientation of the spray, and several other variables.

4.9.14 Determination of Final Toxic Consequence Areas

The final toxic consequence is determined as a probability weighted average of the individual toxic calculated for each release hole size. A consequence area calculation is performed for the personnel injury areas only since toxic releases do not result in component damage. The probability weighting utilizes the generic frequencies of the release hole sizes obtained in Step 2.3. Equation (3.67) is used to calculate the probability weighted toxic consequence area.

$$CA_{\text{f,inj}}^{\text{tox}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{inj},n}^{\text{tox}}}{gff_{\text{total}}} \right) \tag{3.67}$$

4.9.15 Calculation of Toxic Consequence Areas

a) Step 9.1—For each release hole size selected in Step 2.2, calculate the effective duration of the toxic release using Equation (3.66).

b) Step 9.2—Determine the toxic percentage of the toxic component, $mfrac^{\text{tox}}$, in the release material. If the release fluid is a pure fluid, $mfrac^{\text{tox}} = 1.0$.

   NOTE If there is more than one toxic component in the released fluid mixture, this procedure can be repeated for each toxic component.

c) Step 9.3—For each release hole size, calculate the release rate, $rate_n^{\text{tox}}$, and release mass, $mass_n^{\text{tox}}$, to be used in the toxic analysis using Equation (3.60) and Equation (3.61).

d) Step 9.4—For each release hole size, calculate the toxic consequence area for each of the release hole sizes.

1) HF and H_2S—Calculate $CA_{inj,n}^{tox}$ using Equation (3.62) for a continuous release or Equation (3.63) for an instantaneous release. The constants used in these equations are from Table 4.11.

2) Ammonia and Chlorine—Calculate $CA_{inj,n}^{tox}$ using Equation (3.64) for a continuous release or Equation (3.65) for an instantaneous release. The constants used in these equations are from Table 4.12.

3) For Toxic Fluids Listed in Section 4.9.8—Calculate $CA_{inj,n}^{tox}$ using Equation (3.64) for continuous and instantaneous releases (using 3 minute release for instantaneous releases). The constants used in these equations are from Table 4.13.

e) Step 9.5—If there are additional toxic components in the released fluid mixture, Steps 9.2 through 9.4 should be repeated for each toxic component.

f) Step 9.6—Determine the final toxic consequence areas for personnel injury in accordance with Equation (3.67).

4.10 Determine Nonflammable, Nontoxic Consequence

4.10.1 General

Consequences associated with the release of nonflammable, nontoxic materials are not as severe as with other materials; however, they can still result in serious injury to personnel and damage to equipment.

4.10.2 Consequence of Steam Leaks

Steam represents a hazard to personnel who are exposed to it at high temperatures. Steam leaks do not result in a component damage consequence. In general, steam is at 212 °F (100 °C) immediately after exiting a hole in an equipment item. Within a few feet, depending upon its pressure, steam will begin to mix with air, cool, and condense. At a concentration of about 20 %, the steam/air mixture cools to about 140 °F (60 °C). The approach used here is to assume that injury occurs above 140 °F (60 °C). This temperature was selected as the threshold for injury to personnel, as this is the temperature above which OSHA requires that hot surfaces be insulated to protect against personnel burns. This recommended practice assumes that injury occurs as a result of a 5 second exposure [2] to temperatures of 140 °F (60 °C).

To determine an equation for the consequence area of a continuous release of steam, four release cases (0.25 in., 1 in., 4 in., and 16 in.) were run through atmospheric dispersion software for varying steam pressures. A plot of the release rate vs the area covered by a 20 % concentration of steam shows a linear relationship in accordance with Equation (3.68).

$$CA_{inj,n}^{CONT} = C_9 \cdot rate_n \tag{3.68}$$

For instantaneous release cases, four masses of steam were modeled: 10 lb, 100 lb, 1,000 lb, and 10,000 lb (4.5 kg, 45.4 kg, 454.0 kg, and 4,540 kg), and the relationship between release mass and consequence area to 20 % concentration was found to be in accordance with Equation (3.69).

$$CA_{inj,n}^{INST} = C_{10} \left(mass_n \right)^{0.6384} \tag{3.69}$$

For nonflammable releases of steam, the continuous/instantaneous blending of results should be performed as described in Section 4.8.5. The blending factor, $fact_n^{IC}$, for steam leaks is calculated using Equation (3.70).

$$fact_n^{IC} = \min\left[\left\{ \frac{rate_n}{C_5} \right\},\ 1.0 \right] \tag{3.70}$$

4.10.3 Consequences of Acid and Caustic Leaks

For caustics/acids that have splash type consequences, water was chosen as a representative fluid to determine the personnel consequence area. Acid or caustic leaks do not result in a component damage consequence. The consequence area was defined at the 180° semi-circular area covered by the liquid spray or rainout. Modeling was performed at three pressures; 15 psig, 30 psig, and 60 psig (103.4 kPa, 206.8 kPa, and 413.7 kPa) for four release hole sizes (see Table 4.4). Continuous liquid releases were modeled only since instantaneous gas releases are assumed not to produce rainout. The results were analyzed to obtain a correlation between release rate and consequence area and were divided by 5 since it is believed that serious injuries to personnel are only likely to occur within about 20 % of the total splash area as calculated by the above method.

The resulting consequence area for nonflammable releases of acids and caustics is calculated using Equation (3.71) and Equation (3.72).

$$CA_{\text{inj},n}^{\text{CONT}} = 0.2 \cdot a x^{b} \tag{3.71}$$

$$CA_{\text{inj},n}^{\text{INST}} = 0.0 \tag{3.72}$$

The constants a and b shown in Equation (3.71), are functions of pressure and are shown in Table 4.9.

Since there are no consequences associated with an instantaneous release of acid or caustic, the instantaneous/continuous blending factor, $fact_n^{\text{IC}}$, is equal to 0.0.

4.10.4 Blending of Results Based on Release Type

The consequence area calculations yield significantly different results depending on whether the continuous area equations are used or the instantaneous area equations are used. The nonflammable, nontoxic personnel injury consequence area for steam or acid leaks can be calculated for each hole size using Equation (3.73).

$$CA_{\text{inj},n}^{\text{leak}} = CA_{\text{inj},n}^{\text{INST}} \cdot fact_n^{\text{IC}} + CA_{\text{inj},n}^{\text{CONT}} \left(1 - fact_n^{\text{IC}}\right) \tag{3.73}$$

NOTE There is no need to calculate a component damage area for nonflammable releases of steam or acid/caustic.

$$CA_{\text{cmd},n}^{\text{leak}} = 0.0 \tag{3.74}$$

4.10.5 Determination of Final Nonflammable, Nontoxic Consequence Areas

The final nonflammable, nontoxic consequence areas are determined as a probability weighted average of the individual consequence areas calculated for each release hole size. Nonflammable, nontoxic consequences do not impact equipment so damage areas are not calculated. Probability weighting uses the generic frequencies of the release hole sizes provided in Part 2, Table 3.1. Equation (3.75) is used to calculate the probability weighted nonflammable, nontoxic consequence area for steam, caustic, or acid releases.

$$CA_{\text{f,inj}}^{\text{nfnt}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{inj},n}^{\text{leak}}}{gff_{\text{total}}} \right) \tag{3.75}$$

The term $CA_{\text{inj},n}^{\text{leak}}$ in Equation (3.75) represents the personnel injury areas for each of the holes sizes either due to steam or acid releases as described in Section 4.10.2 and Section 4.10.3.

4.10.6 Calculation of Nonflammable, Nontoxic Consequence Areas

a) Step 10.1—For each release hole size, calculate the nonflammable, nontoxic consequence area.

   1) For Steam—Calculate $CA_{\text{inj},n}^{\text{CONT}}$ using Equation (3.68) and $CA_{\text{inj},n}^{\text{INST}}$ using Equation (3.69).

   2) For Acids or Caustics—Calculate $CA_{\text{inj},n}^{\text{CONT}}$ for liquid releases using Equations (3.71) and (3.72).

      NOTE 1 Data are not provided for an instantaneous release; therefore, $CA_{\text{inj},n}^{\text{INST}} = 0.0$.

b) Step 10.2—For each release hole size, calculate the instantaneous/continuous blending factor, $fact_n^{\text{IC}}$. For steam, use Equation (3.70). For acids or caustics, $fact_n^{\text{IC}} = 0.0$.

c) Step 10.3—For each release hole size, calculate the blended nonflammable, nontoxic personnel injury consequence area for steam or acid leaks, $CA_{\text{inj},n}^{\text{leak}}$, using Equation (3.73) based on the consequence areas from Step 10.1 and the blending factor, $fact_n^{\text{IC}}$, from Step 10.2.

   NOTE 2 There is no need to calculate a component damage area for the Level 1 nonflammable releases (steam or acid/caustic):

$$CA_{\text{cmd},n}^{\text{leak}} = 0.0 \tag{3.76}$$

d) Step 10.4—Determine the final nonflammable, nontoxic consequence areas for personnel injury, $CA_{\text{inj}}^{\text{nfnt}}$, using Equation (3.75) based on consequence areas calculated for each release hole size in Step 10.3.

   NOTE 3 There is no need to calculate a final nonflammable, nontoxic consequence area for component damage area for the Level 1 nonflammable releases (steam or acid/caustic), or:

$$CA_{\text{f,cmd}}^{\text{nfnt}} = 0.0 \tag{3.77}$$

4.11 Determine the Component Damage and Personnel Injury Consequence Areas

4.11.1 Overview

The final consequence areas for component damage and personnel injury are the maximum areas of those calculated for:

a) flammable consequence; see Section 4.8,

b) toxic consequence; see Section 4.9, and

c) nonflammable, nontoxic consequence (see Section 4.10).

4.11.2 Final Component Damage Consequence Area

The final component damage consequence area is:

$$CA_{\text{f,cmd}} = \max\left[CA_{\text{f,cmd}}^{\text{flam}},\ CA_{\text{f,cmd}}^{\text{tox}},\ CA_{\text{f,cmd}}^{\text{nfnt}}\right] \tag{3.78}$$

NOTE Since the component damage consequence areas for toxic releases, $CA_{\text{cmd}}^{\text{tox}}$, and nonflammable, nontoxic releases, $CA_{\text{cmd}}^{\text{nfnt}}$, are both equal to zero, the final component damage consequence area is equal to the consequence area calculated for flammable releases, $CA_{\text{cmd}}^{\text{flam}}$.

$$CA_{\text{f,cmd}} = CA_{\text{f,cmd}}^{\text{flam}} \tag{3.79}$$

4.11.3 Final Personnel Injury Consequence Area

The final personnel injury consequence area is:

$$CA_{\text{inj}} = \max\left[CA_{\text{f,inj}}^{\text{flam}},\ CA_{\text{f,inj}}^{\text{tox}},\ CA_{\text{f,inj}}^{\text{nfnt}}\right] \tag{3.80}$$

4.11.4 Final Consequence Area

The final consequence area is:

$$CA_{\text{f}} = \max\left[CA_{\text{f,cmd}}, CA_{\text{f,inj}}\right] \tag{3.81}$$

4.11.5 Calculation of Final Consequence Area

a) Step 11.1—Calculate the final component damage consequence area, $CA_{\text{f,cmd}}$, using Equation (3.79).

b) Step 11.2—Calculate the final personnel injury consequence area, $CA_{\text{f,inj}}$, using Equation (3.80).

c) Step 11.3—Calculate the final consequence area, CA_{f}, using Equation (3.81).

4.12 Determine the Financial Consequence

4.12.1 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} of a loss of containment and subsequent release of hazardous materials can be determined by adding up the individual costs discussed above:

$$C_f^{\text{fin}} = FC_{\text{f,cmd}} + FC_{\text{f,affa}} + FC_{\text{f,prod}} + FC_{\text{f,inj}} + FC_{\text{f,environ}} \tag{3.82}$$

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.

4.12.2 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, $holecast_n$, 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 $holecast_n$ may be multiplied 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 (3.83). The probability weighting utilizes the generic frequencies of the release hole sizes provided in Part 2, Table 3.1.

$$FC_{\text{f,cmd}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot holecost_n}{gff_{\text{total}}} \right) \cdot matcost \cdot costfactor \tag{3.83}$$

4.12.3 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 (3.56) and Equation (3.84).

$$FC_{\text{f,affa}} = CA_{\text{f,cmd}} \cdot equipcost \tag{3.84}$$

4.12.4 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 online 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 (3.85). The probability weighting uses the generic frequencies of the release hole sizes provided in Table 3.1 of Part 2.

$$Outage_{\text{cmd}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot Outage_n}{gff_{\text{total}}} \right) \cdot Outage_{\text{mult}} \tag{3.85}$$

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, $Outage_{\text{mult}}$, 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 (3.86).

$$Outage_{\text{affa}} = 10^{1.242 + 0.585 \cdot \log_{10}\left[FC_{\text{affa}} \cdot (10)^{-6}\right]} \tag{3.86}$$

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.

$$FC_{\text{f,prod}} = \left(Outage_{\text{cmd}} + Outage_{\text{affa}}\right)\left(prodcost\right) \tag{3.87}$$

4.12.5 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.

The costs associated with personnel injury are calculated using Equation (3.88):

$$FC_{\text{inj}} = CA_{\text{inj}} \cdot popdens \cdot injcost \tag{3.88}$$

Alternatively, the consequence related to injury, $C_{\text{f}}^{\text{inj}}$, may be calculated using safety consequence in Section 4.13.

4.12.6 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, $frac_{\text{evap}}$, as a function of the NBP is provided in Table 4.18. As an alternative, the following equation can be used to estimate $frac_{\text{evap}}$:

$$frac_{\text{evap}} = \begin{bmatrix} -7.1408 + 8.5827(10)^{-3} \cdot \left(\left(C_{12} \cdot NBP\right) + C_{41}\right) \\ -3.5594(10)^{-6} \cdot \left(\left(C_{12} \cdot NBP\right) + C_{41}\right)^2 \\ + \dfrac{2331.1}{\left(C_{12} \cdot NBP\right) + C_{41}} - \dfrac{203{,}545}{\left(\left(C_{12} \cdot NBP\right) + C_{41}\right)^2} \end{bmatrix} \tag{3.89}$$

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 (3.90) 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.

$$vol_n^{\text{env}} = \frac{C_{13} \cdot mass_n \left(1 - frac_{\text{evap}}\right)}{\rho_{\text{l}}} \tag{3.90}$$

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 (3.91).

$$FC_{\text{f,environ}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot vol_n^{\text{env}}}{gff_{\text{total}}} \right) \cdot envcost \tag{3.91}$$

4.12.7 Calculation of Financial Consequence

a) Step 12.1—Calculate the cost (consequence in \$) to repair the specific piece of equipment, $FC_{\text{f,cmd}}$, using Equation (3.83) 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, $FC_{\text{f,affa}}$, using Equation (3.84) and component damage consequence area, $CA_{\text{f,cmd}}$, calculated in Step 11.1. The equipment cost factor, $equipcost$, is the unit equipment replacement cost in \$/ft^2 (\$/m^2).

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 (3.85) 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, $Outage_{\text{affa}}$, using Equation (3.86) and the cost of damage to the surrounding equipment in the affected area, $FC_{\text{f,affa}}$, calculated in Step 12.2.

   3) Calculate the cost of business interruption, $FC_{\text{f,prod}}$, using Equation (3.87). 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, $CA_{\text{f,inj}}$, calculated in Step 11.2. The unit population density, $popdens$, is the average number of personnel on the unit per ft^2 (personnel/m^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, $FC_{\text{f,environ}}$, 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} using Equation (3.85), which is the sum of the costs determined in Steps 12.1 through 12.5.

4.13 Determine Safety Consequence

4.13.1 General

The final safety consequence, 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 (3.92). 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.

$$C_f^{inj} = CA_f^{inj} \cdot popdens \tag{3.92}$$

The $popdens$ of a 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-operator. 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 (3.80). Flammable injury COF is calculated using Section 4.8.8, Step 8.15, toxic injury area from Section 4.9.15, Step 9.6, and nonflammable, nontoxic injury area from 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 (3.93).

$$Pers\#_{avg} = \frac{\left(Pers\#_1 \cdot Present\%_n\right) + \left(Pers\#_2 \cdot Present\%_{n1}\right) + \left(Pers\#_3 \cdot Present\%_{n2}\right)....}{100} \tag{3.93}$$

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 (3.94).

$$popdens = \frac{Pers\#_{avg}}{Area_n^{safety}} \tag{3.94}$$

Alternatively, the consequence related to injury, C_f^{inj}, may be calculated potential injury costs as part of the financial consequence in Section 4.12.6.

4.13.3 Calculation of Safety Consequence

a) Step 13.1—Calculate the CA_f^{inj} using Equation (3.80).

b) Step 13.2—Calculate the average personnel, $Pers\#_{avg}$, present in the unit using Equation (3.93).

c) Step 13.3—Calculate the area the unit covers, $Area_n^{\text{safety}}$. The $Area_n^{\text{safety}}$ 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.

d) Step 13.4—Calculate the unit population density, $popdens$, using average population present, $Pers\#_{\text{avg}}$, and the $Area_n^{\text{safety}}$ using Equation (3.94).

e) Step 13.5—Calculate the $SC_{\text{f}}^{\text{inj}}$ using the $CA_{\text{f}}^{\text{inj}}$ and $popdens$ using Equation (3.92).

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

b is a variable provided for reference fluids for Level 1 consequence analysis for analysis

$b_{cmd}^{AIL\text{-}CONT}$ is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area

$b_{cmd}^{AIL\text{-}INST}$ is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area

$b_{cmd}^{AINL\text{-}CONT}$ is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area

$b_{cmd}^{AINL\text{-}INST}$ is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area

$b_{inj}^{AIL\text{-}CONT}$ is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area

$b_{inj}^{AIL\text{-}INST}$ is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area

$b_{inj}^{AINL\text{-}CONT}$ is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area

$b_{inj}^{AINL\text{-}INST}$ is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area

C_d is the release hole coefficient of discharge, unitless

C_f^{area} is the safety consequence impact area, ft^2 (m^2)

C_f^{fin} is the financial consequence, $

C_f^{inj} is the injury consequence, injuries

C_p is the specific heat of the released fluid, Btu/lb-°R (J/kg-K)

CA^{AIL} is the flammable consequence area where autoignition is likely to occur, ft^2 (m^2)

CA^{AINL} is the flammable consequence area where autoignition is not likely to occur, ft^2 (m^2)

$CA^{AIT\text{-}blend}$ is the AIT blended flammable consequence area, ft^2 (m^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, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{AIL-CONT}}$ is the component damage flammable consequence area for continuous releases that is likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{AIL-INST}}$ is the component damage flammable consequence area for instantaneous releases that is likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{AINL}}$ is the continuous/instantaneous blended component damage flammable consequence area that is not likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{AINL-CONT}}$ is the component damage flammable consequence area for continuous releases that is not likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{AINL-INST}}$ is the component damage flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{cmd},n}^{\text{flam}}$ is the blended component damage flammable consequence area, associated with the n^{th} release hole size, ft^2 (m^2)

CA_{f} is the final consequence area, ft^2 (m^2)

$CA_{\text{f,cmd}}$ is the final component damage consequence area, ft^2 (m^2)

$CA_{\text{f,cmd}}^{\text{flam}}$ is the final probability weighted component damage flammable consequence area, ft^2 (m^2)

$CA_{\text{f,cmd}}^{\text{nfnt}}$ is the component damage nonflammable, nontoxic consequence area, ft^2 (m^2)

$CA_{\text{f,cmd}}^{\text{tox}}$ is the final probability weighted component damage toxic consequence area, ft^2 (m^2)

$CA_{\text{f,inj}}$ is the final personnel injury consequence area, ft^2 (m^2)

$CA_{\text{f,inj}}^{\text{flam}}$ is the final probability weighted personnel injury flammable consequence area, ft^2 (m^2)

$CA_{\text{f,inj},n}^{\text{flam}}$ is the blended personnel injury flammable consequence area, associated with the n^{th} release hole size, ft^2 (m^2)

$CA_{\text{f,inj}}^{\text{nfnt}}$ is the final probability weighted personnel injury consequence area for nonflammable, nontoxic releases such as steam or acids, ft^2 (m^2)

$CA_{\text{f,inj}}^{\text{tox}}$ is the final probability weighted personnel injury toxic consequence area, ft^2 (m^2)

$CA_{\text{f,max}}$ is the final maximum consequence area, ft^2 (m^2)

$CA_{\text{f},n}^{\text{CONT}}$ is the consequence area for a continuous release, ft^2 (m^2)

$CA_{\mathrm{f},n}^{\mathrm{INST}}$	is the consequence area for an instantaneous release, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{AIL\text{-}CONT}}$	is the personnel injury flammable consequence area for continuous releases that is likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{AIL\text{-}INST}}$	is the personnel injury flammable consequence area for instantaneous releases that is likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{AINL\text{-}CONT}}$	is the personnel injury flammable consequence area for continuous releases that is not likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{AINL\text{-}INST}}$	is the personnel injury flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{CONT}}$	is the personnel injury consequence area for continuous releases, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{INST}}$	is the personnel injury consequence area for instantaneous releases, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{acid}}$	is the personnel injury consequence area for caustic and acid leaks, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{leak}}$	is the personnel injury nonflammable, nontoxic consequence area for steam or acid leaks, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{stm}}$	is the personnel injury consequence area for steam leaks, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{tox\text{-}CONT}}$	is the personnel injury toxic consequence area for a continuous release, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{inj},n}^{\mathrm{tox\text{-}INST}}$	is the personnel injury toxic consequence area for an instantaneous release, associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{n}^{\mathrm{IC\text{-}blend}}$	is the continuous/instantaneous blended flammable consequence area, ft^2 (m^2)
c	is a gas release constant used in HF and H_2S releases for the COF 1 toxic area analysis
$costfactor$	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, in. (mm)

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 10,000 lb (4,536 kg)
$envcost$	is the environmental cleanup costs, \$/bbl
$equipcost$	is the process unit replacement costs for component, \$/ft^2 (\$/m^2)
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, \$
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.
$fact_{mit}$	is the consequence area adjustment factor, based on the mitigation 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
$frac_{evap}$	is the fraction of the released liquid pool that evaporates, needed to estimate the volume of material for environmental cleanup
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 = $32.2 (\text{lbm}-\text{ft}) / (\text{lbf}-\text{s}^2) \left[1.0 (\text{kg}-\text{m}) / (\text{N}-\text{s}^2)\right]$
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, $
$K_{v,n}$	is the liquid flow viscosity correction factor, associated with the n^{th} release hole size, unitless
k	is the release fluid ideal gas specific heat capacity ratio, 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
MW	is the release fluid molecular weight, lb/lb-mol (kg/kg-mol)
$mass_{add,n}$	is the mass contributed by the surrounding equipment in the inventory group (limited by W_{max8}), associated 3 minutes release of the n^{th} release hole size, lb (kg)
$mass_{avail,n}$	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 n^{th} release hole size, lb (kg)
$mass_{comp}$	is the component mass for the component or piece of equipment being evaluated, lb (kg)
$mass_{comp,i}$	is the component mass for each of the i components or pieces or equipment that is included in the inventory group, lb (kg)
$mass_{inv}$	is the inventory group mass, lb (kg)
$mass_n$	is the adjusted or mitigated discharge mass used associated with the n^{th} release hole size, lb (kg)
$mass_n^{tox}$	is the release mass of toxic component used in the toxic consequence calculation associated with the n^{th} release hole size, lb (kg)
$matcost$	is the material cost factor
$mfrac^{tox}$	is the mass fraction of toxic material in the released fluid mixture
NBP	is the normal boiling point, °F (°C)
$Outage_{affa}$	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

$Outage_{\text{mult}}$	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 n^{th} release hole size, days
P_{atm}	is the atmospheric pressure, psia (kPa)
P_{s}	is the storage or normal operating pressure, psia (kPa)
P_{trans}	is the transition back pressure, psia (kPa). 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
$Pers\#_{\text{avg}}$	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)
$prodcost$	is the cost of lost production due to downtime to repair equipment, \$/day
R	is the universal gas constant = 1545 ft-lbf/(lb-mol-°R) [8.314 J/(kg-mol-K)]
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, lb/s (kg/s)
$rate_n^{\text{tox}}$	is the release mass rate of toxic component used in the consequence calculation, associated with the n^{th} release hole size, lb/s (kg/s)
T_{s}	is the storage or normal operating temperature, °R (K)
t_n	is the time to release 10,000 lb of fluid mass, calculated for each of the n release hole sizes selected, seconds
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_{max8}	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, lb/s (kg/s)
W_n	is the gas or liquid release rate associated with the n^{th} release hole size, lb/s (kg/s)
x_{i}	is the mole fraction of the component and $Property_{\text{i}}$ may be the NBP, MW, or density of the individual components in the fluid mixture

ρ	is the density, lb/ft^3 (kg/m^3)
ρ_{atm}	is the atmospheric air density, lb/ft^3 (kg/m^3)
ρ_l	is the liquid density at storage or normal operating conditions, lb/ft^3 (kg/m^3)
ρ_v	is the vapor density, lb/ft^3 (kg/m^3)

4.15 Tables

Table 4.1—List of Representative Fluids Available for Level 1 Consequence Analysis

Representative Fluid	Fluid Type (see Section 4.1.5)	Examples of Applicable Materials
C_1–C_2	Type 0	Methane, ethane, ethylene, liquefied natural gas (LNG), fuel gas
C_3–C_4	Type 0	Propane, butane, isobutane, liquefied petroleum gas (LPG)
C_5	Type 0	Pentane
C_6–C_8	Type 0	Gasoline, naphtha, light straight run, heptane
C_9–C_{12}	Type 0	Diesel, kerosene
C_{13}–C_{16}	Type 0	Jet fuel, kerosene, atmospheric gas oil
C_{17}–C_{25}	Type 0	Gas oil, typical crude
C_{25+}	Type 0	Residuum, heavy crude, lube oil, seal oil
H_2	Type 0	Hydrogen
H_2S	Type 0	Hydrogen sulfide
HF	Type 0	Hydrogen fluoride
HCl	Type 0	Hydrochloric acid
Water	Type 0	Water
Steam	Type 0	Steam
Acid	Type 0	Acid, caustic
Aromatics	Type 1	Benzene, toluene, xylene, cumene
$AlCl_3$	Type 0	Aluminum chloride
Pyrophoric	Type 0	Pyrophoric materials
Ammonia	Type 0	Ammonia
Chlorine	Type 0	Chlorine
CO	Type 1	Carbon monoxide
DEE	Type 1 (see Note 2)	Diethyl ether
HCl	Type 0 (see Note 1)	Hydrogen chloride
Nitric acid	Type 0 (see Note 1)	Nitric acid
NO_2	Type 0 (see Note 1)	Nitrogen dioxide
Phosgene	Type 0	Phosgene
TDI	Type 0 (see Note 1)	Toluene diisocyanate
Methanol	Type 1	Methanol
PO	Type 1	Propylene oxide
Styrene	Type 1	Styrene
EEA	Type 1	Ethylene glycol monoethyl ether acetate
EE	Type 1	Ethylene glycol monoethyl ether
EG	Type 1	Ethylene glycol
EO	Type 1	Ethylene oxide

NOTE 1 HCl, nitric acid, NO_2, and TDI are Type 1 toxic fluids.

NOTE 2 DEE is a Type 0 toxic fluid.

Table 4.2—Properties of the Representative Fluids Used in Level 1 Consequence Analysis

Fluid	MW	Liquid Density (lb/ft³)	NBP (°F)	Ambient State	Ideal Gas Specific Heat Eq.	C_p Ideal Gas Constant *A*	Ideal Gas Constant *B*	Ideal Gas Constant *C*	Ideal Gas Constant *D*	Ideal Gas Constant *E*	AIT (°F)
C_1–C_2	23	15.639	−193	Gas	Note 1	12.3	1.150E-01	−2.87E-05	−1.30E-09	N/A	1036
C_3–C_4	51	33.61	−6.3	Gas	Note 1	2.632	0.3188	−1.347E-04	1.466E-08	N/A	696
C_5	72	39.03	97	Liquid	Note 1	−3.626	0.4873	−2.6E-04	5.3E-08	N/A	544
C_6–C_8	100	42.702	210	Liquid	Note 1	−5.146	6.762E-01	−3.65E-04	7.658E-08	N/A	433
C_9–C_{12}	149	45.823	364	Liquid	Note 1	−8.5	1.01E+00	−5.56E-04	1.180E-07	N/A	406
C_{13}–C_{16}	205	47.728	502	Liquid	Note 1	−11.7	1.39E+00	−7.72E-04	1.670E-07	N/A	396
C_{17}–C_{25}	280	48.383	651	Liquid	Note 1	−22.4	1.94E+00	−1.12E-03	−2.53E-07	N/A	396
C_{25+}	422	56.187	981	Liquid	Note 1	−22.4	1.94E+00	−1.12E-03	−2.53E-07	N/A	396
Pyrophoric	149	45.823	364	Liquid	Note 1	−8.5	1.01E+00	−5.56E-04	1.180E-07	N/A	Note 4
Aromatic	104	42.7	293	Liquid	Note 2	8.93E+04	2.15E+05	7.72E+02	9.99E+04	2.44E+03	914
Styrene	104	42.7	293	Liquid	Note 2	8.93E+04	2.15E+05	7.72E+02	9.99E+04	2.44E+03	914
Water	18	62.3	212	Liquid	Note 3	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Steam	18	62.3	212	Gas	Note 2	3.34E+04	2.68E+04	2.61e+03	8.90E+03	1.17E+03	N/A
Acid/caustic-LP	18	62.3	212	Liquid	Note 2	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Acid/caustic-MP	18	62.3	212	Liquid	Note 2	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Acid/caustic-HP	18	62.3	212	Liquid	Note 2	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Methanol	32	50	149	Liquid	Note 2	3.93E+04	8.79E+04	1.92E+03	5.37E+04	8.97E+02	867
Anhydrous ammonia	17.03	38.55	−28.2	Gas	Note 1	27.26	2.31E-04	2.24E-07	2.17E-10	5.41E-14	N/A
H_2	2	4.433	−423	Gas	Note 1	27.1	9.270E-03	−1.38E-05	7.650E-09	N/A	752
H_2S	34	61.993	−75	Gas	Note 1	31.9	1.440E-03	2.430E-05	−1.18E-08	N/A	500
HF	20	60.37	68	Gas	Note 1	29.1	6.610E-04	−2.03E-06	2.500E-09	N/A	32000
HCl	36	74	−121	Gas	—	—	—	—	—	—	N/A
CO	28	50	−312	Gas	Note 2	2.91E+04	8.77E+03	3.09E+03	8.46E+03	1.54E+03	1128
DEE	74	45	95	Liquid	Note 2	8.62E+04	2.55E+05	1.54E+03	1.44E+05	−6.89E+02	320
Nitric acid	63	95	250	Liquid	—	—	—	—	—	—	N/A
$AlCl_3$	133.5	152	382	Powder	Note 1	6.49E+01	8.74E+01	1.82E-02	-4.65E-04	N/A	1036
NO_2	46	58	275	Liquid	—	—	—	—	—	—	N/A
Phosgene	99	86	181	Liquid	—	—	—	—	—	—	N/A
TDI	174	76	484	Liquid	—	—	—	—	—	—	1148

Fluid	MW	Liquid Density (lb/ft^3)	NBP (°F)	Ambient State	Ideal Gas Specific Heat Eq.	C_p					AIT (°F)
						Ideal Gas Constant A	Ideal Gas Constant B	Ideal Gas Constant C	Ideal Gas Constant D	Ideal Gas Constant E	
PO	58	52	93	Liquid	Note 2	4.95E+04	1.74E+05	1.56E+03	1.15E+05	7.02E+02	840
EEA	132	61	313	Liquid	Note 2	1.06E+05	2.40E+05	6.59E+02	1.50E+05	1.97E+03	715
EE	90	58	275	Liquid	Note 2	3.25E+04	3.00E+05	1.17E+03	2.08E+05	4.73E+02	455
EG	62	69	387	Liquid	Note 2	6.30E+04	1.46E+05	1.67E+03	9.73E+04	7.74E+02	745
EO	44	55	51	Gas	Note 2	3.35E+04	1.21E+05	1.61E+03	8.24E+04	7.37E+02	804

NOTE 1 $C_p = A + BT + CT^2 + DT^3$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 2 $C_p = A + B\left(\dfrac{\frac{C}{T}}{\sinh\left[\frac{C}{T}\right]}\right)^2 + D\left(\dfrac{\frac{E}{T}}{\cosh\left[\frac{E}{T}\right]}\right)^2$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 3 $C_p = A + BT + CT^2 + DT^3 + ET^4$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 4 Pyrophoric materials, by definition, autoignite and therefore a very low value for the AIT is assumed.

NOTE 5 Conversion factor for units of C_p is 1 J/(kg-mol-K) = 5.27×10^{-4} Btu/(kg-mol-°R).

NOTE 6 For Note 1, R = 8.314 J/mol-K; for Notes 2 and 3, R = 8314 Jkmol-K.

Table 4.2M—Properties of the Representative Fluids Used in Level 1 Consequence Analysis

Fluid	MW	Liquid Density (kg/m³)	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	C_p Ideal Gas Constant *A*	Ideal Gas Constant *B*	Ideal Gas Constant *C*	Ideal Gas Constant *D*	Ideal Gas Constant *E*	AIT (°C)
C_1–C_2	23	250.512	−125	Gas	Note 1	12.3	1.15E-01	−2.87E-05	−1.30E-09	N/A	558
C_3–C_4	51	538.379	−21	Gas	Note 1	2.632	0.3188	−1.35E-04	1.47E-08	N/A	369
C_5	72	625.199	36	Liquid	Note 1	−3.626	0.4873	−2.60E-04	5.30E-08	N/A	284
C_6–C_8	100	684.018	99	Liquid	Note 1	−5.146	6.76E-01	−3.65E-04	7.66E-08	N/A	223
C_9–C_{12}	149	734.012	184	Liquid	Note 1	−8.5	1.01E+00	−5.56E-04	1.18E-07	N/A	208
C_{13}–C_{16}	205	764.527	261	Liquid	Note 1	−11.7	1.39E+00	−7.72E-04	1.67E-07	N/A	202
C_{17}–C_{25}	280	775.019	344	Liquid	Note 1	−22.4	1.94E+00	−1.12E-03	−2.53E-07	N/A	202
C_{25+}	422	900.026	527	Liquid	Note 1	−22.4	1.94E+00	−1.12E-03	−2.53E-07	N/A	202
Pyrophoric	149	734.012	184	Liquid	Note 1	−8.5	1.01E+00	−5.56E-04	1.18E-07	N/A	Note 4
Aromatic	104	683.986	145	Liquid	Note 2	8.93E+04	2.15E+05	7.72E+02	9.99E+04	2.44E+03	490
Styrene	104	683.986	145	Liquid	Note 2	8.93E+04	2.15E+05	7.72E+02	9.99E+04	2.44E+03	490
Water	18	997.947	100	Liquid	Note 3	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Steam	18	997.947	100	Gas	Note 2	3.34E+04	2.68E+04	2.61E+03	8.90E+03	1.17E+03	N/A
Acid/caustic-LP	18	997.947	100	Liquid	Note 3	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Acid/caustic-MP	18	997.947	100	Liquid	Note 3	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Acid/caustic-HP	18	997.947	100	Liquid	Note 3	2.76E+05	−2.09E+03	8.125	−1.41E-02	9.37E-06	N/A
Methanol	32	800.920	65	Liquid	Note 2	3.93E+04	8.79E+04	1.92E+03	5.37E+04	8.97E+02	464
Anhydrous ammonia	17.03	0.769	−33.34	Gas	Note 1	27.26	2.31E-04	2.24E-07	2.17E-10	5.41E-14	N/A
H_2	2	71.010	−253	Gas	Note 1	27.1	9.27E-03	−1.38E-05	7.65E-09	N/A	400
H_2S	34	993.029	−59	Gas	Note 1	31.9	1.44E-03	2.43E-05	−1.18E-08	N/A	260
HF	20	967.031	20	Gas	Note 1	29.1	6.61E-04	−2.03E-06	2.50E-09	N/A	17760
HCl	36	1185.362	−85	Gas	—	—	—	—	—	—	N/A
CO	28	800.920	−191	Gas	Note 2	2.91E+04	8.77E+03	3.09E+03	8.46E+03	1.54E+03	609
DEE	74	720.828	35	Liquid	Note 2	8.62E+04	2.55E+05	1.54E+03	1.44E+05	−6.89E+02	160
Nitric acid	63	1521.749	121	Liquid	—	—	—	—	—	—	N/A
$AlCl_3$	133.5	2434.798	194	Powder	Note 1	6.49E+01	8.74E+01	1.82E-02	-4.65E-04	N/A	558
NO_2	90	929.068	135	Liquid	—	—	—	—	—	—	N/A
Phosgene	99	1377.583	83	Liquid	—	—	—	—	—	—	N/A
TDI	174	1217.399	251	Liquid	—	—	—	—	—	—	620

Fluid	MW	Liquid Density (kg/m^3)	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	C_p Ideal Gas Constant A	Ideal Gas Constant B	Ideal Gas Constant C	Ideal Gas Constant D	Ideal Gas Constant E	AIT (°C)
PO	58	832.957	34	Liquid	Note 2	4.95E+04	1.74E+05	1.56E+03	1.15E+05	7.02E+02	449
EEA	132	977.123	156	Liquid	Note 2	1.06E+05	2.40E+05	6.59E+02	1.50E+05	1.97E+03	379
EE	90	929.068	135	Liquid	Note 2	3.25E+04	3.00E+05	1.17E+03	2.08E+05	4.73E+02	235
EG	62	1105.270	197	Liquid	Note 2	6.30E+04	1.46E+05	1.67E+03	9.73E+04	7.74E+02	396
EO	44	881.013	11	Gas	Note 2	3.35E+04	1.21E+05	1.61E+03	8.24E+04	7.37E+02	429

NOTE 1 $C_p = A + BT + CT^2 + DT^3$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 2 $C_p = A + B\left(\dfrac{\frac{C}{T}}{\sinh\left[\frac{C}{T}\right]}\right)^2 + D\left(\dfrac{\frac{E}{T}}{\cosh\left[\frac{E}{T}\right]}\right)^2$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 3 $C_p = A + BT + CT^2 + DT^3 + ET^4$ with T in K, units for C_p are J/(kg-mol-K).

NOTE 4 Pyrophoric materials, by definition, autoignite and therefore a very low value for the AIT is assumed.

NOTE 5 For Note 1, R = 8.314 J/mol-K; for notes 2 and 3, R = 8314 Jkmol-K.

Table 4.3—Level 1 Guidelines for Determining the Phase of a Fluid

Phase of Fluid at Normal Operating (Storage) Conditions	Phase of Fluid at Ambient (After Release) Conditions	Determination of Final Phase for Consequence Calculation
Gas	Gas	Model as gas
Gas	Liquid	Model as gas
Liquid	Gas	Model as gas *unless* the fluid boiling point at ambient conditions is greater than 80 °F, then model as a liquid
Liquid	Liquid	Model as liquid

Table 4.4—Release Hole Sizes and Areas Used in Level 1 and 2 Consequence Analyses

Release Hole Number	Release Hole Size	Range of Hole Diameters (in.)	Release Hole Diameter, d_n (in.)
1	Small	0 to 1/4	$d_1 = 0.25$
2	Medium	> 1/4 to 2	$d_2 = 1$ $d_2 = \min[D, 1]$
3	Large	> 2 to 6	$d_3 = 4$ $d_3 = \min[D, 4]$
4	Rupture	> 6	$d_4 = \min[D, 16]$

Table 4.4M—Release Hole Sizes and Areas Used in Level 1 and 2 Consequence Analyses

Release Hole Number	Release Hole Size	Range of Hole Diameters (mm)	Release Hole Diameter, d_n (mm)
1	Small	0 to 6.4	$d_1 = 6.4$
2	Medium	> 6.4 to 51	$d_2 = 25$ $d_2 = \min[D, 25]$
3	Large	> 51 to 152	$d_3 = 102$ $d_3 = \min[D, 102]$
4	Rupture	> 152	$d_4 = \min[D, 406]$

Table 4.5—Detection and Isolation System Rating Guide

Type of Detection System	Detection Classification
Instrumentation designed specifically to detect material losses by changes in operating conditions (i.e. loss of pressure or flow) in the system.	A
Suitably located detectors to determine when the material is present outside the pressure-containing envelope.	B
Visual detection, cameras, or detectors with marginal coverage.	C
Type of Isolation System	**Isolation Classification**
Isolation or shutdown systems activated directly from process instrumentation or detectors, with no operator intervention.	A
Isolation or shutdown systems activated by operators in the control room or other suitable locations remote from the leak.	B
Isolation dependent on manually operated valves.	C

Table 4.6—Adjustments to Release Based on Detection and Isolation Systems

System Classifications		Release Magnitude Adjustment	Reduction Factor, $fact_{di}$
Detection	Isolation		
A	A	Reduce release rate or mass by 25 %	0.25
A	B	Reduce release rate or mass by 20 %	0.20
A or B	C	Reduce release rate or mass by 10 %	0.10
B	B	Reduce release rate or mass by 15 %	0.15
C	C	No adjustment to release rate or mass	0.00

Table 4.7—Leak Durations Based on Detection and Isolation Systems

Detection System Rating	Isolation System Rating	Maximum Leak Duration, ld_{max}
A	A	20 minutes for < 1/4 in. leaks 10 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 5 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks
A	B	30 minutes for < 1/4 in. leaks 20 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 10 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks
A	C	40 minutes for < 1/4 in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 20 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks
B	A or B	40 minutes for < 1/4 in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 20 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks
B	C	1 hour for < 1/4 in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 20 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks
C	A, B, or C	1 hour for < 1/4 in. leaks 40 minutes for $d_2 = \frac{1}{4} > D \le 1$ in. leaks 20 minutes for $d_3 = 1 > D \le 4$ in. leaks 60 minutes for $d_4 = D \ge 4$ in. leaks

Table 4.7M—Leak Durations Based on Detection and Isolation Systems

Detection System Rating	Isolation System Rating	Maximum Leak Duration, ld_{max}
A	A	20 minutes for < 6.4 mm leaks 10 minutes for $d_2 = 6.4 > D \le 25$ mm leaks 5 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks
A	B	30 minutes for < 6.4 mm leaks 20 minutes for $d_2 = 6.4 > D \le 25$ mm leaks 10 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks
A	C	40 minutes for < 6.4 mm leaks 30 minutes for $d_2 = 6.4 > D \le 25$ mm leaks 20 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks
B	A or B	40 minutes for < 6.4 mm leaks 30 minutes for $d_2 = 6.4 > D \le 25$ leaks 20 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks
B	C	1 hour for < 6.4 mm leaks 30 minutes for $d_2 = 6.4 > D \le 25$ mm leaks 20 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks
C	A, B, or C	1 hour for < 6.4 mm leaks 40 minutes for $d_2 = 6.4 > D \le 25$ mm leaks 20 minutes for $d_3 = 25 > D \le 102$ mm leaks 60 minutes for $d_4 = D \ge 102$ mm leaks

Table 4.8—Component Damage Flammable Consequence Equation Constants

Fluid	Fluid Type	Continuous Releases Constants								Instantaneous Releases Constants							
		Autoignition Not Likely (AINL-CONT)				Autoignition Likely (AIL-CONT)				Autoignition Not Likely (AINL-INST)				Autoignition Likely (AIL-INST)			
		Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1–C_2	Type 0	43.0	0.98			280.0	0.95			41.0	0.67			1079	0.62		
C_3–C_4	Type 0	49.48	1.00			313.6	1.00			27.96	0.72			522.9	0.63		
C_5	Type 0	25.17	0.99	536.0	0.89	304.7	1.00			13.38	0.73	1.49	0.85	275.0	0.61		
C_6–C_8	Type 0	29.0	0.98	182.0	0.89	312.4	1.00	525.0	0.95	13.98	0.66	4.35	0.78	275.7	0.61	57.0	0.55
C_9–C_{12}	Type 0	12.0	0.98	130.0	0.90	391.0	0.95	560.0	0.95	7.1	0.66	3.3	0.76	281.0	0.61	6.0	0.53
C_{13}–C_{16}	Type 0			64.0	0.90			1023	0.92			0.46	0.88			9.2	0.88
C_{17}–C_{25}	Type 0			20.0	0.90			861.0	0.92			0.11	0.91			5.6	0.91
C_{25+}	Type 0			11.0	0.91			544.0	0.90			0.03	0.99			1.4	0.99
Pyrophoric	Type 1	12.0	0.98	130.0	0.90	391.0	0.95	560.0	0.95	7.1	0.66	3.3	0.76	281.0	0.61	6.0	0.53
Aromatics	Type 1	17.87	1.097	103.0	0	374.5	1.055			11.46	0.667	70.12	0	512.6	0.713	701.2	0
Styrene	Type 1	17.87	1.097	103.0	0	374.5	1.055			11.46	0.667	70.12	0	512.6	0.713	701.2	0
Water	Type 0																
Steam	Type 0																
Acid/caustic-LP	Type 0																
Acid/caustic-MP	Type 0																
Acid/caustic-HP	Type 0																
Methanol	Type 1	0.02256	0.9092	1750.6	0.9342					28.1170	0.6670	1.9188	0.9004				
H_2	Type 0	64.5	0.992			420.0	1.00			61.5	0.657			1430	0.618		
H_2S	Type 0	32.0	1.00			203.0	0.89			148.0	0.63			357.0	0.61		
HF	Type 0																
CO	Type 1	0.107	1.752							69.68	0.667						
DEE	Type 1	39.84	1.134	737.4	1.106	320.7	1.033	6289	0.649	155.7	0.667	5.105	0.919			5.672	0.919
PO	Type 1	14.61	1.114	1295	0.9560					65.58	0.667	3.404	0.869				
EEA	Type 1	0.002	1.035	117.0	0					8.014	0.667	69.0	0				
EE	Type 1	12.62	1.005	173.1	0					38.87	0.667	72.21	0				
EG	Type 1	7.721	0.973	108.0	0					6.525	0.667	69.0	0				
EO	Type 1	31.03	1.069							136.3	0.667						

Table 4.8M—Component Damage Flammable Consequence Equation Constants

Fluid	Fluid Type	Continuous Releases Constants								Instantaneous Releases Constants							
		Autoignition Not Likely (AINL-CONT)				Autoignition Likely (AIL-CONT)				Autoignition Not Likely (AINL-INST)				Autoignition Likely (AIL-INST)			
		Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1–C_2	Type 0	8.669	0.98			55.13	0.95			6.469	0.67			163.7	0.62		
C_3–C_4	Type 0	10.13	1.00			64.23	1.00			4.590	0.72			79.94	0.63		
C_5	Type 0	5.115	0.99	100.6	0.89	62.41	1.00			2.214	0.73	0.271	0.85	41.38	0.61		
C_6–C_8	Type 0	5.846	0.98	34.17	0.89	63.98	1.00	103.4	0.95	2.188	0.66	0.749	0.78	41.49	0.61	8.180	0.55
C_9–C_{12}	Type 0	2.419	0.98	24.60	0.90	76.98	0.95	110.3	0.95	1.111	0.66	0.559	0.76	42.28	0.61	0.848	0.53
C_{13}–C_{16}	Type 0			12.11	0.90			196.7	0.92			0.086	0.88			1.714	0.88
C_{17}–C_{25}	Type 0			3.785	0.90			165.5	0.92			0.021	0.91			1.068	0.91
C_{25+}	Type 0			2.098	0.91			103.0	0.90			0.006	0.99			0.284	0.99
Pyrophoric	Type 1	2.419	0.98	24.60	0.90	76.98	0.95	110.3	0.95	1.111	0.66	0.559	0.76	42.28	0.61	0.848	0.53
Aromatics	Type 1	3.952	1.097	21.10	0	80.11	1.055			1.804	0.667	14.36	0	83.68	0.713	143.6	0
Styrene	Type 1	3.952	1.097	21.10	0	80.11	1.055			1.804	0.667	14.36	0	83.68	0.713	143.6	01.00
Water	Type 0																
Steam	Type 0																
Acid/caustic-LP	Type 0																
Acid/caustic-MP	Type 0																
Acid/caustic-HP	Type 0																
Methanol	Type 1	0.005	0.909	340.4	0.934					4.425	0.667	0.363	0.900				
H_2	Type 0	13.13	0.992			86.02	1.00			9.605	0.657			216.5	0.618		
H_2S	Type 0	6.554	1.00			38.11	0.89			22.63	0.63			53.72	0.61		
HF	Type 0																
CO	Type 1	0.040	1.752							10.97	0.667						
DEE	Type 1	9.072	1.134	164.2	1.106	67.42	1.033	976.0	0.649	24.51	0.667	0.981	0.919			1.090	0.919
PO	Type 1	3.277	1.114	257.0	0.960					10.32	0.667	0.629	0.869				
EEA	Type 1	0	1.035	23.96	0					1.261	0.667	14.13	0				
EE	Type 1	2.595	1.005	35.45	0					6.119	0.667	14.79	0				
EG	Type 1	1.548	0.973	22.12	0					1.027	0.667	14.13	0				
EO	Type 1	6.712	1.069							21.46	0.667						

Table 4.9—Personnel Injury Flammable Consequence Equation Constants

Fluid	Fluid Type	Continuous Releases Constants								Instantaneous Releases Constants							
		Autoignition Not Likely (AINL-CONT)				Autoignition Likely (AIL-CONT)				Autoignition Not Likely (AINL-INST)				Autoignition Likely (AIL-INST)			
		Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1–C_2	Type 0	110.0	0.96			745.0	0.92			79.0	0.67			3100	0.63		
C_3–C_4	Type 0	125.2	1.00			836.7	1.00			57.72	0.75			1769	0.63		
C_5	Type 0	62.05	1.00	1545	0.89	811.0	1.00			28.45	0.76	4.34	0.85	959.6	0.63		
C_6–C_8	Type 0	68.0	0.96	516.0	0.89	828.7	1.00	1315	0.92	26.72	0.67	12.7	0.78	962.8	0.63	224.0	0.54
C_9–C_{12}	Type 0	29.0	0.96	373.0	0.89	981.0	0.92	1401	0.92	13.0	0.66	9.5	0.76	988.0	0.63	20.0	0.54
C_{13}–C_{16}	Type 0			183.0	0.89			2850	0.90			1.3	0.88			26.0	0.88
C_{17}–C_{25}	Type 0			57.0	0.89			2420	0.90			0.32	0.91			16.0	0.91
C_{25+}	Type 0			33.0	0.89			1604	0.90			0.081	0.99			4.1	0.99
Pyrophoric	Type 1	29.0	0.96	373.0	0.89	981.0	0.92	1401	0.92	13.0	0.66	9.5	0.76	988.0	0.63	20.0	0.54
Aromatics	Type 1	64.14	0.963	353.5	0.883	1344	0.937	487.7	0.268	18.08	0.686	0.14	0.935	512.6	0.713	1.404	0.935
Styrene	Type 1	64.14	0.963	353.5	0.883	1344	0.937	487.7	0.268	18.08	0.686	0.14	0.935	512.6	0.713	1.404	0.935
Water	Type 0																
Steam	Type 0																
Acid/caustic-LP	Type 0			2699.5	0.2024			2699.5	0.2024								
Acid/caustic-MP	Type 0			3366.2	0.2878			3366.2	0.2878								
Acid/caustic-HP	Type 0			6690	0.2469			6690	0.2469								
Methanol	Type 1	0.0164	1.0083	4483.7	0.9015					37.71	0.6878	6.2552	0.8705				
H_2	Type 0	165.0	0.933			1117	1.00			118.5	0.652			4193	0.621		
H_2S	Type 0	52.0	1.00			375.0	0.94			271.0	0.63			1253	0.63		
HF	Type 0																
CO	Type 1	27.0	0.991							105.3	0.692						
DEE	Type 1	128.1	1.025	971.9	1.219	1182	0.997	2658	0.864	199.1	0.682	47.13	0.814	821.7	0.657	52.36	0.814
PO	Type 1	38.76	1.047	1955	0.840					83.68	0.682	15.21	0.834				
EEA	Type 1	0.017	0.946	443.1	0.835					11.41	0.687	0.153	0.924				
EE	Type 1	35.56	0.969	46.56	0.800					162.0	0.660	0.152	0.927				
EG	Type 1	25.67	0.947	324.7	0.869					8.971	0.687	0.138	0.922				
EO	Type 1	49.43	1.105							220.8	0.665						

Table 4.9M—Personnel Injury Flammable Consequence Equation Constants

Fluid	Fluid Type	Continuous Releases Constants								Instantaneous Releases Constants							
		Autoignition Not Likely (AINL-CONT)				Autoignition Likely (AIL-CONT)				Autoignition Not Likely (AINL-INST)				Autoignition Likely (AIL-INST)			
		Gas		Liquid		Gas		Liquid		Gas		Liquid		Gas		Liquid	
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
C_1–C_2	Type 0	21.83	0.96			143.2	0.92			12.46	0.67			473.9	0.63		
C_3–C_4	Type 0	25.64	1.00			171.4	1.00			9.702	0.75			270.4	0.63		
C_5	Type 0	12.71	1.00	290.1	0.89	166.1	1.00			4.820	0.76	0.790	0.85	146.7	0.63		
C_6–C_8	Type 0	13.49	0.96	96.88	0.89	169.7	1.00	252.8	0.92	4.216	0.67	2.186	0.78	147.2	0.63	31.89	0.54
C_9–C_{12}	Type 0	5.755	0.96	70.03	0.89	188.6	0.92	269.4	0.92	2.035	0.66	1.609	0.76	151.0	0.63	2.847	0.54
C_{13}–C_{16}	Type 0			34.36	0.89			539.4	0.90			0.242	0.88			4.843	0.88
C_{17}–C_{25}	Type 0			10.70	0.89			458.0	0.90			0.061	0.91			3.052	0.91
C_{25+}	Type 0			6.196	0.89			303.6	0.90			0.016	0.99			0.833	0.99
Pyrophoric	Type 1	5.755	0.96	70.03	0.89	188.6	0.92	269.4	0.92	2.035	0.66	1.609	0.76	151.0	0.63	2.847	0.54
Aromatics	Type 1	12.76	0.963	66.01	0.883	261.9	0.937	56.00	0.268	2.889	0.686	0.027	0.935	83.68	0.713	0.273	0.935
Styrene	Type 1	12.76	0.963	66.01	0.883	261.9	0.937	56.00	0.268	2.889	0.686	0.027	0.935	83.68	0.713	0.273	0.935
HF	Type 0																
Water	Type 0																
Acid/caustic	Type 0			194.280	0.2024			194.280	0.2024								
Acid/caustic	Type 0			392.588	0.2878			392.588	0.2878								
Acid/caustic	Type 0			755.408	0.2469			755.408	0.2469								
Steam	Type 0																
Methanol	Type 1	0	1.008	849.9	0.902					6.035	0.688	1.157	0.871				
H_2	Type 0	32.05	0.933			228.8	1.00			18.43	0.652			636.5	0.621		
H_2S	Type 0	10.65	1.00			73.25	0.94			41.43	0.63			191.5	0.63		
CO	Type 1	5.491	0.991							16.91	0.692						
DEE	Type 1	26.76	1.025	236.7	1.219	241.5	0.997	488.9	0.864	31.71	0.682	8.333	0.814	128.3	0.657	9.258	0.814
PO	Type 1	8.239	1.047	352.8	0.840					13.33	0.682	2.732	0.834				
EEA	Type 1	0	0.946	79.66	0.835					1.825	0.687	0.030	0.924				
EE	Type 1	7.107	0.969	8.142	0.800					25.36	0.660	0.029	0.927				
EG	Type 1	5.042	0.947	59.96	0.869					1.435	0.687	0.027	0.922				
EO	Type 1	11.00	1.105							34.70	0.665						

Table 4.10—Adjustments to Flammable Consequence for Mitigation Systems

Mitigation System	**Consequence Area Adjustment**	**Consequence Area Reduction Factor,** $fact_{mit}$
Inventory blowdown, coupled with isolation system classification B or higher	Reduce consequence area by 25 %	0.25
Fire water deluge system and monitors	Reduce consequence area by 20 %	0.20
Fire water monitors only	Reduce consequence area by 5 %	0.05
Foam spray system	Reduce consequence area by 15 %	0.15

Table 4.11—Gas Release Toxic Consequence Equation Constants for HF and H_2S

Continuous Releases Duration (minutes)	**HF**		**H_2S**	
	c	d	c	d
5	1.1401	3.5683	1.2411	3.9686
10	1.1031	3.8431	1.2410	4.0948
20	1.0816	4.1040	1.2370	4.238
40	1.0942	4.3295	1.2297	4.3626
60	1.1031	4.4576	1.2266	4.4365
Instantaneous Releases	1.4056	0.33606	0.9674	2.7840

Table 4.12—Gas Release Toxic Consequence Equation Constants for Ammonia and Chlorine

Continuous Releases Duration (minutes)	Anhydrous Ammonia		Chlorine	
	e	*f*	*e*	*f*
5	2,690	1.183	15,150	1.097
10	3,581	1.181	15,934	1.095
15	4,459	1.180	17,242	1.092
20	5,326	1.178	19,074	1.089
25	6,180	1.176	21,430	1.085
30	7,022	1.174	24,309	1.082
35	7,852	1.172	27,712	1.077
40	8,669	1.169	31,640	1.072
45	9,475	1.166	36,090	1.066
50	10,268	1.161	41,065	1.057
55	11,049	1.155	46,564	1.046
60	11,817	1.145	52,586	1.026
Instantaneous Releases	14.171	0.9011	14.976	1.177

Table 4.12M—Gas Release Toxic Consequence Equation Constants for Ammonia and Chlorine

Continuous Releases Duration (minutes)	Anhydrous Ammonia		Chlorine	
	e	*f*	*e*	*f*
5	636.7	1.183	3,350	1.097
10	846.3	1.181	3,518	1.095
15	1,053	1.180	3,798	1.092
20	1,256	1.178	4,191	1.089
25	1,455	1.176	4,694	1.085
30	1,650	1.174	5,312	1.082
35	1,842	1.172	6,032	1.077
40	2,029	1.169	6,860	1.072
45	2,213	1.166	7,788	1.066
50	2,389	1.161	8,798	1.057
55	2,558	1.155	9,890	1.046
60	2,714	1.145	10,994	1.026
Instantaneous Releases	2.684	0.9011	3.528	1.177

Table 4.13—Continuous Gas and Liquid Release Toxic Consequence Equation Constants for Miscellaneous Chemicals

Chemical	Release Duration (minutes)	Gas Release Constants		Liquid Release Constants	
		e	*f*	*e*	*f*
Aluminum chloride ($AlCl_3$)	All	17.663	0.9411	N/A	N/A
Carbon monoxide (CO)	3	41.412	1.15	N/A	N/A
	5	279.79	1.06	N/A	N/A
	10	834.48	1.13	N/A	N/A
	20	2,915.9	1.11	N/A	N/A
	40	5,346.8	1.17	N/A	N/A
	60	6,293.7	1.21	N/A	N/A
Hydrogen chloride (HCl)	3	215.48	1.09	N/A	N/A
	5	536.28	1.15	N/A	N/A
	10	2,397.5	1.10	N/A	N/A
	20	4,027.0	1.18	N/A	N/A
	40	7,534.5	1.20	N/A	N/A
	60	8,625.1	1.23	N/A	N/A
Nitric acid	3	53,013	1.25	5,110.0	1.08
	5	68,700	1.25	9,640.8	1.02
	10	96,325	1.24	12,453	1.06
	20	126,942	1.23	19,149	1.06
	40	146,941	1.22	31,145	1.06
	60	156,345	1.22	41,999	1.12
Nitrogen dioxide (NO_2)	3	6,633.1	0.70	21,32.9	0.98
	5	9,221.4	0.68	2,887.0	1.04
	10	11,965	0.68	6,194.4	1.07
	20	14,248	0.72	13,843	1.08
	40	22,411	0.70	27,134	1.12
	60	24,994	0.71	41,657	1.13
Phosgene	3	12,902	1.20	3,414.8	1.06
	5	22,976	1.29	6,857.1	1.10
	10	48,985	1.24	21,215	1.12
	20	108,298	1.27	63,361	1.16
	40	244,670	1.30	178,841	1.20
	60	367,877	1.31	314,608	1.23

Chemical	Release Duration (minutes)	Gas Release Constants		Liquid Release Constants	
		e	*f*	*e*	*f*
Toluene diisocyanate (TDI)	3	N/A	N/A	3,692.5	1.06
	5	N/A	N/A	3,849.2	1.09
	10	N/A	N/A	4,564.9	1.10
	20	N/A	N/A	4,777.5	1.06
	40	N/A	N/A	4,953.2	1.06
	60	N/A	N/A	5,972.1	1.03
Ethylene glycol monoethyl ether (EE)	1.5	3.819	1.171	N/A	N/A
	3	7.438	1.181	N/A	N/A
	5	17.735	1.122	N/A	N/A
	10	33.721	1.111	3.081	1.105
	20	122.68	0.971	16.877	1.065
	40	153.03	0.995	43.292	1.132
	60	315.57	0.899	105.74	1.104
Ethylene oxide (EO)	1.5	2.083	1.222	N/A	N/A
	3	12.32	1.207	N/A	N/A
	5	31.5	1.271	N/A	N/A
	10	185	1.2909	N/A	N/A
	20	926	1.2849	N/A	N/A
	40	4,563	1.1927	N/A	N/A
	60	7,350	1.203	N/A	N/A
Propylene oxide	3	0.0019	1.913	N/A	N/A
	5	0.3553	1.217	10.055	1.198
	10	0.7254	1.2203	40.428	1.111
	20	1.7166	1.2164	77.743	1.114
	40	3.9449	1.2097	152.35	1.118
	60	4.9155	1.2522	1812.8	0.9855

Table 4.13M—Continuous Gas and Liquid Release Toxic Consequence Equation Constants for Miscellaneous Chemicals

Chemical	Release Duration (minutes)	Gas Release Constants		Liquid Release Constants	
		e	*f*	*e*	*f*
Aluminum chloride ($AlCl_3$)	All	3.4531	0.9411	N/A	N/A
Carbon monoxide (CO)	3	9.55	1.15	N/A	N/A
	5	60.09	1.06	N/A	N/A
	10	189.42	1.13	N/A	N/A
	20	651.49	1.11	N/A	N/A
	40	1,252.67	1.17	N/A	N/A
	60	1,521.89	1.21	N/A	N/A
Hydrogen chloride (HCL)	3	47.39	1.09	N/A	N/A
	5	123.67	1.15	N/A	N/A
	10	531.45	1.10	N/A	N/A
	20	950.02	1.18	N/A	N/A
	40	1,851.8	1.20	N/A	N/A
	60	2,118.87	1.23	N/A	N/A
Nitric acid	3	13,230.9	1.25	1,114.96	1.08
	5	17,146	1.25	2,006.1	1.02
	10	23,851.3	1.24	2,674.47	1.06
	20	31,185	1.23	4,112.65	1.06
	40	35,813.7	1.22	6,688.99	1.06
	60	38,105.8	1.22	9,458.29	1.12
Nitrogen dioxide (NO_2)	3	1,071.74	0.70	430	0.98
	5	1,466.57	0.68	610.31	1.04
	10	1,902.9	0.68	1,340.93	1.07
	20	2,338.76	0.72	3,020.54	1.08
	40	3621.1	0.70	6,110.67	1.12
	60	4,070.48	0.71	9,455.68	1.13
Phosgene	3	3,095.33	1.20	733.39	1.06
	5	5,918.49	1.29	1,520.02	1.10
	10	12,129.3	1.24	4,777.72	1.12
	20	27,459.6	1.27	14,727.5	1.16
	40	63,526.4	1.30	42,905	1.20
	60	96,274.2	1.31	77,287.7	1.23

Chemical	Release Duration (minutes)	Gas Release Constants		Liquid Release Constants	
		e	*f*	*e*	*f*
Toluene diisocyanate (TDI)	3	N/A	N/A	793.04	1.06
	5	N/A	N/A	846.54	1.09
	10	N/A	N/A	1,011.9	1.10
	20	N/A	N/A	1,026.06	1.06
	40	N/A	N/A	1,063.8	1.06
	60	N/A	N/A	1,252.57	1.03
Ethylene glycol monoethyl ether (EE)	1.5	0.8954	1.171	N/A	N/A
	3	1.7578	1.181	N/A	N/A
	5	4.0002	1.122	N/A	N/A
	10	7.5400	1.111	0.6857	1.105
	20	24.56	0.971	3.6389	1.065
	40	31.22	0.995	9.8422	1.132
	60	59.67	0.899	23.513	1.104
Ethylene oxide (EO)	1.5	0.5085	1.222	N/A	N/A
	3	2.9720	1.207	N/A	N/A
	5	7.9931	1.271	N/A	N/A
	10	47.69	1.2909	N/A	N/A
	20	237.57	1.2849	N/A	N/A
	40	1,088.4	1.1927	N/A	N/A
	60	1,767.5	1.203	N/A	N/A
Propylene oxide	3	0.0008	1.913	N/A	N/A
	5	0.0864	1.217	2.4084	1.198
	10	0.1768	1.2203	9.0397	1.111
	20	0.4172	1.2164	17.425	1.114
	40	0.9537	1.2097	34.255	1.118
	60	1.2289	1.2522	367.06	0.9855

Table 4.14—Toxic Impact Criteria for Toxic Chemicals

Toxic Component	Probit Parameters			IDLH (ppm)	AEGL3-10 (ppm)	AEGL3-30 (ppm)	AEGL3-60 (ppm)	EPA Toxic Endpoint (mg/L)	ERPG-3
	A	B	N						
Acrolein	−9.93	2.05	1.00	2	—	—	—	0.50	—
Acrylonitrile	−29.42	3.01	1.43	85	—	—	—	0.08	75
Aluminum trichloride	−14.65	2.00	1.00	—	—	—	—	—	—
Ammonia	−35.90	1.85	2.00	300	—	—	—	0.14	750
Benzene	−109.8	5.30	2.00	500	—	—	—		1,000
Bromine	−9.04	0.92	2.00	3	—	—	—	0.01	5
Carbon monoxide	−37.98	3.70	1.00	1,200	1,700	600	330	—	500
Carbon tetrachloride	−6.29	0.41	2.50	200	—	—	—	—	750
Chlorine	−8.29	0.92	2.00	10	—	28	20	0.01	20
Ethylene glycol monoethyl ether	−15.54	1.00	2.00	—	—	—	—	—	—
Ethylene oxide	−6.21	1.00	1.00	800	—	—	—	—	—
Formaldehyde	−12.24	1.30	2.00	20	—	—	—	0.01	25
Hydrogen chloride	−16.85	2.00	1.00	50	620	210	100	0.03	150
Hydrogen cyanide	−29.42	3.01	1.43	50	27	21	15	—	25
Hydrogen fluoride	−48.33	4.853	1.00	30	170	62	44	—	
Hydrogen sulfide	−31.42	3.01	1.43	100	76	60	50	—	100
Methanol	—	—	—	—	15,000	15,000	7,900	—	
Methyl bromide	−56.81	5.27	1.00	—	—	—	—	—	200
Methyl isocyanate	−5.64	1.64	0.65	—	—	—	—	—	—
Nitric acid	−5.48	1.00	2.00	—	—	—	—	—	—
Nitrogen dioxide	−13.79	1.40	2.00	20	—	—	—	—	—
Phosgene	−19.27	3.69	1.00	2	3.6	1.5	0.75	—	—
Propylene oxide	−7.415	0.509	2.00	400	—	—	—	0.59	750
Styrene	—	—	—	700	—	—	—	—	1,000
Sulphur dioxide	−15.67	2.10	1.00	100	—	—	—	—	—
Toluene	−6.79	0.41	2.50	500	1,600	900	630	—	—
Toluene diisocyanate	−4.49	1.00	2.00	—	—	—	—	—	—

NOTE Shaded areas in the above table designate toxic fluids and toxic impact criteria modeled in the Level 1 consequence analysis described in Section 4.9. In the Level 2 consequence analysis, all data can be considered for all other fluids and toxic impact criteria.

Table 4.15—Example Component Damage Costs

Equipment Type	Component Type	Damage Cost (2001 U.S. Dollars), *holecost*			
		Small	Medium	Large	Rupture
Compressor	COMPC	10,000	20,000	100,000	300,000
	COMPR	5,000	10,000	50,000	100,000
Heat exchanger	HEXSS, HEXTS, HEXTUBE	1,000	2,000	20,000	60,000
Pipe	PIPE-1	5	0	0	20
	PIPE-2	5	0	0	40
	PIPE-4	5	10	0	60
	PIPE-6	5	20	0	120
	PIPE-8	5	30	60	180
	PIPE-10	5	40	80	240
	PIPE-12	5	60	120	360
	PIPE-16	5	80	160	500
	PIPEGT16	10	120	240	700
Pump	PUMP2S, PUMP1S	1,000	2,500	5,000	5,000
	PUMPR	1,000	2,500	5,000	10,000
Tank	TANKBOTTOM	5,000	0	0	120,000
	TANKBOTEDGE	5,000	0	0	120,000
	COURSES-10	5,000	12,000	20,000	40,000
FINFAN	FINFAN_TUBE	1,000	2,000	20,000	60,000
	FINFAN HEADER	1,000	2,000	20,000	60,000
Vessel	KODRUM, DRUM	5,000	12,000	20,000	40,000
	FILTER	1,000	2,000	4,000	10,000
	REACTOR	10,000	24,000	40,000	80,000
	COLTOP, COLMID, COLBTM	10,000	25,000	50,000	100,000

Table 4.16—Material Cost Factors

Material	Cost Factor, *matcost*	Material	Cost Factor, *matcost*
Carbon steel	1.0	Clad Alloy 400	6.4
Organic coatings (< 80 mil)	1.2	90/10 Cu/Ni	6.8
1.25Cr-0.5Mo	1.3	Clad Alloy 600	7.0
2.25Cr-1Mo	1.7	CS PTFE lined	7.8
5Cr-0.5Mo	1.7	Clad nickel	8.0
7Cr-0.5Mo	2.0	Alloy 800	8.4
Clad 304 SS	2.1	70/30 Cu/Ni	8.5
Fiberglass	2.5	904L	8.8
PP lined	2.5	Alloy 20	11
9Cr-1Mo	2.6	Alloy 400	15
405 SS	2.8	Alloy 600	15
410 SS	2.8	Nickel	18
304 SS	3.2	Acid brick	20
Clad 316 SS	3.3	Refractory	20
Strip lined alloy	3.3	Alloy 625	26
Organic coating (> 80 mil)	3.4	Titanium	28
CS “saran” lined	3.4	Alloy “C”	29
CS rubber lined	4.4	Zirconium	34
316 SS	4.8	Alloy “B”	36
CS glass lined	5.8	Tantalum	535

Table 4.17—Estimated Equipment Outage

Equipment Type	Component Type	Estimated Outage in Days, $Outage_n$			
		Small	Medium	Large	Rupture
Compressor	COMPC, COMPR	N/A	3	7	N/A
Heat exchanger	HEXSS, HEXTS	2	3	3	10
	HEXTUBE	N/A	N/A	N/A	N/A
Pipe	PIPE-1, PIPE-2	0	N/A	N/A	1
	PIPE-4	0	1	N/A	2
	PIPE-6	0	1	2	3
	PIPE-8	0	2	2	3
	PIPE-10	0	2	2	4
	PIPE-12	1	3	4	4
	PIPE-16	1	3	4	5
	PIPEGT16	1	4	5	7
Pump	PUMP2S, PUMPR, PUMP1S	0	0	0	N/A
Tank	TANKBOTTOM	5	N/A	N/A	50
	TANKBOTEDGE	5	N/A	N/A	50
	COURSE-1 through 10	2	3	3	14
FINFAN	FINFAN_TUBE	0	N/A	N/A	1
	FINFAN HEADER	0	0	2	3
Vessel/FinFan	KODRUM	2	3	3	10
	FILTER	0	1	2	3
	DRUM	2	3	3	10
	REACTOR	4	6	6	21
	COLTOP, COLMID, COLBTM	3	4	5	21

NOTE 1 The outage day values listed above are estimates. The end user should review these to reflect their specific requirements.

NOTE 2 N/A—Not applicable means that these hole sizes are not used for these component types. Refer to Annex 3.A, Section 3.A.3.2.

Table 4.18—Fluid Leak Properties

Fluid	MW	Density (lb/ft^3)	NBP (°F)	Fraction Evaporated in 24 Hours (see Note) $fract_{evap}$
C_1–C_2	23	15.639	−193	1.00
C_3–C_5	58	36.209	31	1.00
C_6–C_8	100	42.702	210	0.90
C_9–C_{12}	149	45.823	364	0.50
C_{13}–C_{16}	205	47.728	502	0.10
C_{17}–C_{25}	280	48.383	651	0.05
C_{25+}	422	56.187	981	0.02
Acid	18	62.3	212	0.90
H_2	2	4.433	−423	1.00
H_2S	34	61.993	−75	1.00
HF	20	60.37	68	1.00
CO	28	50	−312	1.00
DEE	74	45	95	1.00
HCL	36	74	−121	1.00
Nitric acid	63	95	250	0.80
NO_2	90	58	275	0.75
Phosgene	99	86	181	1.00
TDI	174	76	484	0.15
Methanol	32	50	149	1.00
PO	58	52	93	1.00
Styrene	104	42.7	293	0.60
EEA	132	61	313	0.65
EE	90	58	275	0.75
EG	62	69	387	0.45
EO	44	55	51	1.00

NOTE Estimated values.

Table 4.18M—Fluid Leak Properties

Fluid	MW	Density (kg/m^3)	NBP (°C)	Fraction Evaporated in 24 Hours (see Note) $fract_{evap}$
C_1–C_2	23	250.513	−125	1.00
C_3–C_5	58	580.012	−1	1.00
C_6–C_8	100	684.020	99	0.90
C_9–C_{12}	149	734.014	184	0.50
C_{13}–C_{16}	205	764.529	261	0.10
C_{17}–C_{25}	280	775.021	344	0.05
C_{25+}	422	900.029	527	0.02
Acid	18	997.950	100	0.90
H_2	2	71.010	−253	1.00
H_2S	34	993.032	−59	1.00
HF	20	967.034	20	1.00
CO	28	800.923	−191	1.00
DEE	74	720.831	35	1.00
HCL	36	1185.366	−85	1.00
Nitric acid	63	1521.754	121	0.80
NO_2	90	929.071	135	0.75
Phosgene	99	1377.588	83	1.00
TDI	174	1217.403	251	0.15
Methanol	32	800.923	65	1.00
PO	58	832.960	34	1.00
Styrene	104	683.988	145	0.60
EEA	132	977.126	156	0.65
EE	90	929.071	135	0.75
EG	62	1105.274	197	0.45
EO	44	881.015	0	1.00

NOTE Estimated values.

4.16 Figures

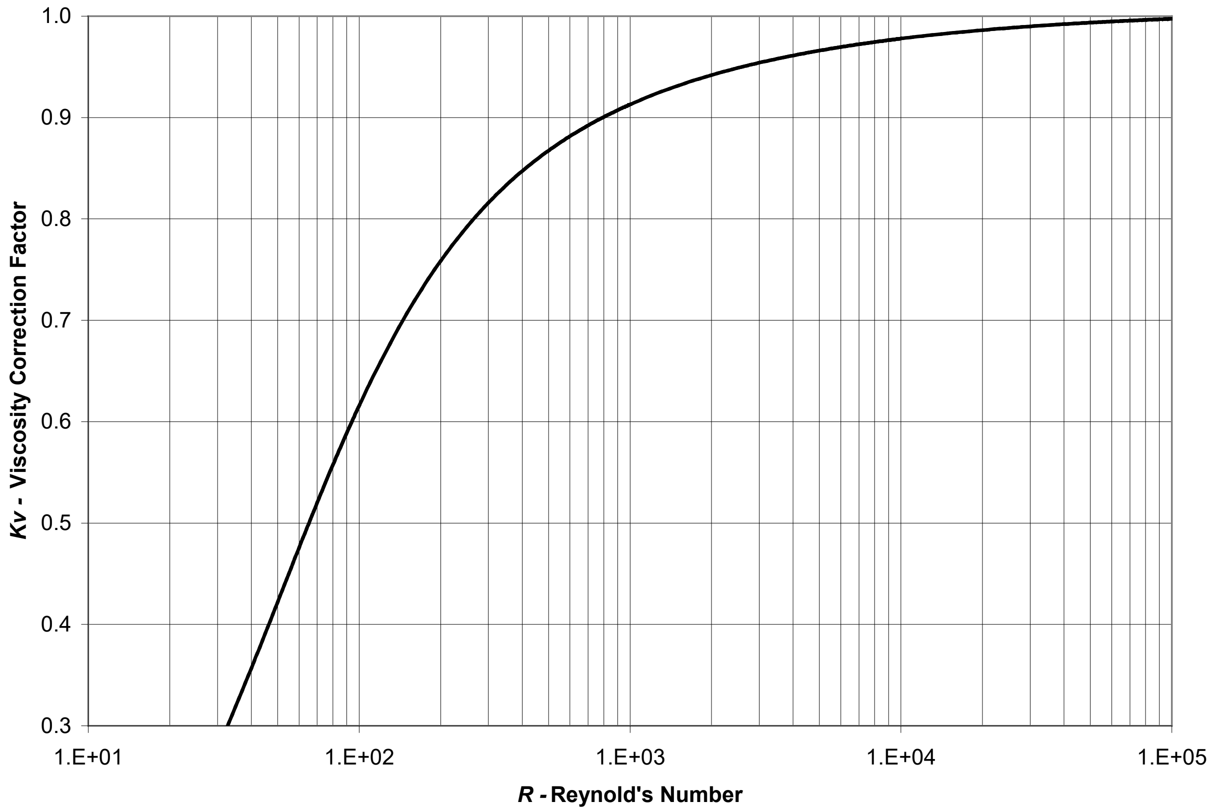


Figure 4.1—Liquid Flow Viscosity Correction Factor, K_v

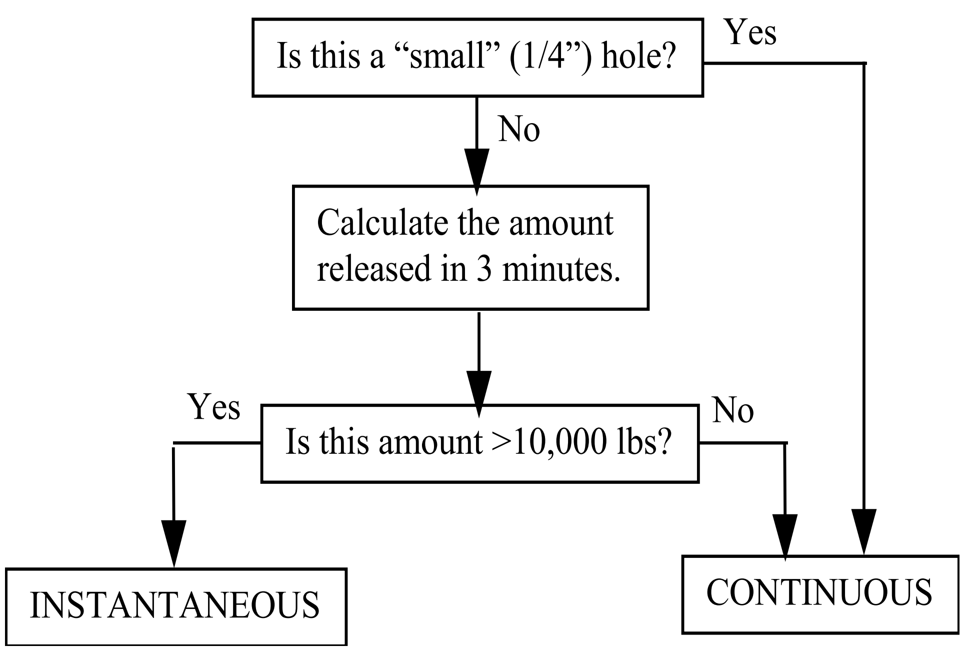


Figure 4.2—Instantaneous and Continuous Determination

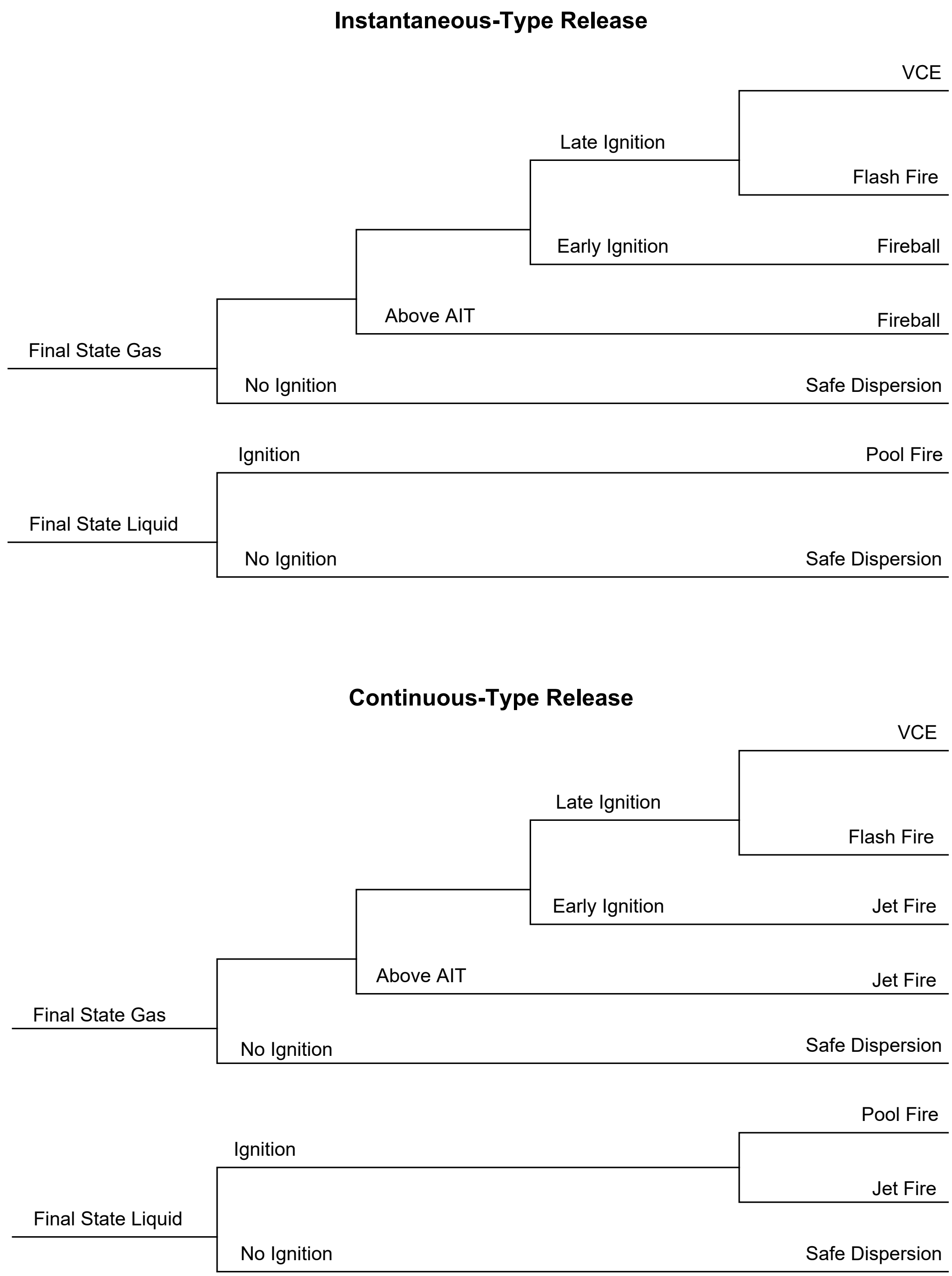


Figure 4.3—Level 1 COF Release Event Tree

5 COF—Level 2

5.1 Determine the Fluid Composition and Associated Properties

5.1.1 General

The Level 2 consequence analysis provides the equations and background information necessary to rigorously calculate consequence areas for several flammable and toxic event outcomes. A summary of these events is provided in Table 5.1.

The actual composition of the fluid, including mixtures, should be used in the analysis. Fluid property solvers are available that allow the analyst to calculate fluid physical properties more accurately. The fluid solver 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 both at storage conditions and conditions after release to the atmosphere.

5.1.2 Required Properties at Storage Conditions

As shown in the flowchart of Figure 5.1, at the start of the consequence analysis, an isothermal flash is used to determine the phase distribution and properties of the multicomponent feed mixture at the storage temperature, T_s, and pressure, P_s. The mass and mole fractions are determined along with the composition of each phase. Thermodynamic properties such as entropy and enthalpy are calculated along with transport properties such as thermal conductivity and viscosity. The required fluid properties at the storage conditions are listed below:

a) storage phase (vapor, liquid, critical, or two-phase),

b) mass fraction liquid, $frac_l$,

c) mass fraction vapor, $frac_v$,

d) MW,

e) liquid density, ρ_l,

f) liquid viscosity, μ_l,

g) ideal gas specific heat ratio, $k = C_p / C_v$,

h) enthalpy of mixture,

i) entropy of mixture (to perform flash calculations),

j) critical pressure and temperature, T_c and P_c,

k) AIT,

l) saturation pressure, $Psat_s$, at storage temperature,

m) flammability limits, LFL and upper flammability limit (UFL),

n) heat of combustion, HC_s, and

o) toxic limits [e.g. IDLH, Emergency Response Planning Guideline (ERPG), acute exposure guideline level (AEGL), probits, etc.].

5.1.3 Required Properties at Flashed Conditions

Analysis requires a fluid property package to isentropically flash (isenthalpic is acceptable) the stored fluid from its normal operating conditions to atmospheric conditions. The effects of flashing on the fluid temperature as well as the phase of the fluid at atmospheric conditions should also be evaluated. Liquid entrainment in the jet release as well as rainout effects could be evaluated to get a more representative evaluation of the release consequences. The isentropic flash calculation from storage conditions to atmospheric pressure, P_{atm}, simulates the release of the fluid from a leaking or ruptured storage container. The resulting flash temperature, T_f, is determined along with the phase distribution and properties of each phase at these conditions. The released mixture can either be a single-phase liquid, a single-phase vapor, or a two-phase mixture of both as shown in Figure 5.1. The required fluid properties at the flashed conditions are listed below:

a) flashed phase (vapor, liquid, or two-phase),

b) flash temperature, T_f,

c) flash fraction, $frac_{fsh}$,

d) density of the liquid, ρ_l,

e) density of the vapor, ρ_v,

f) specific heat of the liquid, Cp_l ,

g) heat of combustion of liquid, HC_l,

h) heat of combustion of vapor, HC_v,

i) latent heat of vaporization of liquid, ΔH_v,

j) bubble point temperature of liquid, T_b, and

k) dew point temperature of vapors, T_d.

As shown in Figure 5.1, where a fluid is flashed to a single-phase liquid, a bubble point temperature calculation is performed at atmospheric pressure to find the temperature, T_b, at which vapor bubbles first appear. Similarly, in the single-phase vapor case, a dew point calculation is performed at atmospheric pressure to find the temperature, T_d, at which liquid drops first start condensing.

For fluids that flash to two-phase, flash calculations at both the bubble point and the dew point of the flashed mixture may be required depending on the composition of the fluid.

a) For pure fluids or binary mixtures (two components in mixture), additional calculations are not necessary because in these cases the bubble point and dew point temperatures are the same and equal to the isentropic flash temperature, i.e. $T_b = T_d = T_f$.

b) For multicomponent mixtures, both the bubble point and the dew point calculations are required.

5.1.4 Calculation of Fluid Properties

a) Step 1.1—Obtain the stored fluid composition. For mixtures, concentrate on the major components within the fluid mixture and attempt to get at least 90 % of the mixture identified and quantified. A more detailed breakdown of the composition is not warranted, unless there are small quantities of toxic materials that are in the mixture.

b) Step 1.2—Using a fluid property solver, determine the fluid properties as specified in Section 5.1.2 a) for the fluid at storage conditions. Research may be required to determine some of the fluid properties required for the analysis, such as LFL, UFL, heat of combustion, and toxic limits. The analyst may need to use MSDSs or other fluid databases, such as DIPPR [3], to determine these properties. Mixing rules (e.g. LaChatalier's mixing principle for LFL and UFL) are available to determine properties of mixtures, but in general a mole weighted method may be used as an estimate.

c) Step 1.3—Using a fluid property solver, perform an isentropic flash (isenthalpic is acceptable) and determine the flash temperature, T_f , the phase of the flashed fluid, and the fraction of fluid flashed, $frac_{fsh}$.

d) Step 1.4—Determine the bubble point or dew point temperature of the flashed fluid, as necessary.

   1) For flashed liquid, determine the bubble point temperature, T_b, at atmospheric pressure.

   2) For flashed vapors, determine the dew point temperature, T_d, at atmospheric pressure.

   3) For fluids that flash to two-phase, the bubble point temperature, T_b, at atmospheric pressure and the dew point temperature, T_d, at atmospheric pressure should be determined.

   NOTE For pure fluids and binary mixtures, no calculation is required since the bubble point temperature and the dew point temperature are equal to the flash temperature, T_f, as determined in Step 1.3.

5.2 Release Hole Size Selection

5.2.1 General

As with the Level 1 approach, a discrete set of release events or release hole sizes are used, as shown in Table 4.4.

5.2.2 Calculation of Release Hole Sizes

The step-by-step methodology for selecting the release hole sizes are in accordance with the Level 1 consequence analysis (see Section 4.2.2).

5.3 Release Rate Calculation

5.3.1 Source Term Modeling

Quantification of the consequence of a release event requires calculations of the release amount (or rate of release), the duration of the release, and the state (e.g. gas, liquid or two-phase) of the material released. The terminology used for determining these parameters is source term modeling. The source term is used as an input to the various consequence models as well as the cloud dispersion analysis.

5.3.2 Determining the Release Phase

Estimation of the release amount or rate is covered for liquids and vapors (gases) in Section 4.3. For calculating the release rate, the release phase must be determined.

NOTE The release phase is different than the phase of the fluid at storage conditions or the phase of the fluid after flashing to atmosphere as described in Section 5.1.2 and Section 5.1.3. This is the phase immediately downstream of the release point and is used for selecting the proper equation for calculating the release rate through the hole or crack opening.

To determine the release phase, the saturation pressure of the stored fluid at the storage temperature, $Psat_s$, must be determined.

$$\text{if } Psat_s \geq P_s \geq P_{atm} \Rightarrow \text{ release phase is vapor} \tag{3.95}$$

$$\text{if } P_s \geq Psat_s > P_{atm} \Rightarrow \text{ release phase is two-phase} \tag{3.96}$$

$$\text{if } P_s \geq P_{atm} > Psat_s \Rightarrow \text{ release phase is liquid} \tag{3.97}$$

5.3.3 Vapor Release Source

As shown in Equation (3.95), if the saturation pressure of the fluid at storage temperature, $Psat_s$, is greater than or equal to the storage pressure, P_s, the fluid will be stored as a gas or vapor and released as a gas or vapor. In this case, calculation of the theoretical release rate, W_n, can be in accordance with Equation (3.6) or Equation (3.7). Most gases will cool as they are depressured through an orifice, so in some cases, condensation will occur and liquid rainout needs to be considered as presented in Section 5.7.2.

For supercritical fluids (stored above critical pressure or temperature), the release rate can be estimated using Equation (3.6); however, in this case the specific heat ratio, k, should be evaluated at the NBP of the fluid mixture or at standard conditions. This will result in a conservative release rate. More rigorous methods, such as the HEM Omega [4] method, can be used to calculate the release rate of a supercritical fluid. In some cases, supercritical fluids will condense upon release, and liquid rainout needs to be considered as presented in Section 5.7.2.

5.3.4 Two-phase Release Source

As shown in Equation (3.96), if the saturation pressure of the fluid at the storage temperature, $Psat_s$, is less than or equal to the storage pressure, P_s, but greater than atmospheric pressure, P_{atm}, the fluid will be stored as a liquid and will be released as a two-phase mixture. In this case, the release rate can be conservatively estimated using the liquid Equation (3.3). Alternatively, a more accurate two-phase flow calculation may be used. For this case, the effect of liquid entrainment in the released jet needs to be considered as well as rainout. Methods for evaluating these effects are presented in Section 5.7.2.

5.3.5 Liquid Release Source

Finally, as shown in Equation (3.97), if the saturation pressure of the fluid at the storage temperature, $Psat_s$, is less than atmospheric pressure, P_{atm}, the fluid will be stored as a liquid and will be released as a liquid. In this case, the release rate can be determined using Equation (3.3).

5.3.6 Calculation of Release Rates

a) Step 3.1—Determine the stored fluid's saturation pressure, $Psat_s$, at the storage temperature.

b) Step 3.2—Determine the release phase using Equations (3.95), (3.96), or (3.97).

c) Step 3.3—For each release hole size selected in Step 2.1, calculate the release hole size area, A_n, using Equation (3.8) based on d_n.

d) Step 3.4—For each release hole size, calculate the release rate, W_n, for each release area, A_n, determined in Step 3.3.

   For liquid releases, use Equation (3.3).

   1) For vapor releases, use Equations (3.6) or (3.7), as applicable.

2) For two-phase releases, use Equation (3.3), for a conservative approximation. As an alternative, a two-phase method, such as the HEM Omega method [4], may be utilized.

5.4 Estimate the Fluid Inventory Available for Release

5.4.1 General

The total amount of fluid inventory available for release is estimated in accordance with the Level 1 consequence analysis (see Section 4.4).

5.4.2 Calculation of Inventory Mass

The step-by-step procedure for estimated the available fluid inventory mass is in accordance with Section 4.4.3.

5.5 Determine Release Type

5.5.1 General

The type of release is established in accordance with the Level 1 consequence analysis, see Section 4.5.

5.5.2 Calculation of Release Type

The step-by-step procedure for determining if the release is classified and continuous or instantaneous is in accordance with Section 4.5.2.

5.6 Estimate the Impact of Detection and Isolation Systems on Release Magnitude

5.6.1 General

The effects of detection and isolation systems are established in accordance with the Level 1 consequence analysis. See Section 4.6.

5.6.2 Calculation for Detection and Isolation Systems

The step-by-step procedure for estimating the impact of detection and isolation systems is in accordance with Section 4.6.6.

5.7 Determine the Release Rate and Mass for COF

5.7.1 General

The Level 2 consequence analysis models two-phase releases and distinguishes between the amount of the theoretical release rate that releases to the atmosphere as vapor or as an aerosol (vapor with entrained liquid) in the form of a jet and the amount of the release that drops to the ground as liquid to form a pool. Analysis requires a fluid property package to isentropically flash (isenthalpic is acceptable) the stored fluid from its normal operating conditions to atmospheric conditions. In addition, the effects of flashing on the fluid temperature as well as the phase of the fluid at atmospheric conditions should be evaluated. Liquid entrainment in the jet release as well as rainout effects could be evaluated to get a more representative evaluation of the release consequences.

5.7.2 Aerosol and Rainout Modeling

When a release is two-phase, there is an amount of liquid entrained in the jet (vapor) portion of the release (aerosol). The remaining liquid portion of the release, or rainout, can be estimated by the following correlation recommended by Kletz [5].

$$frac_{ro} = 1 - 2 \cdot frac_{fsh} \qquad \text{for} \qquad frac_{fsh} < 0.5 \tag{3.98}$$

$$frac_{ro} = 0.0 \qquad \text{for} \qquad frac_{fsh} \geq 0.5 \tag{3.99}$$

Other liquid rainout correlations are available from CCPS [6], Davenport [7], Prugh [8], and Mudan [9].

The fraction that flashes, $frac_{fsh}$, as it is released to the atmosphere can be determined using fluid property software by isentropically (isenthalpically is acceptable) expanding the release fluid from the storage conditions to the atmospheric conditions.

5.7.3 Calculation of Jet Release Rate and Pool Release Rate

Once the release rate is determined and the rainout fraction is estimated, the release rate for modeling pool type consequences, W_n^{pool}, and for modeling jet type consequences, W_n^{jet}, can be determined as follows:

$$W_n^{pool} = rate_n \cdot frac_{ro} \tag{3.100}$$

$$W_n^{jet} = rate_n \left(1 - frac_{ro}\right) \tag{3.101}$$

NOTE The jet release rate may include entrained liquid. To calculate the mass fraction of liquid entrained in the jet, use Equation (3.102).

$$frac_{entl} = \frac{\left(frac_l \cdot frac_{fsh}\right)}{\left(1 - frac_{ro}\right)} \tag{3.102}$$

5.7.4 Vapor Sources from Boiling or Non-boiling Pools

5.7.4.1 General

Vapors evaporating off of the surface of liquid pools, if not ignited immediately, can be the source of vapor clouds that could result in flash fires or VCEs. Quantifying these vapor rates is necessary when determining the impact of these event outcomes. The vapor source rate is dependent on whether the pool is a boiling or a non-boiling pool. The bubble point temperature, T_b, of the liquid is required to determine the type of analysis to be used for liquid pools on the ground.

5.7.4.2 Boiling Liquid Pools

If $T_b < T_g$, where T_g is the ground temperature, then we have the boiling liquid pool case. The temperature of the liquid will remain at its boiling-point temperature T_b (at least near the liquid-vapor interface) while vapor will be rapidly evaporating at a rate that is limited by how fast heat energy can be supplied to the liquid-vapor interface. The partial pressure of the vapor right above the liquid pool will be equal to the atmospheric pressure.

The vapor rate generated off of the surface of a boiling pool, $erate_{\text{b}}$, can be estimated using Equation (3.103) as provided by Shaw and Briscoe [10].

$$erate_n = \pi^{1.5}\left[\frac{X_{\text{surf}} \cdot k_{\text{surf}} \cdot \left(T_{\text{g}} - T_{\text{b}}\right)}{C_{14} \cdot \Delta H_{\text{v}} \sqrt{\pi \cdot \alpha_{\text{surf}}}}\right]\left(2 \cdot g \cdot \dot{V}_{\text{p},n}\right)^{0.5} t_{\text{p},n} \tag{3.103}$$

The surface interaction parameters X_{surf}, k_{surf}, and α_{surf} in the above equation account for the liquid interaction with the surface on which the pool forms. These can be obtained from Table 5.2 repeated from Rijnmond Public Authority [11].

The size of the boiling pool reaches a steady state, when the evaporation rate, $erate_{\text{b}}$, is equal to the pool release rate, W_n^{pool}, as discussed in Section 5.7.3. At this point, the radius of the evaporating pool can be determined using Equation (3.104) as provided by Shaw and Briscoe [10].

$$r_{\text{p},n} = \sqrt{\frac{2}{3}}\left(\frac{8g \cdot \dot{V}_{\text{p},n}}{\pi}\right)^{0.25} t_{\text{p},n}^{0.75} \tag{3.104}$$

5.7.4.3 Non-boiling Liquid Pools

If $T_{\text{b}} > T_{\text{g}}$, then we have the case of a non-boiling (evaporating) liquid pool, where the liquid temperature will be nearly equal to the ground temperature (after some initial transient period), and the vapor pressure right above the pool will be less than atmospheric pressure and equal to the bubble point pressure, $P_{\text{b,g}}$, corresponding to the ground temperature. Thus, an additional thermodynamic calculation is required to determine $P_{\text{b,g}}$. The evaporation rate in this case is primarily limited by how fast the newly generated vapor can be carried away from the interface by diffusion or convection.

The vapor rate generated off of the surface of a non-boiling pool, $erate_{\text{nb}}$, can be estimated using Equation (3.105) as provided by Shaw and Briscoe [10].

$$erate_n = C_{15} \cdot \left(\frac{P_{\text{b,g}} \cdot MW}{RT_{\text{s}}}\right) u_{\text{w}}^{0.78} \cdot r_{\text{p},n}^{1.89} \tag{3.105}$$

The size of the non-boiling pool reaches a steady state when the evaporation rate, $erate_{\text{b},n}$, is equal to the pool release rate, W_n^{pool}, as discussed in Section 5.7.3.

5.7.5 Cloud Dispersion Modeling

The ability to perform cloud dispersion analysis is a key component to performing the Level 2 consequence analyses. 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, account for these important factors and will produce the desired data for the Level 2 assessments [12]. Annex 3.A provides background on performing these studies and provides some guidance on available software. Additional guidance is provided by Hanna and Drivas [13].

The dispersion analysis is needed to determine several things. For flammable releases, such as flash fires, this will typically entail determination of the portion of the cloud area (area footprint, ft^2, at grade) where the air to fuel mixture is between the LFL and the UFL. For VCEs, the amount of flammable mass in the cloud is required. In this case, the amount of flammable material (lb) is required and therefore the cloud dispersion model must be able to predict the volumetric portion within the cloud that is above the LFL of the mixture.

For toxic releases, the cloud dispersion model must be able to calculate the concentration (ppm or vol %) of the toxic component of the release throughout the cloud. The portion of the cloud in terms of plant area that has a higher concentration than the relevant toxic impact criteria is determined. The toxic criteria may be based on a probit value, IDLH, ERPG, AEGL, LC_{50}, or other acceptable value.

5.7.6 Cloud Dispersion Calculation

a) Step 7.1—For each release hole size, calculate the adjusted release rate, $rate_n$, using Equation (3.13) where the theoretical release rate, W_n, is from Step 3.2.

NOTE 1 The release reduction factor, $fact_{\text{di}}$, determined in Step 6.4 accounts for any detection and isolation systems that are present.

b) Step 7.2—For each release hole size, calculate the leak duration, ld_n, of the release using Equation (3.15), based on the available mass, $mass_{\text{avail},n}$, from Step 4.6 and the adjusted release rate, $rate_n$, from Step 7.1.

NOTE 2 The leak duration cannot exceed the maximum duration, $ld_{\text{max},n}$, determined in Step 6.5.

c) Step 7.3—Determine the rainout mass fraction from the released fluid using Equation (3.98) or (3.99), based on the flash fraction calculated in Step 1.3.

d) Step 7.4—For each hole size selected in Step 2.1, calculate the release rate of liquid that settles to the ground for the pool calculations, W_n^{pool}, using Equation (3.100).

e) Step 7.5—For each hole size selected, calculate the release rate of vapor (including entrained liquid remaining in the jet, W_n^{jet}), using Equation (3.101).

f) Step 7.6—Calculate the mass fraction of entrained liquid, $frac_{\text{entl}}$, within the jet portion of the release using Equation (3.102).

g) Step 7.7—Determine the vapor source rate and source area for the vapor cloud and flash fire dispersion analysis.

   1) For vapor releases, use the jet release rate, W_n^{jet}, established in Step 7.5.

   2) For liquid releases, determine whether the pool is boiling or non-boiling in accordance with Section 5.7.4. For boiling pools, calculate the evaporation rate, $erate_n$, and the pool radius, $r_{\text{p},n}$, using Equations (3.103) and (3.104). For non-boiling pools, calculate the evaporation rate, $erate_n$, and the pool radius, $r_{\text{p},n}$, using Equation (3.105).

5.8 Determine Flammable and Explosive Consequences

5.8.1 Event Tree Calculations

5.8.1.1 Overview

Event tree analysis determines the probabilities of various outcomes as a result of release of hazardous fluids to the atmosphere. These probabilities are then used to weight the overall consequences of release.

The CCPS [14] defines an event tree as "a graphical logic model that identifies and quantifies possible outcomes following an initiating event. The event tree provides systematic coverage of the time sequence of event propagation, either through a series of protective system actions, normal plant functions and operator interventions (a preincident application), or where loss of containment has occurred, through the range of consequences possible (a postincident application)."

An overall event tree is presented in Figure 5.2. The COF portion fits within the overall methodology as shown in Figure 5.2. POF (POL for leakage or POR for rupture) is a function of the GFFs for particular pieces of equipment and the calculated damage state (DFs) of the piece of equipment or component being evaluated. The determination of the POF is covered in Part 2 of this document.

The POF is then multiplied by the event probabilities as determined from the consequence analysis. Similar to trees employed by the CCPS [14] to evaluate consequences of releases in process units, the event trees presented in Figure 5.2 through Figure 5.5 display the potential outcomes that could occur from the initiating event (a release). The event tree for the leakage cases, which corresponds to the small, medium, and large release hole sizes as discussed in Section 4.2, is shown in Figure 5.3. The event tree for the rupture case is shown in Figure 5.4.

5.8.1.2 Probability of Ignition Given a Release

For a release of a hazardous fluid, the two main factors that define the event outcome are the probability of ignition and the timing of ignition, in other words, immediate vs delayed ignition.

A study by Cox, Lees, and Ang in 1990 [15] indicates that the probability that a flammable release will ignite is proportional to the release rate of flammable material. Additional research on probabilities of ignition is provided in Reference [16]. The curve fit for the Cox, Lees, and Ang work can be seen as the lowest curves in Figure 5.5, which applies to liquids, and Figure 5.6, which applies to vapors. The additional curves provided in these figures are extrapolated to match the constant values assumed in the Level 1 consequence analysis provided in Annex 3.A, Tables 3.A.3.3 through 3.A.3.6. These curves take into consideration the release rate and flash point. In general, the lower the flash point of the released fluid, the higher the probability of ignition. Using these curves eliminates the need to blend results between the continuous and instantaneous results as required in the Level 1 consequence analysis.

The mass fraction of flammable fluid in the release fluid mixture, $mfrac^{\text{flam}}$, must be known to calculate the release rate of flammable material:

$$rate_n^{\text{flam}} = rate_n \cdot mfrac^{\text{flam}} \tag{3.106}$$

The liquid and vapor portions of the flammable release rate are determined using Equation (3.107) and Equation (3.108).

$$rate_{\text{l},n}^{\text{flam}} = rate_n^{\text{flam}} \cdot \left(1 - frac_{\text{fsh}}\right) \tag{3.107}$$

$$rate_{\text{v},n}^{\text{flam}} = rate_n^{\text{flam}} \cdot frac_{\text{fsh}} \tag{3.108}$$

As an alternative to using Figure 5.5 and Figure 5.6, the probability of ignition at ambient conditions of a flammable liquid or vapor release may be calculated from Equation (3.109) or Equation (3.110), respectively. Since these are a function of release rate, the probabilities of ignition are calculated for each of the release hole sizes selected.

NOTE When the flammable liquid or vapor release rate exceeds a rate that would indicate an instantaneous release 10,000 lb (4,535.9 kg) release in 3 minutes or less], a maximum value of 25.22 kg/s (55.6 lb/s) should be used for $rate_{\text{l},n}^{\text{flam}}$ or $rate_{\text{v},n}^{\text{flam}}$ in Equation (3.109) and Equation (3.110).

$$poi_{l,n}^{amb} = \exp\left(\begin{matrix}\left[a + b\cdot\left(C_{12}\cdot T_{fp}\right) + c\cdot\left(C_{12}\cdot T_{fp}\right)^2 + d\cdot\left(C_{12}\cdot T_{fp}\right)^3\right] + \\ \left[e + f\cdot\left(C_{12}\cdot T_{fp}\right) + g\cdot\left(C_{12}\cdot T_{fp}\right)^2 + h\cdot\left(C_{12}\cdot T_{fp}\right)^3\right]\cdot \ln\left(C_{4B}\cdot rate_{l,n}^{flam}\right)\end{matrix}\right) \tag{3.109}$$

where

$a = –01.368924E\text{-}01$

$b = –07.598764E\text{-}03$

$c = 8.282163E\text{-}06$

$d = –06.124231E\text{-}09$

$e = 6.876128E\text{-}02$

$f = 1.193736E\text{-}04$

$g = 2.081034E\text{-}07$

$h = –04.057289E\text{-}11$

$$poi_{v,n}^{amb} = \exp\left(\begin{matrix}\left[a + b\cdot\left(C_{12}\cdot T_{fp}\right) + c\cdot\left(C_{12}\cdot T_{fp}\right)^2 + d\cdot\left(C_{12}\cdot T_{fp}\right)^3\right] + \\ \left[e + f\cdot\left(C_{12}\cdot T_{fp}\right) + g\cdot\left(C_{12}\cdot T_{fp}\right)^2 + h\cdot\left(C_{12}\cdot T_{fp}\right)^3\right]\cdot \ln\left(C_{4B}\cdot rate_{v,n}^{flam}\right)\end{matrix}\right) a \tag{3.110}$$

where

$a = –06.053124E\text{-}02$

$b = –09.958413E\text{-}03$

$c = 1.518603E\text{-}05$

$d = –01.386705E\text{-}08$

$e = 4.564953E\text{-}02$

$f = 7.912392E\text{-}04$

$g = –06.489157E\text{-}07$

$h = 7.159409E\text{-}10$

The probabilities of ignition calculated above are at ambient temperature. As the temperature approaches the AIT of the released fluid, the probability of ignition approaches a limiting or maximum value. For liquids released at or above the AIT, the maximum probability of ignition, poi_l^{ait}, is equal to 1.0 as shown in Equation (3.111).

$$poi_l^{ait} = 1.0 \tag{3.111}$$

For vapors released at or above the AIT, the maximum probability of ignition, poi_v^{ait}, is function of the MW of the fluid. See Equation (3.112). This equation provides a relationship for the maximum value at the AIT and is in general agreement with the probabilities established for the Level 1 COF (see Annex 3.A, Tables 3.A.3.3 and 3.A.3.4). For fluids with a MW of 170 or greater, the limiting value will be 0.7. For hydrogen, the value will be 0.9. Linear interpolation is assumed in between these two extremes.

$$poi_{\mathrm{v}}^{\mathrm{ait}} = \max\left[0.7,\ \ 0.7 + 0.2\left(\frac{170.0 - MW}{170.0 - 2.0}\right)\right] \tag{3.112}$$

Once the maximum value of the probability of ignition has been established using Equation (3.111) or Equation (3.112), Equation (3.113) for liquids and Equation (3.114) for vapors can be used to determine the probability of ignition for the released fluid at the actual process or storage temperature. These equations assumes linear interpolation between the value calculated at ambient conditions and the maximum value at the AIT.

$$poi_{\mathrm{l},n} = poi_{\mathrm{l},n}^{\mathrm{amb}} + \left(poi_{\mathrm{l}}^{\mathrm{ait}} - poi_{\mathrm{l},n}^{\mathrm{amb}}\right)\left(\frac{T_{\mathrm{s}} - C_{16}}{AIT - C_{16}}\right) \tag{3.113}$$

$$poi_{\mathrm{v},n} = poi_{\mathrm{v},n}^{\mathrm{amb}} + \left(poi_{\mathrm{v}}^{\mathrm{ait}} - poi_{\mathrm{v},n}^{\mathrm{amb}}\right)\left(\frac{T_{\mathrm{s}} - C_{16}}{AIT - C_{16}}\right) \tag{3.114}$$

For two-phase releases, the probability of ignition can be estimated as a mass weighted average of the vapor and liquid probabilities of ignition; see Equation (3.115).

$$poi_{2,n} = poi_{\mathrm{v},n} \cdot frac_{\mathrm{fsh}} + poi_{\mathrm{l},n} \cdot \left(1 - frac_{\mathrm{fsh}}\right) \tag{3.115}$$

5.8.1.3 Probability of Immediate vs Delayed Ignition Given Ignition

Given that ignition occurs, the probability of immediate vs delayed ignition depends on the type of release (continuous or instantaneous), the phase of the release, and how close the released fluid's temperature is to its AIT. The probability of immediate ignition given ignition is designated in Figure 5.3 and Figure 5.4 as $poii$. The probability of delayed ignition given ignition is $(1 - poii)$.

As the event tree figures show, the determination that a specific event occurs is greatly dependent on whether or not an ignition is either immediate or delayed. For example, an immediate ignition of a vapor release results in a jet fire or a fireball. If this same release were to have a delayed ignition, the resulting event could be a VCE or a flash fire. Likewise, a liquid release could either result in a flash fire, a VCE, or a pool fire depending on whether or not it is an immediate or a delayed ignition.

The probability of immediate ignition given ignition of a flammable liquid release, $poii_{\mathrm{l},n}$, and a flammable vapor release, $poii_{\mathrm{v},n}$, can be estimated using Equation (3.116) and Equation (3.117). As an alternative, Cox, Lees, and Ang [15] provides a curve for the probability that an ignition will be an immediate vs a delayed ignition.

$$poii_{\mathrm{l},n} = poii_{\mathrm{l},n}^{\mathrm{amb}} + \left(\frac{T_{\mathrm{s}} - C_{16}}{AIT - C_{16}}\right) \cdot \left(poii^{\mathrm{ait}} - poii_{\mathrm{l},n}^{\mathrm{amb}}\right) \tag{3.116}$$

$$poii_{\mathrm{v},n} = poii_{\mathrm{v},n}^{\mathrm{amb}} + \left(\frac{T_{\mathrm{s}} - C_{16}}{AIT - C_{16}}\right) \cdot \left(poii^{\mathrm{ait}} - poii_{\mathrm{v},n}^{\mathrm{amb}}\right) \tag{3.117}$$

The probabilities of immediate ignition, given ignition at ambient conditions, $poii_{\mathrm{l},n}^{\mathrm{amb}}$ and $poii_{\mathrm{v},n}^{\mathrm{amb}}$, are based on expert opinion and are provided in Table 5.3 for instantaneous and continuous releases of liquids and vapors. At the AIT or higher, it is assumed that the probability of immediate ignition given ignition for all release phases, $poii^{\text{ait}}$, is equal to 1.0. Equation (3.118) provides a linear interpolation for operating temperatures between ambient and the AIT.

For two-phase releases, the probability of immediate ignition given ignition can be assumed to be the mass weighted average of the probability calculated for liquid and the vapor as follows:

$$poii_{2,n} = frac_{\text{fsh}} \cdot poii_{\text{v},n} + \left(1 - frac_{\text{fsh}}\right) \cdot poii_{\text{l},n} \tag{3.118}$$

5.8.1.4 Probability of VCE vs Flash Fire Given Delayed Ignition

A delayed ignition will result in the event outcome of either a VCE or a flash fire. The probability of VCE given a delayed ignition, $pvcedi$, is dependent on what type of release occurs, instantaneous or continuous, and whether the release is a liquid or a vapor. Currently, the assumptions for these probabilities are provided in Table 5.3 and are in general agreement with the assumptions provided in Annex 3.A, Tables 3.A.3.3 through 3.A.3.6 for the Level 1 consequence analysis.

An improvement to these assumptions would be to prorate the probability of a VCE given a delayed ignition, $pvcedi$, based on the NFPA reactivity number. A fluid with a higher NFPA reactivity will have a higher probability of a VCE vs a flash fire. An even better method would be to use the flame speed for the particular fluid of interest. Higher flame speeds will have a higher probability of a VCE vs a flash fire. The problem with this method is that data for the flame speed of a particular fluid in a vapor cloud are not always available.

For liquids and vapors, the probability of VCE given a delayed ignition, $pvcedi_{\text{l},n}$ or $pvcedi_{\text{v},n}$, can be obtained from Table 5.3. For two-phase releases, the probability of VCE given a delayed ignition can be assumed to be the mass weighted average of the probability for liquid and the vapor as shown in Equation (3.119).

$$pvcedi_{2,n} = frac_{\text{fsh}} \cdot pvcedi_{v,n} + \left(1 - frac_{\text{fsh}}\right) \cdot pvcedi_{\text{l},n} \tag{3.119}$$

Since either a VCE or a flash fire occurs as a result of a delayed ignition, the probability of a flash fire given a delayed ignition of a liquid or a vapor release are in accordance with Equation (3.120) and Equation (3.121).

$$pffdi_{\text{l},n} = 1 - pvcedi_{\text{l},n} \tag{3.120}$$

$$pffdi_{\text{v},n} = 1 - pvcedi_{\text{v},n} \tag{3.121}$$

For two-phase releases, the probability of flash fire given a delayed ignition can be assumed to be the mass weighted average of the probability calculated for liquid and the vapor as shown in Equation (3.122).

$$pffdi_{2,n} = frac_{\text{fsh}} \cdot pffdi_{\text{v},n} + \left(1 - frac_{\text{fsh}}\right) \cdot pffdi_{\text{l},n} \tag{3.122}$$

5.8.1.5 Probability of Fireball Given Immediate Ignition

Fireballs occur as a result of an immediate ignition of an instantaneous vapor or two-phase release upon rupture of a component. The probability can be determined using Equation (3.123) and Equation (3.124).

$$pfbii = 1.0 \quad \text{for instantaneous vapor or two-phase releases} \tag{3.123}$$

$$pfbii = 0.0 \quad \text{for all other cases} \tag{3.124}$$

5.8.1.6 Event Outcome Probabilities

Event trees are used to calculate the probability of every possible event or outcome (even safe outcomes) as a result of a hazardous release. The probability of a particular event outcome after a release can be determined by multiplying of all of the individual probabilities along the path of the event tree being taken. For example, the probability of a flash fire given leakage of a vapor can be determined from Figure 5.3 using Equation (3.125).

$$pvce_{\mathrm{v},n} = poi_{\mathrm{v},n} \cdot \left(1 - poii_{\mathrm{v},n}\right) \cdot \left(1 - pvcedi_{\mathrm{v},n}\right) \tag{3.125}$$

The probability of safe release of a leaking two-phase release is given by Equation (3.126).

$$psafe_{2,n} = \left(1 - poi_{2,n}\right) \tag{3.126}$$

The probability of a pool fire given a rupture of a vessel containing liquid per Figure 5.4 is given by Equation (3.127).

$$ppool_{\mathrm{l},n} = poi_{\mathrm{l},n} \cdot poii_{\mathrm{l},n} \tag{3.127}$$

5.8.2 Pool Fires

5.8.2.1 Overview

When a flammable liquid is released from a piece of equipment or pipeline, a liquid pool may form. As the pool forms, some of the liquid will evaporate and, if the vaporizing flammable materials find an ignition source while it is above its LFL, a pool fire can occur. Pool fires are considered to occur as a result of immediate ignition of a flammable liquid from a pressurized process vessel or pipe that develops a hole or ruptures.

Important characteristics of pool fires include its burning velocity, rate of heat release, flame height, flame plume deflection, and radiative heat flux. To model a pool fire correctly, necessary data for the calculations include the extent of the pool surface, the physical properties of the burning fluid, the physical and thermal properties of the substrate, and the ambient conditions.

A method for calculating the consequences associated with a pool fire is provided by CCPS [17]. This method entails calculating the burning rate off the surface of the pool that is a function of the pool area and the heat of combustion, the latent heat of vaporization, and the specific heat of the flammable liquid. The maximum size of the pool is determined at that point where the burning rate off the surface of the pool is equal to the release rate calculated through the hole or rupture from the protected piece of equipment (see Section 5.8.2.3).

The consequence area is estimated by considering the potential for personnel injury and component damage due to the effects of exposure to thermal radiation in the vicinity of the fire.

5.8.2.2 Pool Fire Burning Rate

The burning rate off of the surface of a pool fire is the rate at which the flammable material is evaporated during the fire is given in TNO [18] and can be determined using the following equations.

For non-boiling pools:

$$\dot{m}_{\mathrm{b}} = \frac{C_{17} \cdot HC_{\mathrm{l}}}{Cp_{\mathrm{l}}\left(T_{\mathrm{b}} - T_{\mathrm{atm}}\right) + \Delta H_{\mathrm{v}}} \tag{3.128}$$

For boiling pools, such as cryogenic liquids or LPGs:

$$\dot{m}_{\text{b}} = \frac{C_{17} \cdot HC_{\text{l}}}{\Delta H_{\text{v}}} \tag{3.129}$$

NOTE For liquid mixtures (such as gasoline), the burning rate can be approximated by calculating the burning rate for each component in the mixture, $\dot{m}_{\text{b},i}$, and summing as follows:

$$\dot{m}_{\text{b}} = \sum_{i=1}^{N} frac_{\text{mole},i} \cdot \dot{m}_{\text{b},i} \tag{3.130}$$

5.8.2.3 Pool Fire Size

The ultimate size of the pool fire is then determined to be the size where the liquid portion (rainout) of the release rate from the pressurized system, W_n^{pool}, is equal to the burning rate off the surface of the pool, $\dot{m}_{\text{b}}$, or:

$$Aburn_{\text{pf},n} = \frac{W_n^{\text{pool}}}{\dot{m}_{\text{b}}} \tag{3.131}$$

For instantaneous releases of the flammable liquid inventory to the ground, a practical limit to the amount of pool spread should be used in the consequence calculations. The maximum size of the pool can be determined based on assuming a circle with depth of 0.0164 ft (5 mm), in accordance with The Netherlands Organization for Applied Scientific Research (TNO *Yellow Book*), 1997 [18], recommendations.

$$Amax_{\text{pf},n} = \frac{mass_{\text{avail},n}}{C_{18} \cdot frac_{\text{ro}} \cdot \rho_{\text{l}}} \tag{3.132}$$

The pool fire area to be used in the consequence area calculation is then:

$$A_{\text{pf},n} = \min\left[Aburn_{\text{pf},n},\ Amax_{\text{pf},n} \right] \tag{3.133}$$

The consequence of a pool release is directly dependent on the pool area, which is driven by assumptions made of the pool depth. In practice, areas have slopes for drainage, curbing, trenches, drains, and other ground contours that collect or remove fluids. Applying conservative pool depth values (e.g. 5 mm depth [18], 1 cm [19]) provides unrealistically large pool areas. Site condition should be considered when estimating pool size. A default limit of 10,000 ft^2 may be appropriate for all but the largest releases. From this area, the radius of the pool fire can be determined:

$$R_{\text{pf},n} = \sqrt{\frac{A_{\text{pf},n}}{\pi}} \tag{3.134}$$

5.8.2.4 Flame Length and Flame Tilt

The SPFE Handbook for Fire Protection [20] provides a correlation from Thomas that can be used for calculating the flame length of a pool fire, L_{pf}.

$$L_{\text{pf},n} = 110 \cdot R_{\text{pf},n} \left[\frac{\dot{m}_{\text{b}}}{\rho_{\text{atm}} \sqrt{2 \cdot g \cdot R_{\text{pf},n}}} \right]^{0.67} u_{\text{s}}^{-0.21} \tag{3.135}$$

The nondimensional wind velocity, u_s, cannot be less than 1.0 and is dependent on the wind speed as follows:

$$u_{s,n} = \max\left[1.0\ ,\ u_w \cdot \left(\frac{\rho_v}{2 \cdot g \cdot \dot{m}_b \cdot R_{pf,n}}\right)^{0.333}\right] \quad (3.136)$$

The American Gas Association provides the following correlation for estimating the flame tilt:

$$\cos\theta_{pf,n} = \frac{1}{\sqrt{u_{s,n}}} \quad (3.137)$$

5.8.2.5 Pool Fire Radiated Energy

The amount of energy radiated by the pool fire (often referred to as surface emitted heat flux) is a fraction of the total combustion power of the flame [18]. The fraction of the total combustion power that is radiated, β, is often quoted in the range of 0.15 to 0.35. A conservative value of 0.35 can be chosen. Therefore:

$$Qrad_n^{pool} = \frac{C_{14} \cdot \beta \cdot \dot{m}_b \cdot HC_l \cdot \pi \cdot R_{pf,n}^2}{2 \cdot \pi \cdot R_{pf,n} \cdot L_{pf,n} + \pi \cdot R_{pf,n}^2} \quad (3.138)$$

The amount of the radiated energy that actually reaches a target at some location away from the pool fire is a function of the atmospheric conditions as well as the radiation view factor between the pool and the target. The received thermal flux can be calculated as follows:

$$Ith_n^{pool} = \tau_{atm,n} \cdot Qrad_n^{pool} \cdot Fcyl_n \quad (3.139)$$

The atmospheric transmissivity is an important factor since it determines how much of the thermal radiation is absorbed and scattered by the atmosphere. The atmospheric transmissivity can be approximated using the following formula recommended by Pietersen and Huerta [21]:

$$\tau_{atm,n} = C_{19} \cdot \left(P_w \cdot xs_n\right)^{-0.09} \quad (3.140)$$

The water partial pressure expressed as a function of ambient temperature and RH is given by Mudan and Croce [22] as follows:

$$P_w = C_{20}\left(RH\right) e^{\left[14.4114 - \left(\frac{C_{21}}{T_{atm}}\right)\right]} \quad (3.141)$$

The radiation view factor can be calculated modeling the flame as a vertical cylinder and accounting for flame tilt using the method provided by Mudan [23] as follows:

$$Fcyl_n = \sqrt{Fv_n^2 + Fh_n^2} \quad (3.142)$$

The vertical view factor can be calculated as follows:

$$Fv_n = \begin{pmatrix} \left(\dfrac{X\cos\theta_{\text{pf},n}}{Y - X\sin\theta_{\text{pf},n}}\right)\cdot\left(\dfrac{X^2+(Y+1)^2-2Y\left(1+\sin\theta_{\text{pf},n}\right)}{\pi\sqrt{A'B'}}\right)\cdot\tan^{-1}\left[\dfrac{A'(Y-1)}{B'(Y+1)}\right]+ \\ \left(\dfrac{\cos\theta_{\text{pf},n}}{\pi\sqrt{C'}}\right)\cdot\left(tan^{-1}\left[\dfrac{XY-\left(Y^2-1\right)\sin\theta_{\text{pf},n}}{\sqrt{Y^2-1}\sqrt{C'}}\right]+\tan^{-1}\left[\dfrac{\sin\theta_{\text{pf},n}\sqrt{Y^2-1}}{\sqrt{C'}}\right]\right)- \\ \left(\dfrac{X\cos\theta_{\text{pf},n}}{\pi\left(Y-X\sin\theta_{\text{pf},n}\right)}\right)\cdot\tan^{-1}\left[\sqrt{\dfrac{Y-1}{Y+1}}\right] \end{pmatrix} \tag{3.143}$$

The horizontal view factor can be calculated as follows:

$$Fh_n = \begin{pmatrix} \dfrac{1}{\pi}\tan^{-1}\left[\sqrt{\dfrac{Y+1}{Y-1}}\right]- \\ \left(\dfrac{X^2+(Y+1)^2-2\left(Y+1+XY\sin\theta_{\text{pf},n}\right)}{\pi\sqrt{A'B'}}\right)\cdot\tan^{-1}\left[\sqrt{\dfrac{A'(Y-1)}{B'(Y+1)}}\right]+ \\ \left(\dfrac{\sin\theta_{\text{pf},n}}{\pi\sqrt{C'}}\right)\cdot\left(\tan^{-1}\left[\dfrac{XY-\left(Y^2-1\right)\sin\theta_{\text{pf},n}}{\sqrt{Y^2-1}\sqrt{C'}}\right]+\tan^{-1}\left[\dfrac{\sin\theta_{\text{pf},n}\sqrt{Y^2-1}}{\sqrt{C'}}\right]\right) \end{pmatrix} \tag{3.144}$$

In Equation (3.143) and Equation (3.144), the following parameters are used.

$$X = \frac{L_{\text{pf},n}}{R_{\text{pf},n}} \tag{3.145}$$

$$Y = \frac{xs_n}{R_{\text{pf},n}} \tag{3.146}$$

$$A' = X^2 + (Y+1)^2 - 2X(Y+1)\sin\theta_{\text{pf},n} \tag{3.147}$$

$$B' = X^2 + (Y-1)^2 - 2X(Y-1)\sin\theta_{\text{pf},n} \tag{3.148}$$

$$C' = 1 + \left(Y^2-1\right)\cos^2\theta_{\text{pf},n} \tag{3.149}$$

5.8.2.6 Pool Fire Safe Distance and Consequence Area

The procedure for determining the consequence area associated with a pool fire consists of calculating the distance away from the pool fire where the radiated energy from the pool fire is equal to the exposure limits (impact criteria) for thermal radiation as provided in Section 4.8.2. A maximum permissible radiation of 4,000 Btu/hr-ft^2 (12.6 kW/m^2) is used for serious personnel injury. The maximum permissible radiation for component damage is 12,000 Btu/hr-ft^2 (37.8 kW/m^2).

NOTE The atmospheric transmissivity and the source view factor are functions of the distance from the flame source to the target. These are the two parameters that account for the fact that the received thermal radiation at any point away from the fire goes down as the distance increases. An iterative approach is required to determine the acceptable or safe distance away from the pool fire.

This procedure is carried out for personnel injury as well as component damage for each of the release hole sizes selected as described in Section 4.2. Once the safe distances, $xs^{\text{pool}}_{\text{cmd},n}$ and $xs^{\text{pool}}_{\text{inj},n}$, are determined, Equation (3.150) and Equation (3.151) are used to calculate the pool fire consequence areas.

$$CA^{\text{pool}}_{\text{f,cmd},n} = \pi \cdot \left(xs^{\text{pool}}_{\text{cmd},n} + R_{\text{pf},n}\right)^2 \tag{3.150}$$

$$CA^{\text{pool}}_{\text{f,inj},n} = \pi \cdot \left(xs^{\text{pool}}_{\text{inj},n} + R_{\text{pf},n}\right)^2 \tag{3.151}$$

5.8.3 Jet Fires

5.8.3.1 General

Jet fires occur as a result of immediate ignition of a flammable fluid from a pressurized process vessel or pipe that develops a hole. Jet fires do not occur as a result of an immediate ignition from a loss of containment due to a rupture. See Figure 5.4. Similar to pool fires, the main deleterious effect is the heat flux produced by the jet fire.

One method for calculating the consequences from a jet fire is provided in CCPS [17]. The method involves calculating the flame length of the jet fire and the radiative heat flux at distances away from the jet source. The distance at which the calculated thermal radiation from the jet fire equals the thermal radiation limit specified by the risk analyst [limit is 4,000 Btu/hr-ft^2 (12.6 kW/m^2) for personnel and 12,000 Btu/hr-ft^2 (37.8 kW/m^2) for equipment] provides the radius for the consequence area.

A conservative assumption is made that the jet fire arises vertically at a point located at grade since this will provide the largest effected area that exceeds the thermal radiation limit.

5.8.3.2 Jet Fire Radiated Energy

The amount of energy radiated by the jet (often referred to as surface emitted heat flux) is a fraction of the total combustion power of the flame. The fraction of the total combustion power that is radiated, β, is often quoted in the range of 0.15 to 0.35. A conservative value of 0.35 can be chosen. Therefore:

$$Qrad^{\text{jet}}_n = C_{14} \cdot \beta \cdot W^{\text{jet}}_n \cdot HC_{\text{v}} \tag{3.152}$$

For mixtures, the heat of combustion can be evaluated using a mole weighted average of the individual component heats of combustion.

5.8.3.3 Jet Fire Safe Distance and Consequence Area

The amount of the radiated energy that actually reaches a target at some location away from the jet fire is a function of the atmospheric conditions as well as the radiation view factor between the source and the target. The received thermal flux can be calculated as follows:

$$Ith_n^{\text{jet}} = \tau_{\text{atm},n} \cdot Qrad_n^{\text{jet}} \cdot Fp_n \tag{3.153}$$

If a point source model is used, then the radiation view factor between the source flame and the target can be approximated as follows:

$$Fp_n = \frac{1}{4\pi \cdot xs_n^2} \tag{3.154}$$

The point source view factor provides a reasonable estimate of received flux at distances far from the flame. More rigorous formulas that are based on specific flame shapes (e.g. cylinders; see Equation (3.142)] or that assume a solid plume radiation model may be used as alternatives to the simplified calculation shown above.

NOTE The atmospheric transmissivity and the point source view factor are functions of the distance from the flame source to the target. An iterative approach is required to determine the acceptable distance away from the jet fire and the resultant consequence area.

This procedure is carried out for personnel injury as well as component damage for each of the release hole sizes selected as described in Section 4.2. Once the safe distances, $xs_{\text{cmd},n}^{\text{jet}}$ and $xs_{\text{inj},n}^{\text{jet}}$, are determined, Equation (3.155) and Equation (3.156) are used to calculate the jet fire consequence areas.

$$CA_{\text{f,cmd},n}^{\text{jet}} = \pi \cdot xs_{\text{cmd},n}^{\text{jet}\ 2} \tag{3.155}$$

$$CA_{\text{f,inj},n}^{\text{jet}} = \pi \cdot xs_{\text{inj},n}^{\text{jet}\ 2} \tag{3.156}$$

5.8.4 Fireballs

5.8.4.1 General

Fireballs result from the immediate ignition of a flammable, superheated liquid/vapor. Fireballs always occur in combination with a physical explosion or a BLEVE. The effects of fireballs need to be evaluated for instantaneous releases (or ruptures). Continuous releases do not result in fireballs.

CCPS [17] provides a suitable methodology for determining the effects of fireballs. Four factors have to be considered to determine the heat flux of a fireball: the mass of the flammable fluid, the fireball's diameter, duration, and thermal emissive power. The main parameter needed is the mass of flammable fluid in the stored equipment prior to rupture. The flammable mass for the fireball, $mass_{\text{fb}}$, is the fraction of the released mass that contains flammable material and can be determined using Equation (3.157).

$$mass_{\text{fb}} = mfrac^{\text{flam}} \cdot mass_{\text{avail},n} \tag{3.157}$$

The maximum mass available for release, $mass_{\text{avail},n}$, is defined in Section 4.4.2 [see Equation (3.11)].

Once the flammable mass of the fireball is known, the diameter, duration, and height of the fireball can be readily calculated. The effects of thermal radiation on personnel and equipment can be determined in much the same way as has been previously done for jet fires and pool fires.

5.8.4.2 Fireball Size and Duration

The diameter of the fireball is a function of the flammable mass as follows:

$$Dmax_{\text{fb}} = C_{22} \cdot mass_{\text{fb}}^{\ 0.333} \tag{3.158}$$

The center height of the fireball is assumed to be:

$$H_{\text{fb}} = 0.75 \cdot Dmax_{\text{fb}} \tag{3.159}$$

The duration of the fireball is also a function of the flammable mass as follows:

$$t_{\text{fb}} = C_{23} \cdot mass_{\text{fb}}^{\ 0.333} \qquad \text{for } mass_{\text{fb}} \leq 66{,}000 \text{ lb } [29{,}937 \text{ kg}] \tag{3.160}$$

$$t_{\text{fb}} = C_{24} \cdot mass_{\text{fb}}^{\ 0.167} \qquad \text{for } mass_{\text{fb}} > 66{,}000 \text{ lb } [29{,}937 \text{ kg}] \tag{3.161}$$

5.8.4.3 Fireball Radiated Energy

The amount of energy radiated by the fireball (often referred to as surface emitted heat flux) is a fraction of its total combustion power. The fraction of the total combustion power that is radiated, β_{fb}, is often quoted in the range of 0.25 to 0.4; see Equation (3.162).

$$Qrad^{\text{fball}} = \frac{C_{14} \cdot \beta_{\text{fb}} \cdot mass_{\text{fb}} \cdot HC_{\text{l}}}{\pi \cdot Dmax_{\text{fb}}^{2} \cdot t_{\text{fb}}} \tag{3.162}$$

The fraction of combustion power that is radiated from a fireball can be calculated from a correlation by [24]:

$$\beta_{\text{fb}} = C_{25} \cdot P_{\text{B}}^{\ 0.32} \tag{3.163}$$

The burst pressure used above for determining the radiation fraction depends on the consequence being calculated. If the calculation is for pressurized fixed equipment where the concern is for rupture during normal operation, the normal operating pressure is used. When the calculation is to be performed at elevated pressures such as the case when the COFs of PRDs are being evaluated, the likely overpressure that results from the failure to open upon demand should be used.

5.8.4.4 Fireball Safe Distance and Consequence Area

The amount of the radiated energy that actually reaches a target at some location away from the fireball is a function of the atmospheric conditions as well as the radiation view factor between the source and the target. The received thermal flux can be determined as before:

$$Ith^{\text{fball}} = \tau_{\text{atm}} \cdot Qrad^{\text{fball}} \cdot Fsph \tag{3.164}$$

For a fireball, the spherical model for the geometric view factor is used:

$$Fsph = \frac{\left(Dmax_{\text{fb}}\right)^2}{4C_{\text{fb}}^{\ 2}} \tag{3.165}$$

where

$$C_{\text{fb}} = \sqrt{\left(\frac{Dmax_{\text{fb}}}{2.0}\right)^2 + \left(\frac{xs^{\text{fball}}}{2.0}\right)^2} \tag{3.166}$$

NOTE The atmospheric transmissivity and the geometric view factor are functions of the distance from the flame source to the target, xs^{fball}. An iterative approach is required to determine the acceptable distance away from the fireball.

This procedure is carried out for personnel injury as well as component damage for the rupture case. Once the safe distances, $xs_{\text{cmd}}^{\text{fball}}$ and $xs_{\text{inj}}^{\text{fball}}$, are determined, Equation (3.167) and Equation (3.168) are used to calculate the fireball consequence areas.

$$CA_{\text{f,cmd}}^{\text{fball}} = \pi \cdot \left(xs_{\text{cmd}}^{\text{fball}}\right)^2 \tag{3.167}$$

$$CA_{\text{f,inj}}^{\text{fball}} = \pi \cdot \left(xs_{\text{inj}}^{\text{fball}}\right)^2 \tag{3.168}$$

5.8.5 VCEs

5.8.5.1 General

When a sizable amount of flammable fluid is suddenly released into the air and is not immediately ignited, three things can happen: the cloud can encounter an ignition source and explode, producing a VCE; the cloud can encounter an ignition source and flash back, producing a flash fire (Section 5.8.6); or the cloud can safely disperse. For a VCE or flash fire to occur, the released material must form a partially mixed vapor cloud that contains vapor concentrations above the LFL. The cloud then encounters an ignition source and either explodes or flashes back. Since VCEs produce devastating effects on plants if they occur, significant research on their causes has been performed. From research on VCEs that have occurred, Lees [25] has identified several parameters that affect VCE behavior:

a) quantity of material released,

b) fraction of material vaporized,

c) probability of ignition of the cloud,

d) distance traveled by the cloud,

e) time delay before ignition of the cloud,

f) probability of explosion rather than fire,

g) existence of a threshold quantity of material,

h) efficiency of the explosion,

i) location of ignition source with respect to the release.

VCEs can occur as a result of a delayed ignition of a vapor cloud. The source of the vapor cloud could either be from a vapor or two-phase jet release or evaporation off the surface of an un-ignited liquid flammable pool. Dispersion modeling of the cloud is required to evaluate the extent of a vapor cloud, since the amount of flammable material in the cloud is needed. (See the general discussion on cloud modeling presented in Section 5.7.4.) A VCE is a deflagration (not detonation) that produces significant overpressure (blast wave) and occurs when the flame propagation through the cloud travels at extremely high velocities. If the flame propagates at a relatively slow velocity, a VCE, with the resulting overpressure, does not occur. In this case, a relatively low consequence, low energy, flash fire is the outcome (see Section 5.8.6).

5.8.5.2 Source of Vapor

The source of flammable vapor for the VCE could either be from a jet release or from an evaporating liquid pool release. For the jet release case, the source rate is simply the jet release rate as discussed in Section 5.7.3.

For an evaporating pool, the vapor rate used as the source for the VCE is dependent on whether the pool is a boiling or non-boiling, as discussed in Section 5.7.4 and shown in Figure 5.1.

5.8.5.3 Amount of Flammable Material

The first step in evaluating the effects of a VCE is to determine the amount of flammable material that is in the source cloud. The mass is a function of the release rate, the atmospheric dispersion of the cloud, and the time of ignition. A suitable cloud dispersion model that can handle plumes (continuous release with steady state analysis) as well as puffs (instantaneous releases that required a transient model) should be used to evaluate the amount of flammable material that exists in the cloud at the time of ignition.

5.8.5.4 Explosion Yield Factor

An important parameter in the evaluation of the vapor cloud is the explosion yield factor, η. This is an empirical value that determines how much of the combustion power in the cloud is released into the pressure wave. Where the flammable mass in the cloud is calculated as the portion of the cloud between the LFL and the UFL of the flammable material, a conservative value for the explosion yield factor of 1.0 should be used.

Where the flammable mass is based on the total amount of flammable fluid released, then a yield factor, η, with a range of between $0.03 \le \eta \le 0.19$ is typically used, and this is a function of the material released. For example, typical hydrocarbons have a yield factor of 0.03, while highly reactive fluids, such as ethylene oxide, have yield factors up around 0.19. Additional yield factors are provided by Zebetakis [26].

5.8.5.5 Determination of Blast Overpressure

a) General—There are several approaches to estimating the overpressure that results from a VCE. The first method is the TNT equivalency method, explained in Reference [27] and detailed in Section 5.8.5.5 b). In this method, the source of the explosion is assumed to be at a point (point source model) and the characteristics of the explosion are similar to that of a TNT explosion. This approach will likely result in conservative estimates of the damage at locations closest to the source of the explosion. The TNT model has been adopted for its ease of use, ability to be consistently applied, and effectiveness in conservatively modeling the damage potential of VCEs.

   Another model that will not be presented here is more complicated and highly dependent on user experience and knowledge but can provide more accurate (less conservative) results in the near field of the explosion. This method is known as the TNO multi-energy method (MEM), and it focuses on the characteristics of the site, rather than on the size of the release. This method recognizes that portions of the vapor cloud that are obstructed or partially confined could undergo blast-generating combustion. The key site characteristics that must be identified and classified by the user are equipment congestion and flame confinement. Due to lack of reliable guidance in the current research on congestion and confinement, it is very challenging for the user to consistently apply this approach and, therefore, is not recommended for RBI purposes where consistency is key.

Yet another model is the Baker-Strehlow-Tang Energy Model [27], which essentially uses the same TNO multi-energy methodology, but along with congestion and flame confinement, it includes fuel mixture reactivity as a key parameter. As with the TNO MEM, the Baker-Strehlow-Tang approach requires user judgment to classify the site's congestion and flame confinement, which inherently leads to inconsistent applications. It is, therefore, not a recommended approach.

b) TNT Equivalency Method—The TNT equivalency method, presented in CCPS [17], determines the amount of available energy in the cloud and relates this to an equivalent amount of TNT using Equation (3.169).

$$W_{\text{TNT}} = \frac{\eta \cdot mass_{\text{vce}} \cdot HC_{\text{s}}}{HC_{\text{TNT}}} \tag{3.169}$$

For mixtures, a mole weighting of the individual component heats of combustions can be used to estimate the heat of combustion for the mixture in the cloud. The heat of combustion of TNT, HC_{TNT}, is approximately 2000 Btu/lb (4648 J/kg).

c) Use of Blast Curves—To determine the blast effect, the side-on blast wave overpressure can be calculated using blast curves. An acceptable curve for estimating the overpressure is the Hopkinson-scaled curved that is reproduced by CCPS [17]. Equation (3.170) is a curve fit of the Hopkinson-scaled data that provide a closed form solution for determining the side-on overpressure (units are bar):

$$P_{\text{SO},n} = C_{26} \cdot \left(\begin{array}{l} -0.059965896 + \dfrac{1.1288697}{\ln\left[\bar{R}_{\text{HS},n}\right]} - \dfrac{7.9625216}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^2} + \\ \dfrac{25.106738}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^3} - \dfrac{30.396707}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^4} + \dfrac{19.399862}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^5} - \\ \dfrac{6.8853477}{\left(\ln\left[\bar{R}_{HS,n}\right]\right)^6} + \dfrac{1.2825511}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^7} - \dfrac{0.097705789}{\left(\ln\left[\bar{R}_{\text{HS},n}\right]\right)^8} \end{array} \right) \tag{3.170}$$

For use in Equation (3.171), the Hopkinson-scaled distance, $\bar{R}_{\text{HS},n}$, presented above requires units of m/kg$^{1/3}$ and is calculated from the actual distance from the blast center as follows:

$$\bar{R}_{\text{HS},n} = C_{27} \cdot \frac{xs_n^{\text{vce}}}{W_{\text{TNT}}^{1/3}} \tag{3.171}$$

5.8.5.6 VCE Safe Distance and Consequence Area

The consequence areas for serious injury to personnel and component damage can be determined once the overpressure as a function of distance from the blast is known. For serious injuries to personnel, the consequence area can be based on the following probit equation provided by Eisenberg [28].

$$Pr = -23.8 + 2.92 \cdot \ln\left[C_{28} \cdot P_{\text{SO},n}\right] \tag{3.172}$$

This probit equation provides the probability of process building collapse due to structural damage as a result of overpressure. Data show that personnel can withstand much higher overpressures (15 to 30 psi overpressure for lung hemorrhage) when out in the open and that typical serious injury occurs as a result of the collapse of buildings.

For component damage, an overpressure of 34.5 kPa (5.0 psi) has proven to be a good value to use when evaluating the consequence area to equipment as a result of overpressures from explosions.

NOTE The side-on overpressure is a function of the distance from the blast source to the target. An iterative approach is required to determine the acceptable distance away from the explosion.

This procedure is carried out for personnel injury as well as component damage for each of the release hole sizes selected as described in Section 4.2. Once the safe distances, $xs_{\text{cmd},n}^{\text{vce}}$ and $xs_{\text{inj},n}^{\text{vce}}$, are determined, Equation (3.173) and Equation (3.174) are used to calculate the VCE consequence areas.

$$CA_{\text{f,cmd},n}^{\text{vce}} = \pi \cdot \left(xs_{\text{cmd},n}^{\text{vce}} \right)^2 \tag{3.173}$$

$$CA_{\text{f,inj},n}^{\text{vce}} = \pi \cdot \left(xs_{\text{inj},n}^{\text{vce}} \right)^2 \tag{3.174}$$

5.8.6 Flash Fires

5.8.6.1 General

Flash fires, like VCEs, can occur as a result of a delayed ignition of a vapor cloud. The source of the vapor cloud could either be from a vapor or two-phase jet release or evaporation off the surface of an un-ignited liquid flammable pool. Dispersion modeling of the cloud is required to evaluate the extent of a vapor cloud since the amount of flammable material and the area covered by the flammable portion in the cloud is needed. See the general discussion on cloud modeling presented in Annex 3.A.

5.8.6.2 Flash Fire Consequence Area

A flash fire is a deflagration (not detonation); however, unlike VCEs, the flame speed is relatively slow and overpressures (blast waves) do not occur. Flash fires are much more common than VCEs and last for no more than a few tenths of a second. Unlike pool or jet fires (immediate ignition), flash fires need not consider radiation effects away from the fire boundary, since the combustion process is of short duration and relatively low intensity. The consequence area for personnel from a flash fire, $CA_{\text{inj},n}^{\text{flash}}$, is merely the flammable cloud boundary and no further.

As with VCEs, a suitable cloud dispersion model that can handle plumes (continuous release with steady state analysis) as well as puffs (instantaneous releases that required a transient model) should be used. The cloud dispersion model is used to determine the boundary area of the vapor cloud that contains flammable material that is at or above the LFL of the mixture in the cloud. The resultant boundary area will equal the consequence area for serious injury to personnel. As a general rule of the thumb, the consequence area associated with damage to an equipment component from flash fires, $CA_{\text{cmd},n}^{\text{flash}}$, is limited to 25 % of the area for serious injury to personnel.

$$CA_{\text{f,cmd},n}^{\text{flash}} = 0.25 \cdot CA_{\text{inj},n}^{\text{flash}} \tag{3.175}$$

5.8.7 Determination of Flammable Consequence for Each Release Case (Hole Size)

For each hole size or release case selected, the flammable consequence area is calculated as a probability weighted consequence area of all of the potential event outcomes on the event tree as shown in Equation (3.176) and Equation (3.177). For component damage, use Equation (3.176); for personnel injury, use Equation (3.177).

$$CA_{\text{f,cmd},n}^{\text{flam}} = \begin{pmatrix} ppool_n \cdot CA_{\text{f,cmd},n}^{\text{pool}} + pjet_n \cdot CA_{\text{f,cmd},n}^{\text{jet}} + pfball_n \cdot CA_{\text{f,cmd}}^{\text{fball}} + \\ pvce_n \cdot CA_{\text{f,cmd},n}^{\text{vce}} + pflash_n \cdot CA_{\text{f,cmd},n}^{\text{flash}} \end{pmatrix} \tag{3.176}$$

$$CA_{\text{f,inj},n}^{\text{flam}} = \begin{pmatrix} ppool_n \cdot CA_{\text{f,inj},n}^{\text{pool}} + pjet_n \cdot CA_{\text{f,inj},n}^{\text{jet}} + pfball_n \cdot CA_{\text{f,inj}}^{\text{fball}} + \\ pvce_n \cdot CA_{\text{f,inj},n}^{\text{vce}} + pflash_n \cdot CA_{\text{f,inj},n}^{\text{flash}} \end{pmatrix} \tag{3.177}$$

5.8.8 Determination of Final Flammable Consequence Areas

The final flammable consequence areas are determined as a probability weighted average of the individual flammable consequence areas calculated for each release hole size. This is performed for both the component damage and the personnel injury consequence areas. The probability weighting utilizes the generic frequencies of the release hole sizes selected per Section 4.2.

The equation for probability weighting of the component damage consequence areas is given by Equation (3.178).

$$CA_{\text{f,cmd}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{f,cmd},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.178}$$

The equation for probability weighting of the personnel injury consequence areas is given by Equation (3.179).

$$CA_{\text{f,inj}}^{\text{flam}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{f,inj},n}^{\text{flam}}}{gff_{\text{total}}} \right) \tag{3.179}$$

In Equation (3.178) and Equation (3.179), the total GFF is as calculated in Step 2.2.

5.8.9 Calculation of Flammable Consequence Areas

a) Step 8.1—Determine the mass fraction of the release rate that contains a flammable component, $mfrac^{\text{flam}}$. This can be determined by adding the mass fractions of all flammable components in the mixture.

b) Step 8.2—For each hole size, calculate the flammable release rate, $rate_n^{\text{flam}}$, using Equation (3.106). Also calculate the liquid portion, $rate_{\text{l},n}^{\text{flam}}$, and the vapor portion, $rate_{\text{v},n}^{\text{flam}}$, of the flammable release rate using Equation (3.107) and/or Equation (3.108), as applicable.

NOTE 1 For two-phase releases both values should be calculated.

c) Step 8.3—For each hole size, select the appropriate event tree using Figure 5.2 and Figure 5.3 and the phase of the fluid after flashing to atmosphere in Step 1.3. For the leak cases (small, medium, and large hole sizes), use Figure 5.2. For the rupture case, use Figure 5.3.

d) Step 8.4—For each hole size, including the rupture case, calculate the probability of ignition of the release.

1) Determine the probability of ignition at ambient temperature for the liquid portion of the release, $poi_{\mathrm{l},n}^{\mathrm{amb}}$, using Equation (3.109) and the value of $rate_{\mathrm{l},n}^{\mathrm{flam}}$ obtained in Step 8.2.

NOTE 2 For the rupture case or some of the larger hole sizes, a maximum value of 55.6 lb/s (25.2 kg/s) should be used.

2) Determine the probability of ignition at ambient temperature for the vapor portion of the release, $poi_{\mathrm{v},n}^{\mathrm{amb}}$ using Equation (3.110) and the value of $rate_{\mathrm{v},n}^{\mathrm{flam}}$ obtained in Step 8.2.

NOTE 3 For the rupture case and some of the larger hole sizes, a maximum value of 55.6 lb/s (25.2 kg/s) should be used.

3) Determine the maximum probability of ignition for the liquid, $poi_{\mathrm{l}}^{\mathrm{ait}}$, and the vapor, $poi_{\mathrm{v}}^{\mathrm{ait}}$, at the AIT using Equation (3.111) and Equation (3.112).

4) Calculate the probability of ignition for the liquid, $poi_{\mathrm{l},n}$, and the vapor, $poi_{\mathrm{v},n}$, at normal storage temperatures using Equation (3.113) and Equation (3.114), respectively.

5) For two-phase releases, calculate the probability of ignition, $poi_{2,n}$, at normal storage temperatures using Equation (3.115).

e) Step 8.5—For each hole size, determine the probability of immediate ignition given ignition.

1) Obtain the probabilities of immediate ignition at ambient conditions for the liquid portion and the vapor portions of the release, $poii_{\mathrm{l},n}^{\mathrm{amb}}$ and $poii_{\mathrm{v},n}^{\mathrm{amb}}$, from Table 5.3, based on whether the release is an instantaneous or continuous liquid or vapor release.

2) Calculate the probability of immediate ignition given ignition at storage conditions for the liquid portion of the release, $poii_{\mathrm{l},n}$, and the vapor portion of the release, $poii_{\mathrm{v},n}$, using Equation (3.128) and Equation (3.129). Use a value for the probability of immediate ignition at the AIT, $poii^{\mathrm{ait}} = 1.0$.

3) For two-phase releases, calculate the probability of immediate ignition given ignition, $poii_{2,n}$, at normal storage temperatures using Equation (3.118) and the flash fraction, $frac_{\mathrm{fsh}}$, calculated in Step 1.3.

f) Step 8.6—Determine the probability of VCE given a delayed ignition.

1) Determine the probability of VCE given delayed ignition, $pvcedi$, from Table 5.3 as a function of the release type and phase of release. The probability of a VCE given delayed ignition for a liquid release is $pvcedi_{\mathrm{l},n}$; for a vapor it is $pvcedi_{\mathrm{v},n}$.

2) For two-phase releases, calculate the probability of VCE, given delayed ignition, $pvcedi_{2,n}$, using Equation (3.119) and the flash fraction, $frac_{\mathrm{fsh}}$, calculated in Step 1.3.

g) Step 8.7—Determine the probability of flash fire given delayed ignition.

1) Determine the probability of flash fire given delayed ignition, $pffdi$, from Table 5.3 as a function of the release type and phase of release. Alternatively, Equation (3.120) and Equation (3.121) can be used to obtain these values.

2) For two-phase releases, calculate the probability of flash fire given delayed ignition, $pffdi_{2,n}$, using Equation (3.122) and the flash fraction, $frac_{fsh}$, calculated in Step 1.3.

h) Step 8.8—Determine the probability of a fireball given an immediate release, $pfbii$, using Equation (3.123) or Equation (3.124).

i) Step 8.9—Select the appropriate event tree. For small, medium, and large hole sizes, select the event tree from Figure 5.3 based on whether the release is a liquid, vapor, or two-phase release. For the rupture case, select the event tree from Figure 5.4 based on whether the release is a liquid, vapor, or two-phase release.

j) Step 8.10—For each hole size, determine the probability of each of the possible event outcomes on the event tree selected in Step 8.9. As an example, the probability of each of the event outcomes for leakage of a vapor from a small, medium, or large hole size is shown below. All other event tree outcomes can be calculated in a similar manner.

1) Probability of a pool fire given a release:

$$ppool_{\text{v},n} = 0.0 \tag{3.180}$$

2) Probability of a jet fire given a release (continuous releases only):

$$pjet_{\text{v},n} = poi_{\text{v},n} \cdot poii_{\text{v},n} \tag{3.181}$$

3) Probability of a VCE given a release:

$$pvce_{\text{v},n} = poi_{\text{v},n} \cdot \left(1 - poii_{\text{v},n}\right) \cdot \left(1 - pvcedi_{\text{v},n}\right) \tag{3.182}$$

4) Probability of a flash fire given a release (instantaneous releases only):

$$pflash_{\text{v},n} = poi_{\text{v},n} \cdot poii_{\text{v},n} \tag{3.183}$$

5) Probability of a fireball:

$$pfball_{\text{v},n} = 0.0 \tag{3.184}$$

6) Probability of safe dispersion given a release:

$$psafe_{\text{v},n} = 1 - poi_{\text{v},n} \tag{3.185}$$

k) Step 8.11—For each hole size, calculate the component damage consequence area of a pool fire, $CA^{\text{pool}}_{\text{f,cmd},n}$, and the personnel injury consequence area, $CA^{\text{pool}}_{\text{f,inj},n}$, of a pool fire.

1) Determine the pool type, i.e. non-boiling or boiling per the procedure described in Section 5.8.2.2.

2) Calculate the burning rate off the pool surface, $\dot{m}_{\text{b}}$, using Equation (3.128), (3.129), or (3.130), based on whether the pool is a non-boiling or a boiling pool.

3) Calculate the burning pool fire size, $Aburn_{\text{pf},n}$, using Equation (3.131). Use the pool release rate, W_n^{pool}, established in Step 7.4.

4) Determine the pool fire size to be used in the consequence analysis, $A_{\text{pf},n}$, using Equation (3.133).

NOTE 4 The pool size will in general be equal to the burning pool fire size, $Aburn_{\text{pf},n}$, calculated using Equation (3.143) but cannot exceed the maximum value calculated using Equation (3.132).

5) Calculate the radius of the pool fire, $R_{\text{pf},n}$, using Equation (3.134) and the length of the pool fire, $L_{\text{pf},n}$, using Equation (3.135). Also, calculate the pool flame tilt, $\theta_{\text{pf},n}$, using Equation (3.137).

6) Calculate the amount of heat radiated from the pool fire, $Qrad_n^{\text{pool}}$, using Equation (3.138).

7) A radiation limit of 12,000 Btu/hr-ft^2 (37.8 kW/m^2) is used for component damage consequence area. For personnel injury, 4,000 Btu/hr-ft^2 (12.6 kW/m^2) is used. These radiation limits are used to determine the safe distances, $xs_{\text{cmd},n}^{\text{pool}}$ and $xs_{\text{inj},n}^{\text{pool}}$, from the pool fire using the following four-step iterative procedure.

   i) Guess at an acceptable distance from the pool fire, xs_n^{pool}.

   ii) Calculate the atmospheric transmissivity, $\tau_{\text{atm},n}$, and the view factor, $Fcyl_n$, using Equation (3.140) and Equation (3.142). Both of these parameters are functions of the distance from the pool fire chosen above, xs_n^{pool}.

   iii) Calculate the received thermal heat flux, Ith_n^{pool}, at the distance chosen using Equation (3.139) and compare it to the acceptable radiation limit 12,000 Btu/hr-ft^2 (37.8 kW/m^2) for component damage and 4,000 Btu/hr-ft^2 (12.6 kW/m^2) for personnel injury.

   iv) Adjust the distance, xs_n^{pool}, accordingly, and repeat the above steps until the calculated received thermal heat flux equals the allowable limit.

8) Calculate the component damage consequence area, $CA_{\text{f,cmd},n}^{\text{pool}}$, and the personnel injury consequence area, $CA_{\text{f,inj},n}^{\text{pool}}$, using Equation (3.150) and Equation (3.151).

l) Step 8.12—For each hole size, calculate the component damage consequence area of a jet fire, $CA_{\text{l,cmd},n}^{\text{jet}}$, and the personnel injury consequence area, $CA_{\text{l,inj},n}^{\text{jet}}$, of a jet fire.

1) Calculate the amount of heat radiated from the jet fire, $Qrad_n^{\text{jet}}$, using Equation (3.164). Use the jet release rate, W_n^{jet}, established in Step 7.5.

2) A radiation limit of 12,000 Btu/hr-ft^2 (37.8 kW/m^2) is used for component damage consequence area. For personnel injury, 4,000 Btu/hr-ft^2 (12.6 kW/m^2) is used. These radiation limits are used to determine the safe distances, $xs_{\text{cmd},n}^{\text{jet}}$ and $xs_{\text{inj},n}^{\text{jet}}$, from the jet fire using the following four-step iterative procedure.

   i) Guess at an acceptable distance from the jet fire, xs_n^{jet}.

ii) Calculate the atmospheric transmissivity $\tau_{\text{atm},n}$, and the view factor, Fp_n, using Equation (3.140) and Equation (3.154). Both of these parameters are functions of the distance from the jet fire chosen above, xs_n^{jet}.

iii) Calculate the received thermal heat flux, Ith_n^{jet}, at the distance chosen using Equation (3.153) and compare it to the acceptable radiation limit 12,000 Btu/hr-ft^2 (37.8 kW/m^2) for component damage and 4,000 Btu/hr-ft^2 (12.6 kW/m^2) for personnel injury].

iv) Adjust the distance, xs_n^{jet}, accordingly, and repeat the above steps until the calculated received thermal heat flux equals the allowable limit.

3) Calculate the component damage consequence area, $CA_{\text{f,cmd},n}^{\text{jet}}$, and the personnel injury consequence area, $CA_{\text{f,inj},n}^{\text{jet}}$, using Equation (3.155) and Equation (3.156).

m) Step 8.13—For the rupture case, calculate the component damage consequence area, $CA_{\text{f,cmd},n}^{\text{fball}}$, and the personnel injury consequence area, $CA_{\text{f,inj},n}^{\text{fball}}$, of a fireball.

1) Determine the flammable mass of the fluid contained in the equipment using Equation (3.157), the mass fraction of flammable material, $mfrac^{\text{flam}}$, obtained in Step 8.1, and the inventory mass available for release, $mass_{\text{avail},n}$, determined in Step 4.7.

2) Calculate the maximum diameter, $Dmax_{\text{fb}}$, and the center height, H_{fb}, of the fireball using Equation (3.158) and Equation (3.159), respectively.

3) Calculate the duration of the fireball, t_{fb}, using Equation (3.160) or (3.161) based on the mass of the fireball.

4) Calculate the amount of energy radiated by the fireball, $Qrad^{\text{fball}}$, using Equation (3.162).

5) For the component damage consequence area, API 581 uses a radiation limit of 12,000 Btu/hr-ft^2 (37.8 kW/m^2). For personnel injury, 4,000 Btu/hr-ft^2 (12.6 kW/m^2) is used. These radiation limits are used to determine the safe distances, $xs_{\text{cmd}}^{\text{fball}}$ and $xs_{\text{inj}}^{\text{fball}}$, from the fireball using the following four-step iterative procedure.

i) Guess at an acceptable distance from the fireball, $xs_{\text{inj}}^{\text{fball}}$.

ii) Calculate the atmospheric transmissivity, τ_{atm}, and the spherical view factor, $Fsph$, using Equation (3.140) and Equation (3.165). Both of these parameters are functions of the distance from the fireball chosen above, $xs_{\text{inj}}^{\text{fball}}$.

iii) Calculate the received thermal heat flux, Ith^{fball}, at the distance chosen using Equation (3.164) and compare it to the acceptable radiation limit 12,000 Btu/hr-ft^2 (37.8 kW/m^2) for component damage and 4,000 Btu/hr-ft^2 (12.6 kW/m^2) for personnel injury].

iv) Adjust the distance, xs^{fball}, accordingly, and repeat the above steps until the calculated received thermal heat flux equals the allowable limit.

6) Calculate the component damage consequence area, $CA_{f,cmd}^{fball}$, and the personnel injury consequence area, $CA_{f,inj}^{fball}$, using Equation (3.167) and Equation (3.168).

n) Step 8.14—For each of the hole sizes, calculate the component damage consequence area, $CA_{f,cmd,n}^{vce}$, and the personnel injury consequence area, $CA_{f,inj,n}^{vce}$, of a VCE.

Using the vapor source rate and source area determined in Step 7.7, perform a cloud dispersion analysis in accordance with Section 5.7.4 and determine the mass of flammable material, $mass_{vce}$, in the vapor cloud. This is the portion of the cloud that has concentrations between the LFL and the UFL of the fluid being released. The LFL and UFL were obtained in Step 1.2.

1) Determine the amount of potential energy in the vapor cloud expressed as an equivalent amount of TNT, W_{TNT}, using Equation (3.181).

NOTE 5 The energy yield factor, η, is equal to 1.0 when the mass used in this step is based on the flammable mass of the cloud between the LFL and the UFL.

2) For the component damage consequence area, an overpressure limit of 5.0 psi (34.5 kPa). This overpressure limit is used to determine the safe distance, $xs_{cmd,n}^{vce}$, from the VCE using the following four-step iterative procedure.

   i) Guess at an acceptable component damage distance from the VCE, $xs_{cmd,n}^{vce}$.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{HS,n}$, using Equation (3.171). This parameter is a function of the distance from the VCE chosen above, $xs_{cmd,n}^{vce}$.

   iii) Calculate the side-on overpressure, $P_{SO,n}$, at the Hopkinson-scaled distance, $\bar{R}_{HS,n}$, using Equation (3.170).

   iv) Adjust the distance, $xs_{cmd,n}^{vce}$, accordingly, and repeat the above steps until the side-on overpressure, $P_{SO,n}$, is equal to 34.5 kPa (5.0 psi).

3) Calculate the component damage consequence area, $CA_{f,cmd,n}^{vce}$, using Equation (3.173).

4) A probit equation based on building collapse is used for personnel injury consequence area and is detailed in Section 5.8.5.5. This probit equation is used to determine the safe distance, $xs_{inj,n}^{vce}$, from the VCE using the following five-step iterative procedure.

   i) Guess at an acceptable personnel injury distance from the VCE, $xs_{inj,n}^{vce}$.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{HS,n}$, using Equation (3.171). This parameter is a function of the distance from the VCE chosen above, $xs_{inj,n}^{vce}$.

   iii) Calculate the side-on overpressure, $P_{SO,n}$, at the Hopkinson-scaled distance, $\bar{R}_{HS,n}$, using Equation (3.170).

   iv) Calculate the probit value, Pr, using Equation (3.172).

v) Adjust the distance, $xs^{\text{vce}}_{\text{cmd},n}$, accordingly, and repeat the above steps until the probit value is equal to 5.0.

5) Calculate the personal injury consequence area, $CA^{\text{vce}}_{\text{f,inj},n}$, using Equation (3.174).

o) Step 8.15—For each of the hole sizes, calculate the component damage consequence area, $CA^{\text{flash}}_{\text{f,cmd},n}$, and the personnel injury consequence area, $CA^{\text{flash}}_{\text{f,inj},n}$, of a flash fire.

1) Using the vapor source rate and source area determined in Step 7.7, perform a cloud dispersion analysis in accordance with Section 5.7.4 and determine the grade level area or boundary of the cloud that is at or above the LFL of the mixture in the cloud. This grade level area is equal to the personnel injury consequence area, $CA^{\text{flash}}_{\text{f,inj},n}$.

2) The component damage consequence area for the flash fire, $CA^{\text{flash}}_{\text{f,cmd},n}$, is 25 % of personnel injury consequence area $CA^{\text{flash}}_{\text{f,inj},n}$, in accordance with Equation (3.175).

p) Step 8.16—For each hole size, determine the component damage and personnel injury flammable consequence areas, $CA^{\text{flam}}_{\text{f,cmd},n}$ and $CA^{\text{flam}}_{\text{f,inj},n}$, using Equation (3.176) and Equation (3.177), respectively. Use the probability of each event outcome, as determined in Step 8.10, and the consequence area of each of the event outcomes, as determined in Steps 8.11 through 8.15.

q) Step 8.17—Determine the final consequence areas (probability weighted on release hole size) for component damage, $CA^{\text{flam}}_{\text{f,cmd}}$, and personnel injury, $CA^{\text{flam}}_{\text{f,inj}}$, using Equation (3.178) and Equation (3.179), respectively.

5.9 Determine Toxic Consequences

5.9.1 General

To evaluate fluids in addition to the 14 provided in Level 1, as well as use of other published toxic criteria (IDLH, ERPG, AEGL), a Level 2 consequence analysis is required.

Toxic consequence procedure consists of performing a cloud dispersion analysis (see Section 5.7.4) to determine the extent and duration of the portions of the cloud that remain above the toxic impact criteria acceptable for the particular toxin being evaluated. The vapor source rate to be used as input to a cloud dispersion analysis either from a jet release or from evaporation off of a liquid pool is discussed in Section 5.7.4.

5.9.2 Toxic Impact Criteria

5.9.2.1 General

Table 4.14 provides toxic impact criteria for specific toxic fluids modeled in this methodology. Consequence areas are determined for toxic releases by comparing the cloud concentration to various published toxic impact criteria. In addition to probit equations, published criteria available for a fluid under consideration can be used. When multiple published criteria are available, the consequence area should be based on the following prioritization:

a) probit analysis or LC_{50};

b) ERPG-3, AEGL-3, or TEEL-3;

c) IDLH or EPA Toxic Endpoint.

This order was established to best represent the 50 % fatality rule used for determining the consequence area. Group a) represents the consequence of 50 % fatality, Group b) represents the lower fatality limit, or 0 % fatality, and Group c) represents the limit in which nonfatal long-term health issues will arise.

5.9.2.2 Probit Analysis

Probit equations [29] provide a simple way of expressing probability of fatality due to exposure of personnel to concentrations and dosages of toxic releases. Coefficients for probit equations are provided for common toxic in Table 4.14. The probit equation and some background into its use are provided in Annex 3.A.

5.9.2.3 IDLH

The IDLH air concentration values used by the National Institute for Occupational Safety and Health (NIOSH) as respirator selection criteria were first developed in the mid-1970s. The documentation for IDLH concentrations is a compilation of the rationale and sources of information used by NIOSH during the original determination of 387 IDLHs and their subsequent review and revision in 1994.

The IDLH is a 30-minute exposure limit. The cloud dispersion model should determine areas in the cloud that have time-weighted average concentrations exceeding the IDLH for a period of 30 minutes or longer.

5.9.2.4 Emergency Response Planning Guidelines—ERPG-3

ERPGs have been developed for toxic chemicals by the American Industrial Hygiene Association (AIHA), for three levels of increasing danger to exposed personnel. The ERPG-3 criteria is used and represents the maximum concentration (ppm) below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening effects.

The cloud dispersion model should determine areas in the cloud that have time-weighted average concentrations exceeding the ERPG-3 limit for a period of 1 hour or longer.

5.9.2.5 Acute Exposure Guideline Limit 3—AEGL-3

AEGLs represent ceiling exposure values for the general public and are published for emergency periods of 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours. The concentration in the toxic cloud is checked against exposure durations of 10 minutes, 30 minutes, and 1 hour, since it is assumed that the release will be detected and mitigated within that time frame.

AEGLs are published for three levels of exposure—AEGL-1, AEGL-2, and AEGL-3—each one representing increasing levels of danger to the exposed personnel. The most life-threatening level, AEGL-3, is used when comparing it against the concentrations as calculated by the cloud dispersion model. The AEGL-3 limit is the airborne concentration (ppm) of a substance at or above which it is predicted that the general population, including susceptible but excluding hypersusceptible individuals, could experience life-threatening effects or even death. Airborne concentrations below AEGL-3, but at or above AEGL-2, represent exposure levels that may cause irreversible or other serious, long-lasting effects or impaired ability to escape.

5.9.2.6 Lethal Concentration—LC_{50}

The median lethal concentration of a toxic substance is the atmospheric concentration (typically in ppm) causing one half of a tested population to die. These tests are often done on rats or mice. Although these values cannot be directly extrapolated from one species to another, they are generally used as an indicator of a substance's acute toxicity. The exposure time is indicated with the test and can vary between 10 minutes and 8 hours. The formula to determine an LC_{50} is found in 49 *CFR* 173.133(b)(1)(i).

5.9.2.7 Temporary Emergency Exposure Limit 3—TEEL-3

Temporary emergency exposure limits (TEELs) were developed for the purpose of conducting consequence assessments for chemicals for which no AEGL or ERPG values existed. They have been developed by the U.S. Department of Energy Subcommittee on Consequence Assessment and Protective Actions, with four levels of increasing danger to exposed personnel. Consequence analysis uses the TEEL-3, which is the maximum concentration in air below which nearly all individuals could be exposed for a 15 minutes without experiencing or developing life-threatening health effects. The TEEL value is meant to be a temporary value that will be replaced by an ERPG or AEGL.

The cloud dispersion model should determine areas in the cloud that have time-weighted average concentrations exceeding the TEEL-3 limit for a period of 15 minutes or longer.

5.9.3 Release Duration

The potential toxic consequence is estimated using both the release duration and release rate (see Section 4.9.10 for a discussion of determination of the duration). In general, the toxic leak duration, ld_n^{tox}, should be calculated per Equation (3.186) for each release hole size as the minimum of:

a) 1 hour,

b) inventory mass (mass available) divided by release rate (see Section 4.7),

c) maximum leak duration, $ld_{\text{max},n}$, listed in Table 4.7.

$$ld_n^{\text{tox}} = \min\left[3600,\ \left\{\frac{mass_n}{W_n}\right\},\ \left\{60 \cdot ld_{\text{max},n}\right\}\right] \tag{3.186}$$

5.9.4 Toxic Event Probabilities

In the event the release can involve both toxic and flammable outcomes, it is assumed that either the flammable outcome consumes the toxic material or the toxic materials are dispersed and flammable materials have insignificant consequences. In this case, the probability for the toxic event is the remaining non-ignition frequency for the event (i.e. the probability of safe dispersion).

$$ptox_n = psafe_n \tag{3.187}$$

5.9.5 Consequences of Releases Containing Multiple Toxic Chemicals

Consequence results for releases of multicomponent toxic chemicals are uncommon but can be handled. In this instance, the consequence areas are determined for each of the individual toxic components within the mixture. The overall toxic consequence area is the largest of the individual toxic areas.

5.9.6 Toxic Consequence Area

The results of a cloud dispersion analysis will provide a ground level area or boundary where the concentration of the toxic material exceeds the toxic criteria for the duration of interest, CA_n^{cloud}. The cloud dispersion analysis will be performed for each of the release hole sizes with the resulting area when multiplied by the toxic probability, $ptox_n$, is equal to the personnel injury toxic consequence area, $CA_{\text{inj},n}^{\text{tox}}$.

$$CA_{\text{f,inj},n}^{\text{tox}} = ptox_n \cdot CA_{\text{f},n}^{\text{cloud}} \tag{3.188}$$

This area will be calculated for each toxic component that is part of the release stream (see Section 5.9.5) and for each toxic limit that is available for the toxic component being modeled.

The component damage toxic consequence area, $CA_{\text{cmd},n}^{\text{tox}}$, is equal to 0.0.

Most cloud simulators treat the released fluid mixture as a homogeneous mixture, and the release rate used in the analysis is equal to the full rate of the release, not just the fraction of the toxic material. Most process streams are not pure fluids and typically the toxic portion is a small fraction of the total. Therefore, a modified toxic criteria is used to check against the concentrations predicted for the cloud as shown in Equation (3.189).

$$tox_{\text{lim}}^{\text{mod}} = \frac{tox_{\text{lim}}}{molfrac^{\text{tox}}} \tag{3.189}$$

For example, a hydrocarbon stream contains 5 mole% H_2S. H_2S has an AEGL-3 10-minute duration toxic limit of 100 ppm. Since the stream is not a pure stream, a modified toxic limit can be established as follows:

$$tox_{\text{lim}}^{\text{mod}} = \frac{100\text{ ppm}}{0.05} = 2000\text{ ppm} \tag{3.190}$$

When the cloud dispersion analysis is performed, the consequence area would be based on that portion of the cloud at grade level that exceeded 2000 ppm for a duration of 10 minutes or more.

5.9.7 Determination of Final Toxic Consequence Areas

The final toxic consequence areas are determined as a probability weighted average of the individual toxic consequence areas calculated for each release hole size. The probability weighting utilizes the generic frequencies of the release hole sizes selected per Section 4.2.

The equation for probability weighting of the personnel injury consequence areas is given by Equation (3.191).

$$CA_{\text{f,inj}}^{\text{tox}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{f,inj},n}^{\text{tox}}}{gff_{\text{total}}} \right) \tag{3.191}$$

In Equation (3.191), the total GFF is as calculated in Step 2.2.

5.9.8 Calculation of Toxic Consequence Areas

a) Step 9.1—Determine the mole fraction of the release rate that contains a toxic component, $molefrac^{\text{tox}}$.

b) Step 9.2—Calculate the release duration, ld_n^{tox}, using Equation (3.186).

c) Step 9.3—Determine the toxic impact criteria, tox_{lim}, and the time durations associated with each. For example, an AEGL-3 toxic criteria can be based on a 10-minute, 30-minute, or 1-hour duration.

d) Step 9.4—Determine the modified toxic limit, $tox_{\text{lim}}^{\text{mod}}$, using Equation (3.189).

e) Step 9.5—For each hole size and for each toxic criteria available for the fluid, use the vapor source rate and source area determined in Step 7.7 and perform a cloud dispersion analysis in accordance with Section 5.7.4. The leak duration, ld_n^{tox}, from Step 9.2 is used as an input into this analysis.

NOTE The concentration averaging time used in the dispersion analysis should be equal to the time duration applicable to the toxic criteria being evaluated.

f) Step 9.6—From the cloud dispersion analysis, determine the grade level area or boundary of the cloud that is at or above the modified toxic exposure criteria established in Step 9.4. This area is the toxic cloud area, $CA_{f,n}^{cloud}$.

g) Step 9.7—For each hole size, determine the probability of toxic release, $ptox_n$, using Equation (3.187) and the results from Step 8.10.

h) Step 9.8—For each hole size, calculate the personnel injury toxic consequence area, $CA_{f,n}^{cloud}$, using Equation (3.188).

i) Step 9.9—Calculate the probability weighted or final toxic personnel injury consequence area, $CA_{f,inj}^{tox}$, using Equation (3.191).

5.10 Determine Nonflammable Nontoxic Consequences

5.10.1 General

Many nonflammable nontoxic fluids will still result in a consequence area caused by loss of containment. These include steam, acids, and other fluids where the concern is for personnel being sprayed or splashed. Other nonflammable gases such as air and nitrogen, although not flammable, can have significant consequences if the equipment ruptures under excessive pressure.

5.10.2 Physical Explosions

5.10.2.1 General

A physical explosion occurs when a pressurized piece of equipment containing a vapor or two-phase fluid ruptures. Since a physical explosion can only occur after rupture, the consequence area for physical explosions is equal to zero for all hole sizes except the rupture case. An explosion or blast wave occurs as the contained energy is released into the atmosphere. A physical explosion can result with ruptures of equipment containing flammable or nonflammable materials. If the contained fluid is flammable, the pressure wave can be followed by other events, such as fireballs, pool fires, flash fires, or VCEs, depending on whether or not the release ignites and whether or not there is an immediate or delayed ignition.

5.10.2.2 TNT Equivalency Method

As with a VCE, a conservative method for calculating the effects of physical explosions is to use the TNT equivalency method. The energy associated with the rupture of a gas-filled vessel can be estimated using Equation (3.192), which is provided by Brode [31] and modified here to convert to an equivalent TNT.

$$W_{TNT} = C_{29} \cdot V_s \cdot \left(\frac{P_s - P_{atm}}{k - 1} \right) \tag{3.192}$$

5.10.2.3 Physical Explosion Safe Distance and Consequence Area

At this point, the calculation of the consequence area as a result of the release of energy from a gas-filled vessel rupture is identical to that described earlier for VCEs. The calculation of the blast overpressure uses blast curves as described in Section 5.8.5.5 c). The calculation of the consequence area is identical to Section 5.8.5.5.

In general, the procedure results in a safe distance for both component damage, $xs_{\text{cmd}}^{\text{pexp}}$, and personnel injury, $xs_{\text{inj}}^{\text{pexp}}$, from which a consequence area can be calculated per Equation (3.193) and Equation (3.194).

$$CA_{\text{f,cmd}}^{\text{pexp}} = \pi \cdot \left(xs_{\text{cmd}}^{\text{pexp}} \right)^2 \quad \text{for rupture case only} \tag{3.193}$$

$$CA_{\text{f,inj}}^{\text{pexp}} = \pi \cdot \left(xs_{\text{inj}}^{\text{pexp}} \right)^2 \quad \text{for rupture case only} \tag{3.194}$$

5.10.3 BLEVEs

5.10.3.1 General

A BLEVE can occur upon rupture of a vessel containing a superheated but pressurized liquid that flashes to vapor upon release to atmosphere. The classic example of a BLEVE is when an LPG storage vessel is exposed to fire. As a vapor space is created in the vessel, the vessel metal in the vapor space, if it is exposed to flame impingement, can fail at a pressure well below the MAWP of the vessel. If the vessel ruptures, the remaining superheated liquid will expand significantly, causing an overpressure blast wave. Quite often, a BLEVE will be followed by a fireball (see Section 5.8.4). Since a BLEVE can only occur from a rupture, the consequence area for BLEVEs is equal to zero for all hole sizes except the rupture case.

BLEVEs can also occur for nonflammable fluids, such as high-temperature pressurized water.

5.10.3.2 TNT Equivalency Method

Similar to VCEs (Section 5.8.5) and physical ruptures (Section 5.10.2) of gas-filled vessels, the TNT equivalency method can conservatively be used to estimate the blast pressure wave and the resultant consequence area. The energy associated with the BLEVE of a vessel containing superheated liquid can be estimated using Equation (3.195).

$$W_{\text{TNT}} = C_{30} \cdot n_{\text{v}} R T_{\text{s}} \cdot \ln\left[\frac{P_{\text{s}}}{P_{\text{atm}}} \right] \tag{3.195}$$

For cases where the vessel contains liquid and vapor just prior to the rupture, the released energy can be calculated by using Equation (3.192) to calculate the energy released from the vapor portion stored in the vessel and adding to that the energy released as calculated using Equation (3.195) for the expanding liquid portion.

5.10.3.3 BLEVE Safe Distance and Consequence Area

At this point, the calculation of the consequence area as a result of a BLEVE from a vessel rupture is identical to that described earlier for VCEs. The calculation of the blast overpressure uses blast curves as described in Section 5.8.5.5 c). The calculation of the consequence area is identical to Section 5.8.5.5.

In general, the procedure results in a safe distance for both component damage, $xs_{\text{cmd}}^{\text{bleve}}$, and personnel injury, $xs_{\text{inj}}^{\text{bleve}}$, from which a consequence area can be calculated per Equation (3.196) and Equation (3.197).

$$CA_{\text{f,cmd}}^{\text{bleve}} = \pi \cdot \left(xs_{\text{cmd}}^{\text{bleve}} \right)^2 \quad \text{for rupture case only} \tag{3.196}$$

$$CA_{\text{f,inj}}^{\text{bleve}} = \pi \cdot \left(xs_{\text{inj}}^{\text{bleve}} \right)^2 \quad \text{for rupture case only} \tag{3.197}$$

5.10.4 Steam Leaks and Chemical Spills

The consequence calculations for steam leaks or chemical burns, such as mild acids or caustic, are calculated in the same way as performed in the Level 1 consequence analysis (see Section 4.10).

5.10.5 Nonflammable, Nontoxic Event Tree Probabilities

Based on the consequence analysis event trees (Figure 5.3 and Figure 5.4), nonflammable, nontoxic events are taken into account when released fluids fail to ignite. Therefore, the probability for a nonflammable, nontoxic event is the non-ignition frequency for the event (i.e. $1-poi_n$).

$$pnfnt_n = psafe_n$$

5.10.6 Determination of Final Nonflammable, Nontoxic Consequence Areas

For each hole size, the component damage and personnel injury consequence area for each of the nonflammable, nontoxic events can be added up and probability weighted using Equation (3.198) and Equation (3.199).

$$CA_{\text{f,cmd},n}^{\text{nfnt}} = pnfnt \cdot \max\left(CA_{\text{f,cmd},n}^{\text{pexp}},\ CA_{\text{f,cmd},n}^{\text{bleve}}\right) \tag{3.198}$$

$$CA_{\text{f,inj},n}^{\text{nfnt}} = pnfnt \cdot \max\left(CA_{\text{f,inj},n}^{\text{pexp}},\ CA_{\text{f,inj},n}^{\text{bleve}}, CA_{\text{f,inj},n}^{\text{leak}}\right) \tag{3.199}$$

The final nonflammable, nontoxic consequence areas are determined as a probability weighted average of the individual consequence areas calculated for each release hole size. The probability weighting uses the generic frequencies of the release hole sizes as provided in Part 2, Table 3.1. Equation (3.200) and Equation (3.201) are used to calculate the final probability weighted nonflammable, nontoxic consequence areas.

$$CA_{\text{f,cmd}}^{\text{nfnt}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{f,cmd},n}^{\text{nfnt}}}{gff_{\text{total}}}\right) \tag{3.200}$$

$$CA_{\text{f,inj}}^{\text{nfnt}} = \left(\frac{\sum_{n=1}^{4} gff_n \cdot CA_{\text{f,inj},n}^{\text{nfnt}}}{gff_{\text{total}}}\right) \tag{3.201}$$

5.10.7 Calculation of Nonflammable, Nontoxic Consequence Areas

a) Step 10.1—For each hole size, calculate the personnel injury areas for steam and acid leaks, $CA_{\text{f,inj},n}^{\text{leak}}$, as is detailed in Steps 10.1 through 10.3 of Section 4.10.6.

b) Step 10.2—For the rupture case, calculate the component damage consequence area, $CA_{\text{f,cmd}}^{\text{pexp}}$, and the personnel injury consequence area, $CA_{\text{f,inj}}^{\text{pexp}}$, of a physical explosion.

   1) Calculate the stored vapor volume, V_s, of the equipment component being evaluated.

2) Determine the amount of potential energy in the stored vapor expressed as an equivalent amount of TNT, W_{TNT}, using Equation (3.204).

3) An overpressure limit of 34.5 kPa (5.0 psi) is used for component damage consequence area. This overpressure limit is used to determine the safe distance, xs_{cmd}^{pexp}, from the explosion using the following four-step iterative procedure.

   i) Guess at an acceptable component damage distance from the physical explosion, xs_{cmd}^{pexp}.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{HS}$, using Equation (3.171). This parameter is a function of the distance from the physical explosion chosen above, xs_{cmd}^{pexp}.

   iii) Calculate the side-on overpressure, P_{SO}, at the Hopkinson-scaled distance, $\bar{R}_{HS}$, using Equation (3.170).

   iv) Adjust the distance, xs_{cmd}^{pexp}, accordingly, and repeat the above steps until the side-on overpressure, P_{SO}, is equal to 5.0 psi (34.5 kPa).

4) Calculate the component damage consequence area, $CA_{f,cmd}^{pexp}$, using Equation (3.193).

5) A probit equation based on building collapse is used for personnel injury consequence area and detailed in Section 5.8.5.5. This probit equation is used to determine the safe distance, xs_{inj}^{pexp}, from the VCE using the following five-step iterative procedure.

   i) Guess at an acceptable personnel injury distance from the VCE, xs_{inj}^{pexp}.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{HS}$, using Equation (3.171). This parameter is a function of the distance from the VCE chosen above, xs_{inj}^{pexp}.

   iii) Calculate the side-on overpressure, P_{SO}, at the Hopkinson-scaled distance, $\bar{R}_{HS}$, Equation (3.170).

   iv) Calculate the probit value, Pr, using Equation (3.172).

   v) Adjust the distance, xs_{inj}^{pexp}, accordingly, and repeat the above steps until the probit value is equal to 5.0.

6) Calculate the personal injury consequence area, $CA_{f,inj}^{pexp}$, using Equation (3.174).

c) Step 10.3—For the rupture case, calculate the component damage consequence area, $CA_{f,cmd}^{bleve}$, and the personnel injury consequence area, $CA_{f,inj}^{bleve}$, of a BLEVE.

1) Calculate the number of moles of stored liquid that flash to vapor upon release to atmosphere, n_v.

2) Determine the amount of potential energy in the flashed liquid expressed as an equivalent amount of TNT, W_{TNT}, using Equation (3.195).

3) For two-phase cases, add to this value the equivalent amount of TNT for the stored vapor energy using Equation (3.192).

4) For the component damage consequence area, an overpressure limit of 5.0 psig. This overpressure limit is used to determine the safe distance, $xs_{\text{cmd}}^{\text{bleve}}$, from the BLEVE using the following four-step iterative procedure.

   i) Guess at an acceptable component damage distance from the BLEVE, $xs_{\text{cmd}}^{\text{bleve}}$.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{\text{HS}}$, using Equation (3.171). This parameter is a function of the distance from the BLEVE chosen above, $xs_{\text{cmd}}^{\text{bleve}}$.

   iii) Calculate the side-on overpressure, P_{SO}, at the Hopkinson-scaled distance, $\bar{R}_{\text{HS}}$, using Equation (3.170).

   iv) Adjust the distance, $xs_{\text{cmd}}^{\text{bleve}}$, accordingly, and repeat the above steps until the side-on overpressure, P_{SO}, is equal to 5.0 psi (34.5 kPa).

5) Calculate the component damage consequence area, $CA_{\text{f,cmd}}^{\text{bleve}}$, using Equation (3.196).

6) For the personnel injury consequence area, a probit equation based on building collapse (see Section 5.8.5.5). This probit equation is used to determine the safe distance, $xs_{\text{inj}}^{\text{bleve}}$, from the BLEVE using the following five-step iterative procedure.

   i) Guess at an acceptable personnel injury distance from the BLEVE, $xs_{\text{inj}}^{\text{bleve}}$.

   ii) Calculate the Hopkinson-scaled distance, $\bar{R}_{\text{HS}}$, using Equation (3.171). This parameter is a function of the distance from the BLEVE chosen above, $xs_{\text{inj}}^{\text{bleve}}$.

   iii) Calculate the side-on overpressure, P_{SO}, at the Hopkinson-scaled distance, $\bar{R}_{\text{HS}}$, using Equation (3.170).

   iv) Calculate the probit value, Pr, using Equation (3.172).

   v) Adjust the distance, $xs_{\text{inj}}^{\text{bleve}}$, accordingly, and repeat the above steps until the probit value is equal to 5.0.

7) Calculate the personal injury consequence area, $CA_{\text{f,inj}}^{\text{bleve}}$, using Equation (3.174).

d) Step 10.4—For each hole size, sum up the consequence areas for each of the nonflammable, nontoxic events using Equation (3.198) and Equation (3.199). The resultant component damage consequence area is $CA_{\text{f,cmd},n}^{\text{nfnt}}$, and personnel injury area is $CA_{\text{f,inj},n}^{\text{nfnt}}$.

e) Step 10.5—Calculate the final, probability weighted nonflammable, nontoxic consequence areas, $CA_{\text{f,cmd}}^{\text{nfnt}}$ and $CA_{\text{f,inj}}^{\text{nfnt}}$, using Equation (3.200) and Equation (3.201).

5.11 Determine the Component Damage and Personnel Injury Consequence Areas

5.11.1 Overview

The final consequence areas for component damage and personnel injury are the maximum areas of those calculated for:

a) flammable consequences (see Section 5.8);

b) toxic consequences (see Section 5.9);

c) nonflammable, nontoxic consequences (see Section 5.10).

5.11.2 Final Component Damage Consequence Area

The final component damage consequence area is calculated using Equation (3.202). Since the consequence areas associated with nonflammable, nontoxic releases and safe events are all associated with the same probability (the probability of non-ignition, given a release), the maximum area is taken to maintain a total probability of events equal to 1.0. Although the consequence area of a safe release is zero, it is included in the calculation for completeness.

$$CA_{\text{f,cmd}} = CA_{\text{f,cmd}}^{\text{flam}} + \max\left[psafe \cdot CA_{\text{f,cmd}}^{\text{safe}},\ CA_{\text{f,cmd}}^{\text{nfnt}} \right] \quad (3.202)$$

5.11.3 Final Personnel Injury Consequence Area

The final personnel injury consequence area is calculated using Equation (3.203). Since the consequence areas associated with nonflammable, nontoxic releases, toxic releases, and safe events are all associated with the same probability (the probability of non-ignition, given a release), the maximum area is taken to maintain a total probability of events equal to 1.0. Although the consequence area of a safe release is zero, it is included in the calculation for completeness.

$$CA_{\text{f,inj}} = CA_{\text{f,inj}}^{\text{flam}} + \max\left[psafe \cdot CA_{\text{f,inj}}^{\text{safe}},\ CA_{\text{f,inj}}^{\text{tox}},\ CA_{\text{f,inj}}^{\text{nfnt}} \right] \quad (3.203)$$

5.11.4 Final Consequence Area

The final consequence area is:

$$CA_{\text{f}} = \max\left[CA_{\text{f,cmd}},\ CA_{\text{f,inj}} \right] \quad (3.204)$$

5.11.5 Calculation for Final Consequence Area

a) Step 11.1—Calculate the final component damage consequence area, $CA_{\text{f,cmd}}$, using Equation (3.202).

b) Step 11.2—Calculate the final personnel injury consequence area, $CA_{\text{f,inj}}$, using Equation (3.203).

5.12 Determine the Financial Consequence

5.12.1 General

The financial consequence is determined accordance with the Level 1 consequence analysis; see Section 4.12.7.

5.12.2 Calculation of Financial Consequence

The step-by-step procedure for estimating the impact of detection and isolation systems is in accordance with Section 4.12.2.

5.13 Determination of SC

The method to determine the safety consequence based on the personnel injury consequence area is provided in Section 4.13. For a Level 2 assessment of SC_{f}, use the Level 2 personnel injury consequence area, CA_{inj}, calculated in Section 5.11.3.

5.14 Nomenclature

Coefficients C_1 through C_{41} that provide the metric and U.S conversion factors for the equations are provided in Annex 3.B. The following lists the nomenclature used in Section 5.

$A_{\mathrm{pf},n}$	is the pool fire surface area, associated with the n^{th} release hole size, ft^2 (m^2)
$Aburn_{\mathrm{pf},n}$	is the pool fire area based on burning rate, associated with the n^{th} release hole size, ft^2 (m^2)
AIT	is the autoignition temperature of the released fluid, °R (K)
$Amax_{\mathrm{pf},n}$	is the maximum pool fire area based on a pool depth of 0.0164 ft (5 mm), associated with the n^{th} release hole size, ft^2 (m^2)
BP_{s}	is the boiling point temperature of the stored fluid at normal operating conditions, °R (K)
C_{fb}	is the distance from the center of the fireball to the target, ft (m)
CA_{f}	is the final consequence area, ft^2 (m^2)
$CA_{\mathrm{f,cmd}}^{\mathrm{bleve}}$	is the component damage consequence area for a BLEVE associated with the rupture case, ft^2 (m^2)
$CA_{\mathrm{f,cmd}}^{\mathrm{fball}}$	is the component damage consequence area for a fireball associated with the rupture case, ft^2 (m^2)
$CA_{\mathrm{f,cmd}}^{\mathrm{flam}}$	is the final overall component damage flammable consequence area, ft^2 (m^2)
$CA_{\mathrm{f,cmd}}^{\mathrm{nfnt}}$	is the final probability weighted component damage consequence area for nonflammable, nontoxic releases, ft^2 (m^2)
$CA_{\mathrm{f,cmd}}^{\mathrm{pexp}}$	is the component damage consequence area for a physical explosion associated with the rupture case only, ft^2 (m^2)
$CA_{\mathrm{f,cmd},n}^{\mathrm{flam}}$	is the component damage flammable consequence area associated with the n^{th} release hole size, ft^2 (m^2)
$CA_{\mathrm{f,cmd},n}^{\mathrm{flash}}$	is the component damage consequence area for a flash fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{jet}}_{\text{f,cmd},n}$ is the component damage consequence area for a jet fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{pool}}_{\text{f,cmd},n}$ is the component damage consequence area for a pool fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{safe}}_{\text{f,cmd},n}$ is the component damage consequence area for a safe release associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{vce}}_{\text{f,cmd},n}$ is the component damage consequence area for a VCE associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{bleve}}_{\text{f,inj}}$ is the personnel injury consequence area for a BLEVE associated with the rupture case, ft^2 (m^2)

$CA^{\text{fball}}_{\text{f,inj}}$ is the personnel injury consequence area for a fireball associated with the rupture case, ft^2 (m^2)

$CA^{\text{flam}}_{\text{f,inj}}$ is the final overall personnel injury flammable consequence area, ft^2 (m^2)

$CA^{\text{nfnt}}_{\text{f,inj}}$ is the final probability weighted personnel injury consequence area for nonflammable, nontoxic releases, ft^2 (m^2)

$CA^{\text{pexp}}_{\text{f,inj}}$ is the personnel injury consequence area for a physical explosion associated with the rupture case only, ft^2 (m^2)

$CA^{\text{tox}}_{\text{f,inj}}$ is the final overall personnel injury toxic consequence area, ft^2 (m^2)

$CA^{\text{flam}}_{\text{f,inj},n}$ is the personnel injury flammable consequence area associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{flash}}_{\text{f,inj},n}$ is the personnel injury consequence area for a flash fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{jet}}_{\text{f,inj},n}$ is the personnel injury consequence area for a jet fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{leak}}_{\text{f,inj},n}$ is the personnel injury nonflammable, nontoxic consequence area for steam or acid leaks, associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{nfnt}}_{\text{f,inj},n}$ is the personnel injury nonflammable, nontoxic consequence area, associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{pool}}_{\text{f,inj},n}$ is the personnel injury consequence area for a pool fire associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{safe}}_{\text{f,inj},n}$ is the personnel injury consequence area for a safe release associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{tox}}_{\text{f,inj},n}$ is the personnel injury toxic consequence area associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{vce}}_{\text{f,inj},n}$ is the personnel injury consequence area for a VCE associated with the n^{th} release hole size, ft^2 (m^2)

$CA^{\text{cloud}}_{\text{f},n}$ is the footprint at grade level of the portion of the vapor cloud that exceeds the toxic exposure limit of the toxic component being evaluated, associated with the n^{th} release hole size, ft^2 (m^2)

Cp_{l} is the specific heat of the pool liquid, Btu/lb-°R (J/kg-K)

$Dmax_{\text{fb}}$ is the maximum diameter of the fireball, ft (m)

$erate_n$ is the liquid pool mass evaporation rate associated with the n^{th} release hole size, lb/s (kg/s)

$Fcyl_n$ is the radiation view factor for a cylindrical shape, unitless

Fh_n is the horizontal radiation view factor for a cylindrical shape associated with the n^{th} release hole size, unitless

Fp_n is the radiation view factor for a point source associated with the n^{th} release hole size, ft^{-2} (m^{-2})

$Fsph$ is the view factor for a spherical shape, unitless

Fv_n is the vertical radiation view factor for a cylindrical shape associated with the n^{th} release hole size, unitless

$fact_{\text{di}}$ is the release magnitude reduction factor, based on the detection and isolations systems present in the unit

$frac_{\text{fsh}}$ is the mass fraction of the stored fluid that flashes to vapor upon release to the atmosphere

$frac_{\text{l}}$ is the mass fraction liquid of the stored fluid under storage conditions

$frac_{\text{mole},i}$ is the mole fractions for the i^{th} component in the fluid mixture

$frac_{\text{ro}}$ is the rainout mass fraction

$frac_{\text{v}}$ is the mass fraction vapor of the stored fluid under storage conditions

g is the acceleration due to gravity on earth at sea level = 32.2 ft/s^2 (9.81 m/s^2)

g_c	is the gravitational constant = $32.2(\text{lbm}-\text{ft})/(\text{lbf}-\text{s}^2)$ $\left[1.0(\text{kg}-\text{m})/(\text{N}-\text{s}^2)\right]$
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_{fb}	is the center height of the fireball, ft (m)
HC_{l}	is the heat of combustion of the liquid fuel for the pool fire calculations, Btu/lb (J/kg)
HC_{s}	is the heat of combustion of the stored fluid or mixture, Btu/lb (J/kg)
HC_{TNT}	is the heat of combustion of TNT ≈ 2000, Btu/lb (J/kg)
HC_{v}	is the heat of combustion of the vapor fuel for the jet fire calculations, Btu/lb (J/kg)
Ith^{fball}	is the radiant heat flux received at a distant receiver location from a fireball associated with the rupture case, Btu/hr-ft^2 (W/m^2)
Ith_n^{jet}	is the radiant heat flux received at a distant receiver location from a jet fire associated with the n^{th} release hole size, Btu/hr-ft^2 (W/m^2)
Ith_n^{pool}	is the radiant heat flux received at a distant receiver location from a pool fire associated with the n^{th} release hole size, Btu/hr-ft^2 (W/m^2)
k	is the release fluid ideal gas specific heat capacity ratio, unitless
k_{surf}	is the thermal conductivity of the surface for liquid pools, Btu/hr-ft^2 (W/m^2)
$ld_{\text{max},n}$	is the maximum leak duration 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 actual 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
$L_{\text{pf},n}$	is the pool fire flame length, associated with the n^{th} release hole size, ft (m)
LFL	is the lower flammability limit for the fluid
$\dot{m}_{\text{b}}$	is the burning flux rate of a pool fire, lb/ft^2-s (kg/m^2-s)
$\dot{m}_{\text{b},i}$	is the burning flux rate of a pool fire for the i^{th} component in the fluid mixture in the pool fire, lb/ft^2-s (kg/m^2-s)
$mass_{\text{avail},n}$	is the available mass for release for each of the release hole sizes selected, associated with the n^{th} release hole size, lb (kg)
$mass_{\text{fb}}$	is the flammable mass of the stored liquid used in the fireball calculation, lb (kg)

$mass_{vce}$	is the mass of flammable material in the vapor cloud used in the VCE calculation, lb (kg)
$mfrac^{flam}$	is the flammable mass fraction of the released fluid mixture
$mfrac^{tox}$	is the toxic mass fraction of the released fluid mixture
$molefrac^{tox}$	is the toxic mole fraction of the released fluid mixture
MW	is the release fluid molecular weight, lb/lb-mol (kg/kg-mol)
n_v	is the moles that flash from liquid to vapor upon release to atmosphere, lb/lb-mol (kg/kg-mol)
P_{atm}	is the atmospheric pressure, psia (kPa)
P_B	is the component or equipment burst pressure, psia (kPa)
$P_{b,g}$	is the bubble point pressure of the released fluid at the ground temperature, psia (kPa)
Pr	is the probit value, typically set at 5 (50 % probability)
P_s	is the storage or normal operating pressure, psia (kPa)
$P_{SO,n}$	is the side-on overpressure associated with the n^{th} release hole size, psia (kPa)
P_w	is the atmospheric water partial pressure, psia (kPa)
$Psat_s$	is the saturation pressure of the stored fluid at operating (storage) temperature, psia (kPa)
$pfball_n$	is the probability of a fireball given a release associated with the n^{th} release hole size
$pfball_{v,n}$	is the probability of a fireball given a vapor release associated with the n^{th} release hole size
$pfbii$	is the probability of fireball given an immediate ignition of a vapor or two-phase instantaneous release
$pffdi$	is the probability of flash fire given a delayed ignition
$pffdi_{l,n}$	is the probability of flash fire given a delayed ignition of a release of a flammable liquid associated with the n^{th} release hole size
$pffdi_{v,n}$	is the probability of flash fire given a delayed ignition of a release of a flammable vapor associated with the n^{th} release hole size
$pflash_n$	is the probability of a flash fire given a release associated with the n^{th} release hole size
$pflash_{v,n}$	is the probability of a flash fire given a vapor release associated with the n^{th} release hole size

$pjet_n$ is the probability of a jet fire given a release associated with the n^{th} release hole size

$pjet_{\mathrm{v},n}$ is the probability of a jet fire given a vapor release associated with the n^{th} release hole size

$pnfnt_n$ is the probability of nonflammable, nontoxic event given a release associated with the n^{th} hole size

poi is the probability of ignition given a release

$poi_{\mathrm{l},n}$ is the probability of ignition given a liquid release associated with the n^{th} release hole size

$poi_{\mathrm{l}}^{\mathrm{ait}}$ is the maximum probability of ignition for a liquid release at or above the AIT

$poi_{\mathrm{l},n}^{\mathrm{amb}}$ is the probability of ignition given a liquid release at ambient temperature associated with the n^{th} release hole size

$poi_{\mathrm{v},n}$ is the probability of ignition given a vapor release associated with the n^{th} release hole size

$poi_{\mathrm{v}}^{\mathrm{ait}}$ is the maximum probability of ignition for a vapor release at or above the AIT

$poi_{\mathrm{v},n}^{\mathrm{amb}}$ is the probability of ignition given a vapor release at ambient temperature associated with the n^{th} release hole size

$poi_{2,n}$ is the probability of ignition given a two-phase release associated with the n^{th} release hole size

$poii$ is the probability of immediate ignition given ignition

$poii^{\mathrm{ait}}$ is the probability of immediate ignition given ignition if the fluid were to be released at or above its AIT, assumed = 1.0

$poii_{\mathrm{l},n}$ is the probability of immediate ignition given ignition of a liquid release associated with the n^{th} release hole size

$poii_{\mathrm{l},n}^{\mathrm{amb}}$ is the probability of immediate ignition given ignition if a liquid were to be released at ambient temperature associated with the n^{th} release hole size

$poii_{\mathrm{v},n}$ is the probability of immediate ignition given ignition of a vapor release associated with the n^{th} release hole size

$poii_{\mathrm{v},n}^{\mathrm{amb}}$ is the probability of immediate ignition given ignition if a vapor were to be released at ambient temperature associated with the n^{th} release hole size

$poii_{2,n}$ is the probability of immediate ignition given ignition of a two-phase release associated with the n^{th} release hole size

$ppool_{\mathrm{l},n}$ is the probability of a pool fire given a release of a flammable liquid associated with the n^{th} release hole size

$ppool_n$	is the probability of a pool fire given a release associated with the n^{th} release hole size
$ppool_{\text{v},n}$	is the probability of a pool fire given a release of a flammable vapor associated with the n^{th} release hole size
$psafe_n$	is the probability of a safe release given a release associated with the n^{th} release hole size
$psafe_{\text{v},n}$	is the probability of a safe release given a vapor release associated with the n^{th} release hole size
$psafe_{2,n}$	is the probability of a safe release given a release of a flammable two-phase fluid associated with the n^{th} release hole size
$ptox_n$	is the probability of a toxic release given a release associated with the n^{th} release hole size
$pvce_{\text{l},n}$	is the probability of a VCE given a release of a flammable vapor associated with the n^{th} release hole size
$pvce_n$	is the probability of a VCE given a release associated with the n^{th} release hole size
$pvce_{\text{v},n}$	is the probability of a VCE given a vapor release associated with the n^{th} release hole size
$pvcedi$	is the probability of VCE given a delayed ignition
$pvcedi_{\text{l},n}$	is the probability of VCE given a delayed ignition of a release of a flammable liquid associated with the n^{th} release hole size
$pvcedi_{\text{v},n}$	is the probability of VCE given a delayed ignition of a release of a flammable vapor associated with the n^{th} release hole size
$Qrad^{\text{fball}}$	is the total energy flux radiated from a fireball, Btu/hr-ft^2 (W/m^2)
$Qrad_n^{\text{jet}}$	is the total energy radiated from a jet fire associated with the n^{th} release hole size, Btu/hr (W)
$Qrad_n^{\text{pool}}$	is the total energy flux radiated from a pool fire associated with the n^{th} release hole size, Btu/hr-ft^2 (W/m^2)
R	is the universal gas constant = 1545 ft-lbf/(lb-mol-°R) [8314 J/(kg-mol-K)]
$R_{\text{pf},n}$	is the pool fire radius, calculated for each of the n release hole sizes selected, ft (m)
RH	is the atmospheric relative humidity, %
$\overline{R}_{\text{HS},n}$	is the Hopkinson's scaled distance used in the blast calculations associated with the n^{th} release hole size, lb/ft$^{1/3}$ (m/kg$^{1/3}$)
$r_{\text{p},n}$	is the pool radius, calculated for each of the n^{th} release hole sizes selected, ft (m)

$rate^{flam}_{l,n}$ is the flammable liquid portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, lb/s (kg/s)

$rate_n$ is the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, lb/s (kg/s)

$rate^{flam}_{n}$ is the flammable portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, lb/s (kg/s)

$rate^{tox}_{n}$ is the toxic portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, lb/s (kg/s)

$rate^{flam}_{v,n}$ is the flammable vapor portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, lb/s (kg/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_{atm} is the atmospheric temperature, °R (K)

T_b is the bubble point temperature of released liquid, °R (K)

T_d is the dew point temperature of released vapor, °R (K)

T_f is the flash temperature of the released fluid, °R (K)

T_{fp} is the flash point of the released fluid, °R (K)

T_g is the ground temperature, °R (K)

T_s is the storage or normal operating temperature, °R (K)

t_{fb} is the fireball duration, seconds

$t_{p,n}$ is the time it takes for the liquid pool to reach steady state, seconds

tox_{lim} is the toxic exposure limit for a toxic component in the released stream (e.g. IDLH, AEGL-3, ERPG), usually expressed in ppm.

tox^{mod}_{lim} is the modified toxic exposure limit to account for cloud modeling of mixtures, ppm

UFL is the upper flammability limit for the fluid

$u_{s,n}$ is the nondimensional wind speed associated with the n^{th} release hole size, unitless

u_w is the wind speed measured at 6 ft off of grade, ft/s (m/s)

$\dot{V}_{p,n}$ is the volumetric vapor rate leaving the pool surface associated with the n^{th} release hole size, m^3/s (ft^3/s)

V_{s}	is the equipment stored vapor volume, ft^3 (m^3)
W_n	is the theoretical release rate associated with the n^{th} release hole size, lb/s (kg/s)
W_n^{jet}	is the portion of the release rate that forms a jet associated with the n^{th} release hole size, lb/s (kg/s)
W_n^{pool}	is the portion of the release rate that forms a pool on the ground associated with the n^{th} release hole size, lb/s (kg/s)
W_{TNT}	is the energy released in an explosion expressed as an equivalent mass of TNT, lb (kg)
X_{surf}	is the surface roughness factor, unitless
xs^{fball}	is the safe distance from the flame surface of a fireball, ft (m)
$xs_{\text{cmd}}^{\text{bleve}}$	is the safe distance from a BLEVE for component damage associated with the rupture case, ft (m)
$xs_{\text{cmd}}^{\text{fball}}$	is the safe distance from a fireball for component damage associated with the rupture case, ft (m)
$xs_{\text{cmd}}^{\text{pexp}}$	is the safe distance from a physical explosion for component damage associated with the rupture case, ft (m)
$xs_{\text{cmd},n}^{\text{jet}}$	is the safe distance from the jet fire flame surface for component damage associated with the n^{th} release hole size, ft (m)
$xs_{\text{cmd},n}^{\text{pool}}$	is the safe distance from the pool fire flame surface for component damage associated with the n^{th} release hole size, ft (m)
$xs_{\text{cmd},n}^{\text{vce}}$	is the safe distance from the VCE for component damage associated with the n^{th} release hole size, ft (m)
$xs_{\text{inj}}^{\text{bleve}}$	is the safe distance from a BLEVE for personnel injury associated with the rupture case, ft (m)
$xs_{\text{inj}}^{\text{fball}}$	is the safe distance from a fireball for personnel injury associated with the rupture case, ft (m)
$xs_{\text{inj}}^{\text{pexp}}$	is the safe distance from a physical explosion for personnel injury associated with the rupture case, ft (m)
$xs_{\text{inj},n}^{\text{jet}}$	is the safe distance from the jet fire flame surface for personnel injury associated with the n^{th} release hole size, ft (m)

$xs_{\text{inj},n}^{\text{pool}}$ is the safe distance from the pool fire flame surface for personnel injury associated with the n^{th} release hole size, ft (m)

$xs_{\text{inj},n}^{\text{vce}}$ is the safe distance from the VCE for personnel injury associated with the n^{th} release hole size, ft (m)

xs_n is the safe distance from the flame surface to the target location associated with the n^{th} release hole size, ft (m)

xs_n^{jet} is the safe distance from the jet fire flame surface associated with the n^{th} release hole size, ft (m)

xs_n^{pool} is the safe distance from the pool fire flame surface associated with the n^{th} release hole size, ft (m)

xs_n^{vce} is the safe distance from the VCE associated with the n^{th} release hole size, ft (m)

α_{surf} is the thermal diffusivity of the surface under the liquid pool, ft^2/s (m^2/s)

β is the fraction of combustion power radiated from a flame

β_{fb} is the fraction of combustion power radiated from a fireball

ΔH_{v} is the latent heat of vaporization of the liquid in the pool, Btu/lb (J/kg)

η is the explosion yield factor, unitless

ρ_{atm} is the atmospheric air density, lb/ft^3 (kg/m^3)

ρ_{l} is the liquid density at storage or normal operating conditions, lb/ft^3 (kg/m^3)

ρ_{v} is the vapor density at storage or normal operating conditions, lb/ft^3 (kg/m^3)

$\theta_{\text{pf},n}$ is the pool fire flame tilt associated with the n^{th} release hole size, radians

τ_{atm} is the atmospheric transmissivity, unitless

$\tau_{\text{atm},n}$ is the atmospheric transmissivity associated with the n^{th} release hole size, unitless

5.15 Tables

Table 5.1—Event Outcomes for Level 2 Consequence Analysis

Event Outcome	Description	General Procedure
Pool fires [10], [17], [18], [19], [21], [22], [24]	Occur as a result of immediate ignition of a flammable liquid from a pressurized process vessel or pipe that leaks or ruptures.	1. Determine pool fire size 2. Calculate burning rate 3. Calculate flame length and tilt 4. Determine radiant energy emitted 5. Determine energy received at distant points (need view factor and atmospheric transmissivity) 6. Calculate safe distance
Jet fires [17], [18], [20]	Occur as a result of immediate ignition of a flammable vapor or two-phase jet release from a pressurized process vessel or pipe that develops a hole.	1. Calculate flame length 2. Determine radiant energy emitted 3. Determine energy received at distant points (need view factor and atmospheric transmissivity) 4. Calculate safe distance
Fireballs [17], [18], [20]	Occur as result of the immediate ignition of a flammable, superheated liquid/vapor released due to a vessel or pipe rupture. Fireballs always occur in combination with a physical explosion or a BLEVE.	1. Determine available flammable mass 2. Determine fireball diameter, height and duration 3. Determine radiant energy emitted 4. Determine energy received at distant points (need view factor and atmospheric transmissivity) 5. Calculate safe distance
Flash fires [6], [17], [18]	Occur as a result of a delayed ignition of a vapor cloud. The source of the vapor cloud could either be from a vapor or two-phase jet release or evaporation off the surface of an un-ignited liquid flammable pool.	1. Determine if cloud source is continuous (plume) or instantaneous (puff) 2. Utilize cloud dispersion model to determine the grade level area of flammable material (greater than LFL) that is in the source cloud
Vapor cloud explosions [5], [6], [7], [17], [18], [21], [22], [4]		1. Determine if cloud source is continuous (plume) or instantaneous (puff) 2. Utilize cloud dispersion model to determine the amount of flammable material (between LFL and UFL) that is in the source cloud 3. Determine equivalent amount of TNT 4. Calculate overpressure as a function of distance 5. Calculate safe distance
BLEVEs [17], [18], [26]	Occur upon rupture of a vessel containing a superheated but pressurized liquid that flashes to vapor upon release to atmosphere	1. Determine equivalent amount of TNT that is a function of the storage pressure and the amount of liquid that flashes to vapor upon release 2. Calculate overpressure as a function of distance 3. Calculate safe distance
Physical explosions [17], [18], [33], [30]	Occur upon rupture of a vessel containing a pressurized flammable or nonflammable vapor	1. Determine equivalent amount of TNT that is a function of the storage pressure and volume of vapor 2. Calculate overpressure as a function of distance 3. Calculate safe distance
Toxic releases	Occurs upon release of toxic fluid to the atmosphere through a hole or due to a rupture	1. Determine if cloud source is continuous (plume) or instantaneous (puff) 2. Utilize cloud dispersion model to determine the portion of the cloud at grade level that exceeds the toxic limit (concentration and duration) of the fluid

Table 5.2—Surface Interaction Parameters with Liquid Pools

Surface	Thermal Conductivity, k_{surf} (Btu/hr-ft-°R)	Thermal Diffusivity, α_{surf} (ft²/s)	Surface Roughness, X_{surf} (unitless)
Concrete [1]	0.53	4.48×10^{-6}	1.0
Soil (average)	0.56	4.94×10^{-6}	3.0
Soil (sandy, dry)	0.15	2.13×10^{-6}	3.0
Soil (moist, 8 % water, sandy)	0.34	3.62×10^{-6}	3.0

NOTE 1 Use as default.

NOTE 2 Rijnmond Public Authority [11].

Table 5.2M—Surface Interaction Parameters with Liquid Pools

Surface	Thermal Conductivity, k_{surf} (W/m-K)	Thermal Diffusivity, α_{surf} (m²/s)	Surface Roughness, X_{surf} (unitless)
Concrete [1]	0.92	4.16×10^{-7}	1.0
Soil (average)	0.96	4.59×10^{-7}	3.0
Soil (sandy, dry)	0.26	1.98×10^{-7}	3.0
Soil (moist, 8 % water, sandy)	0.59	3.36×10^{-7}	3.0

NOTE 1 Use as default.

NOTE 2 Rijnmond Public Authority [11].

Table 5.3—Event Probabilities

Release Type	Fluid Phase	Probability of Immediate Ignition, Given Ignition		Probability of VCE or Flash Fire, Given Delayed Ignition	
		At Ambient Temperature $poii_n^{amb}$	At AIT $poii^{ait}$	VCE, $pvcedi_{l,n}$ or $pvcedi_{v,n}$	Flash Fire, $pffdi_{l,n}$ or $pffdi_{v,n}$
Continuous	Liquid	0.20	1.00	0.25	0.75
Continuous	Vapor	0.50	1.00	0.50	0.50
Instantaneous	Liquid	0.20	1.00	0.125	0.875
Instantaneous	Vapor	0.10	1.00	0.25	0.75

5.16 Figures

Thermodynamic Calculations Used in Consequence Analysis

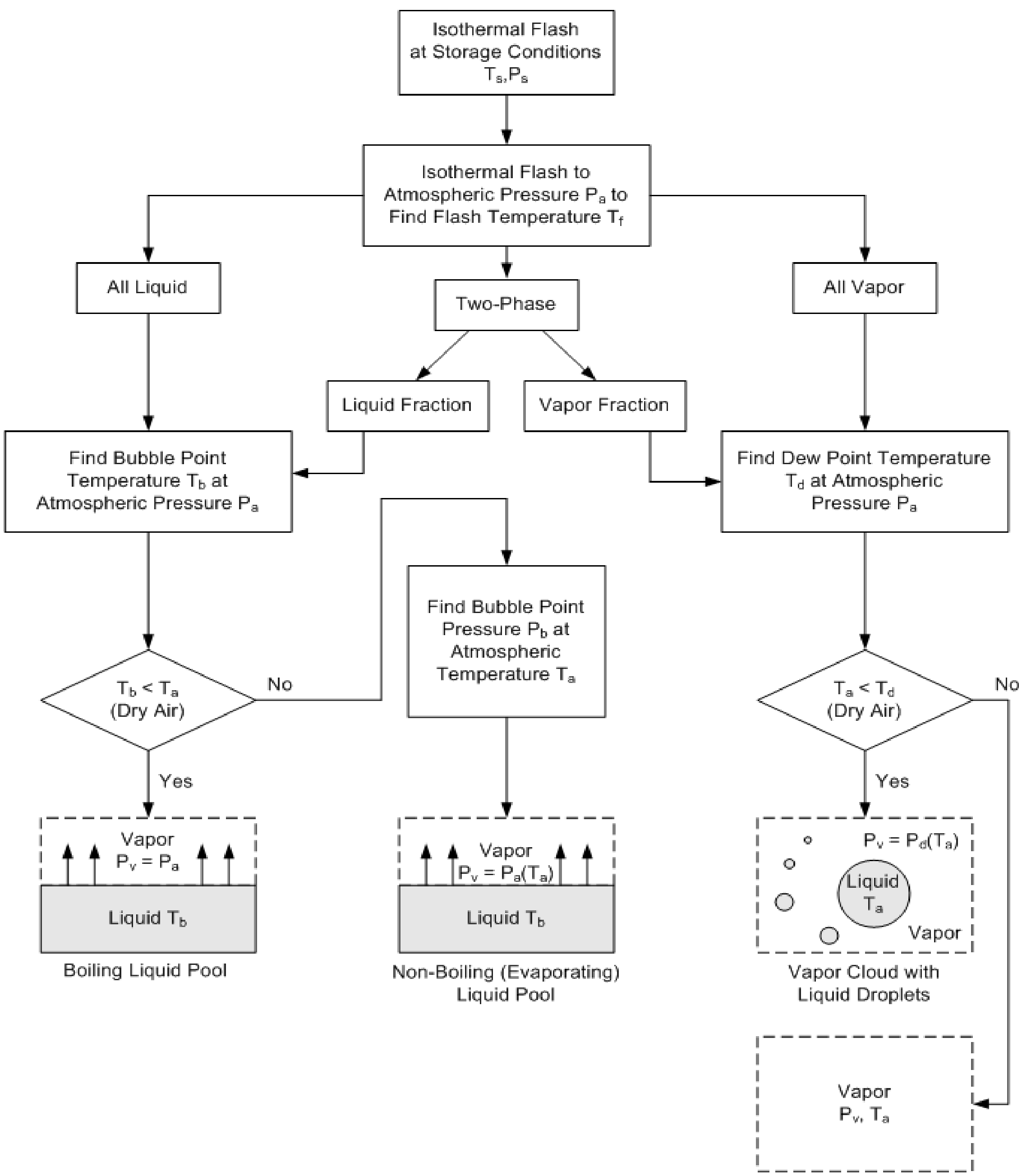


Figure 5.1—Source Term Modeling—Thermodynamic Modeling

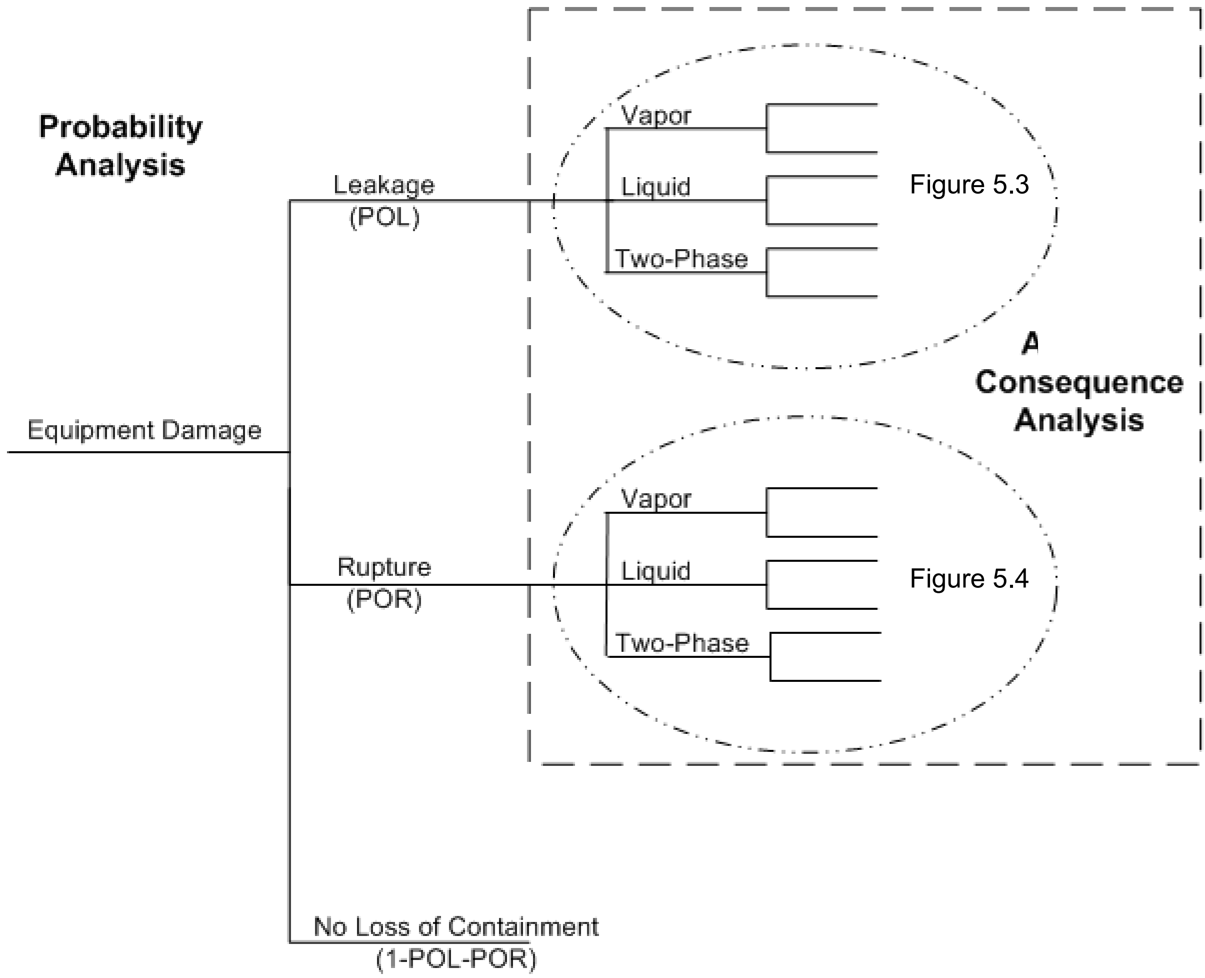
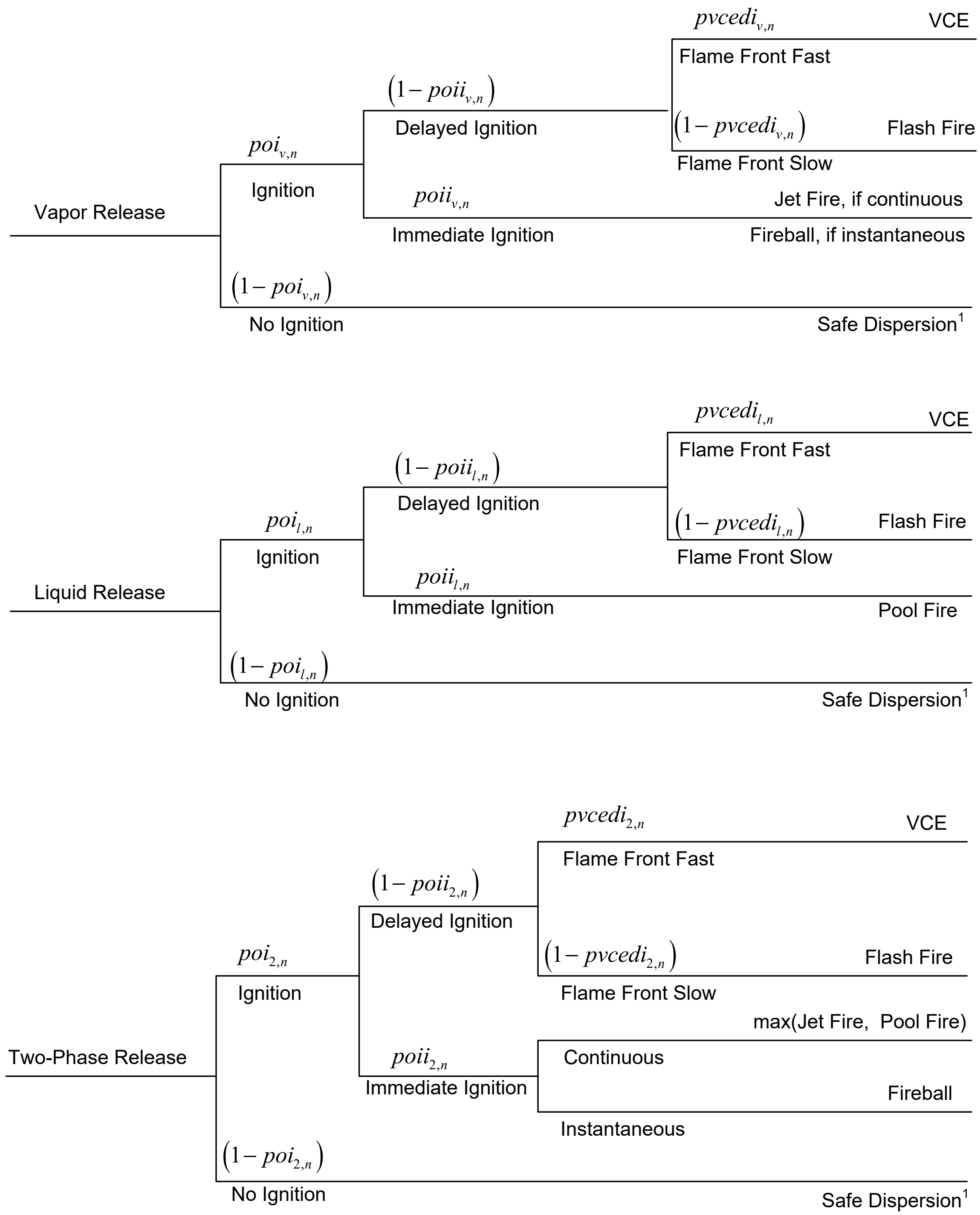
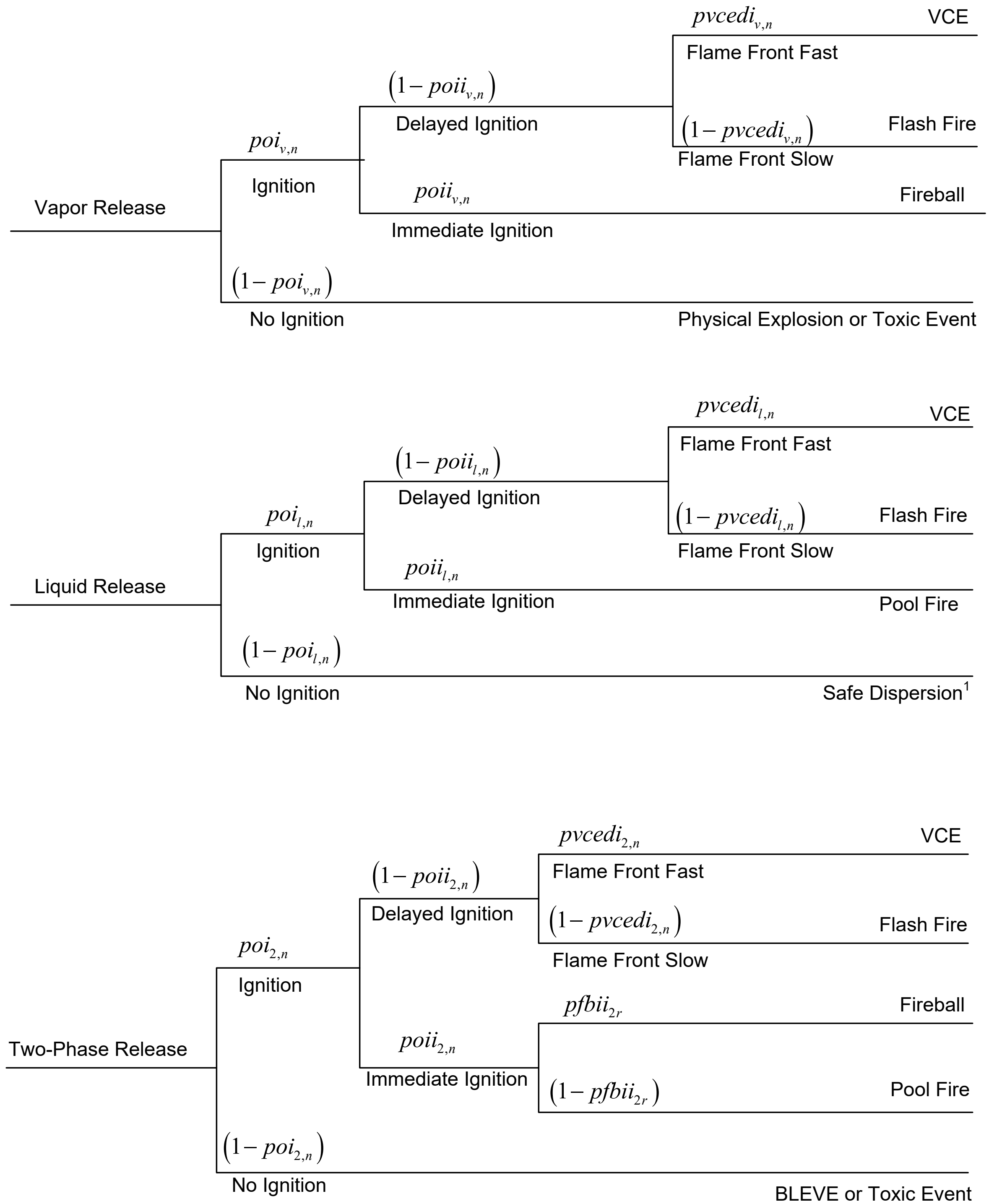


Figure 5.2—Overall Event Tree



[1] If released fluid is toxic, or could result in steam burns or acid splashes, these consequences are considered before a safe dispersion.

Figure 5.3—Level 2 Consequence Analysis Event Tree for Leakage Case



[1] If released fluid is toxic, or could result in steam burns or acid splashes, these consequences are considered before a safe dispersion.

Figure 5.4—Level 2 Consequence Analysis Event Tree for Rupture Case

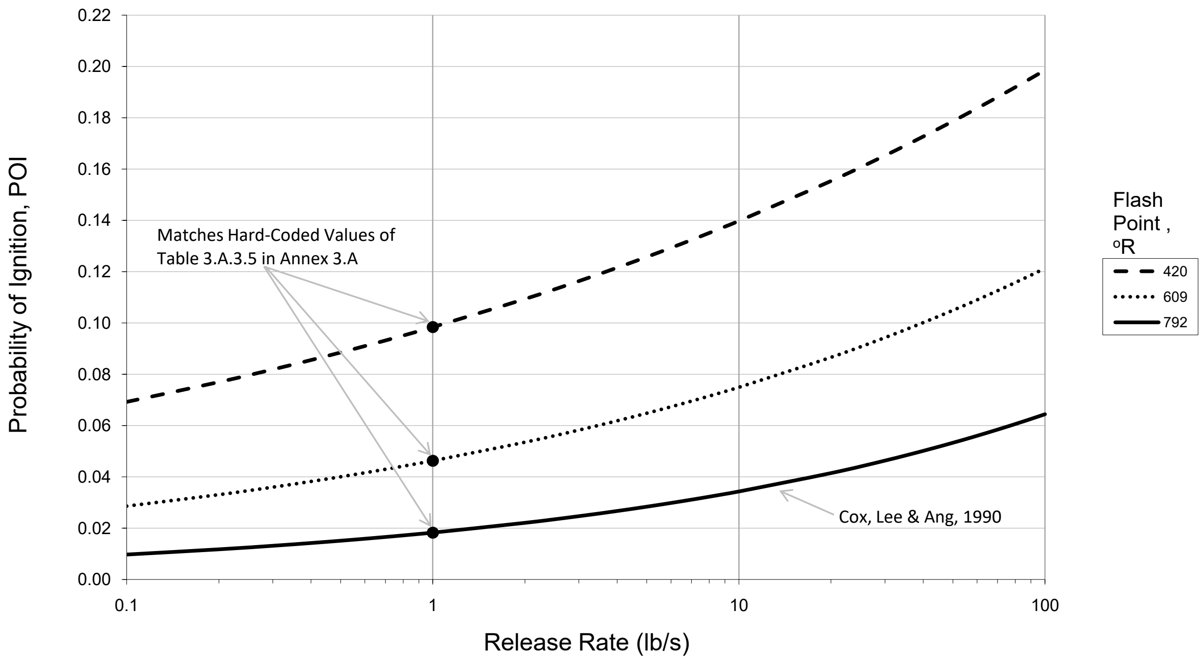


Figure 5.5—Probability of Ignition for Liquids (U.S. Customary Units)

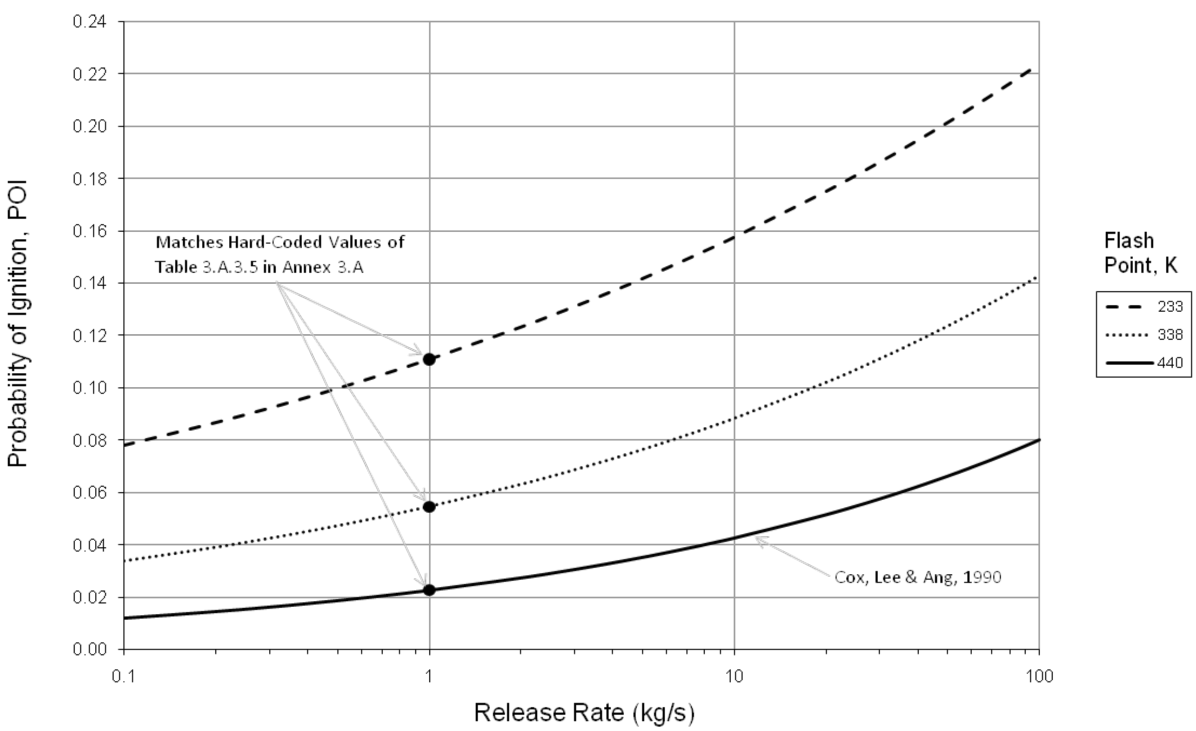


Figure 5.5M—Probability of Ignition for Liquids (Metric Units)

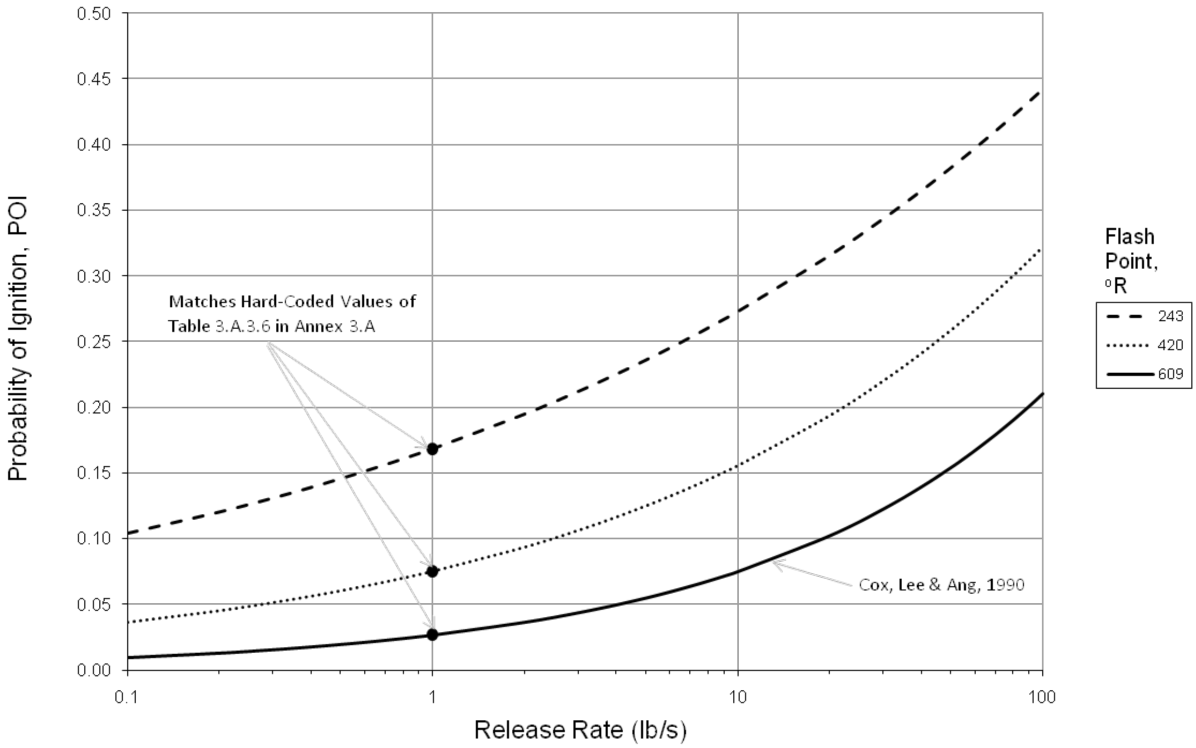


Figure 5.6—Probability of Ignition for Vapors (U.S. Customary Units)

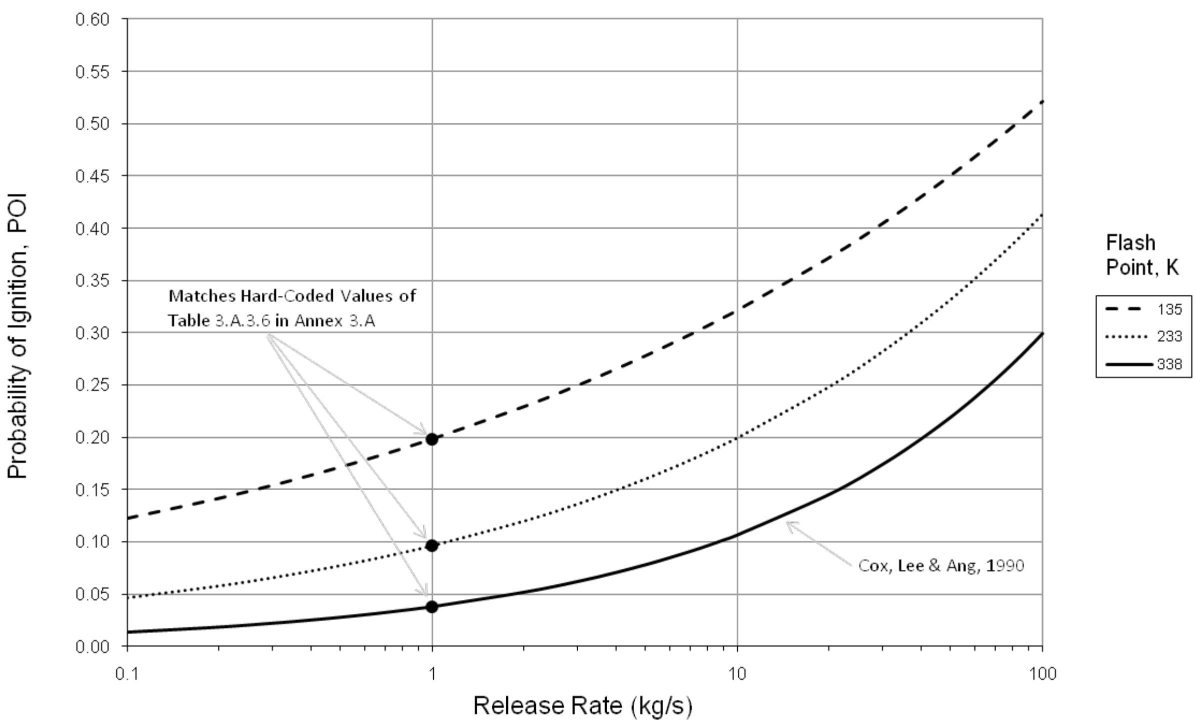


Figure 5.6M—Probability of Ignition for Vapors (Metric Units)

Part 3, Annex 3.A—Basis for Consequence Methodology

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Risk-based Inspection Methodology
Part 3—Consequence of Failure Methodology
Annex 3.A—Basis for Consequence Methodology

3.A.1 General

The consequence analysis is performed to aid in establishing a relative ranking of equipment items on the basis of risk. The consequence methodologies presented in Part 3 of this document are intended as simplified methods for establishing relative priorities for inspection programs. If more accurate consequence estimates are needed, the analyst should refer to more rigorous analysis techniques, such as those used in quantitative risk assessments.

This annex provides background and supplemental information to the specific procedures for conducting the consequence analysis provided in Part 3.

3.A.2 References

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 1—Introduction to Risk-Based Inspection Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 3—Consequence of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 4—Inspection Planning Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 5—Special Equipment*

API, *A Survey of API Members' Aboveground Storage Tank Facilities*, 1994

OFCM [1], *Directory of Atmospheric Transport and Diffusion Consequence Assessment Models* (FC-I3-1999), published by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) with the assistance of SCAPA members.

3.A.3 Level 1 Consequence Methodology

3.A.3.1 Representative Fluid and Associated Properties

3.A.3.1.1 Overview

In the Level 1 consequence analysis, a representative fluid that most closely matches the fluid contained in the pressurized system being evaluated is selected from the representative fluids shown in Table 3.A.3.1. Because very few refinery and chemical plant streams are pure materials, the selection of a representative fluid involves making assumptions. The assumptions and the sensitivity of the results are dependent on the type of consequences being evaluated. If assumptions are not valid or the fluid in question is not properly represented by the fluids provided in Table 3.A.3.1, a Level 2 consequence analysis is recommended using the methodology in Part 3, Section 5.

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[1] Office of the Federal Coordinator for Meteorological Services and Supporting Research, now known as the Interagency Council on Advancing Meteorological Services (ICAMS), Silver Spring, MD, www.icams-portal.gov.

3.A.3.1.2 Choice of Representative Fluids for Mixtures

3.A.3.1.2.1 General

For mixtures, the choice of the representative material should primarily be based on the NBP and the MW, and secondly on the density. If these values are unknown, an estimated property value for the mixture can be calculated using Equation (3.A.1) to assist in representative fluid selection using mole fraction weighting.

$$Property_{\text{mix}} = \sum x_i \cdot Property_i \tag{3.A.1}$$

It is important to note that the flammable consequence results are not highly sensitive to the exact material selected, provided the MWs are similar, because air dispersion properties and heats of combustion are similar for all hydrocarbons with similar MWs. This is particularly true for straight chain alkanes but becomes less true as the materials become less saturated or aromatic. Therefore, caution should be used when applying the Level 1 consequence analysis table lookups to materials (such as aromatics, chlorinated hydrocarbons, etc.) not explicitly defined in the representative fluid groups of Table 3.A.3.1. In such cases, a Level 2 consequence analysis may be performed using a fluid property solver to determine the consequences of release.

3.A.3.1.2.2 Example

As an example of determining the various properties of mixtures, by applying Equation (3.A.1), a material containing 10 mol % C_3, 20 mol % C_4, 30 mol % C_5, 30 mol % C_6, and 10 mol % C_7 would have the following average key properties:

a) MW = 74.8;

b) AIT = 629.8 °F (322.1 °C) ;

c) NBP = 102.6 °F (39.2 °C);

d) density = 38.8 lb/ft^3 (621.5 kg/m^3).

The best selection from the materials in the representative fluids list of Table 3.A.3.1 would be C_5, since the property of first importance is the NBP, and C_5 has a NBP of 97 °F (36 °C), which is lower than the calculated NBP of our example mixture. It is nonconservative to select a representative fluid with a higher NBP than the fluid being considered (e.g. C_6–C_8) when modeling a fluid with a weighted NBP of 210 °F (99 °C).

3.A.3.1.2.3 Example with a Mixture

If a mixture contains inert materials such as CO_2 or water, the choice of representative fluid may be based on the flammable/toxic materials of concern, excluding these materials. This is a conservative assumption that will result in higher COF results, but it is sufficient for risk prioritization. For example, if the material is 93 mol % water and 7 mol % C_{20}, using C_{20} and the corresponding inventory of the hydrocarbon provides a conservative COF. A Level 2 consequence methodology may be used to more quantitively model the release.

3.A.3.1.2.4 Toxic Mixture

If the mixture contains toxic components and a toxic consequence analysis is required, a flammable representative fluid is still required, even when the toxic component is a small fraction of the mixture. In this situation, the representative fluid is selected, as described in Section 3.A.3.1.2.1 and Equation (3.A.1).

3.A.3.1.3 Fluid Properties

Representative fluid properties for the Level 1 consequence analysis are provided in Table 3.A.3.1. The properties of fluids (or individual components of mixtures) can be found in standard chemical reference books.

3.A.3.2 Release Hole Size Selection

3.A.3.2.1 Overview

Part 3 of this document defines release hole sizes that represent small, medium, large, and rupture cases for various components or equipment types. This predefined set of release hole sizes are based on failure size distributions observed in piping and pressure vessels. The range of release hole sizes were chosen to address potential on-site and off-site consequences. For on-site effects, small and medium hole size cases usually dominate the risk due to a higher likelihood and potential for on-site consequences.

For off-site effects, medium and large hole size cases dominate risk. To address both on-site and off-site consequences and provide discrimination between components, four release hole sizes per component are used. The following sections discuss the criteria for selecting release hole sizes for specific equipment types.

3.A.3.2.2 Piping

Piping uses the standard four release hole sizes ($^1/_4$ in., 1 in., 4 in., and rupture), provided that the diameter of the leak is less than or equal to the diameter of the pipe. For example, an NPS 1 pipe has $^1/_4$-in. and rupture release hole sizes, because the diameter is equal to a 1-in. release hole size. An NPS 4 pipe will have $^1/_4$-in., 1-in., and rupture release hole sizes because the diameter is equal to a 4-in. hole size.

3.A.3.2.3 Pressure Vessels

The standard four release hole sizes are assumed for all sizes and pressure vessel types. Equipment types included in this general classification are as follows.

a) Vessel—standard pressure vessels such as knock-out (KO) drums, accumulators, and reactors.

b) Filter—standard types of filters and strainers.

c) Column—distillation columns, absorbers, strippers, etc.

d) Heat exchanger shell—shell side of reboilers, condensers, heat exchangers.

e) Heat exchanger tube—tube side of reboilers, condensers, heat exchangers.

f) Fin/fan coolers—fin/fan-type heat exchangers.

3.A.3.2.4 Pumps

Pumps are assumed to have $^1/_4$-in., 1-in., and 4-in. possible release hole sizes. If the suction line is less than NPS 4, the release hole size should be the full diameter of the suction line. The use of three release hole sizes for pumps is consistent with historical failure data and ruptures are not modeled for pumps.

3.A.3.2.5 Compressors

Both centrifugal and reciprocating compressors use 1-in. and 4-in. (or suction line full bore rupture, whichever is smaller) release hole sizes. The selection of only two release hole sizes is consistent with historical failure data.

3.A.3.3 Fluid Inventory Available for Release

3.A.3.3.1 Overview

The consequence analysis requires an upper limit for the amount of fluid inventory that is available for release from a component. In theory, the total amount of fluid that can be released is the amount that is held within pressure-containing equipment between isolation valves that can be quickly closed. In reality, emergency operations can be performed over time to close manual valves, de-inventory sections, or otherwise stop a leak. In addition, piping restrictions and differences in elevation can serve to slow or stop a leak. The inventory calculation as presented here is used as an upper limit and does not indicate that this amount of fluid would be released in all leak scenarios.

The Level 1 COF methodology is based on a procedure that determines the mass of fluid that could realistically be released in the event of a leak. When a component or equipment type is evaluated, the inventory of the component is combined with inventory from associated equipment that can contribute fluid mass to the leaking component. These items together form an *Inventory Group*. The procedure calculates the release mass as the lesser of the:

a) mass of the component plus a 3-minute release through the hole to a maximum rupture hole size of 8 in. using the calculated release rate;

b) total mass of the inventory group.

A 3-minute release time is based on the dynamics of a large leak scenario, where the leaking component will de-inventory and adjacent equipment provides additional inventory for the leak. Large leaks are detected within a few minutes because of the operational indications that a leak exists. The amount of time that a large leak or rupture will be fed is expected to range from 1 to 5 minutes, with 3 minutes selected as the midpoint of the range.

The 3-minute assumption is not as applicable to small leaks, since it is far less likely that small leaks will persist long enough to empty the inventory from the leaking component and additional inventory from other components in the inventory group. In these situations, plant detection, isolation, and mitigation techniques will limit the duration of the release so that the actual mass released to atmosphere will be significantly less than the available mass as determined above.

Calculating the inventories for equipment and piping can be done using the guidelines provided in Section 3.A.3.3.2 through Section 3.A.3.3.4.

3.A.3.3.2 Liquid Inventory

Liquid inventories for components are calculated using the assumptions presented in Table 3.A.3.2 (normal operating levels should be used, if known). Common equipment and piping groups for liquid systems include:

a) the bottom half of a distillation column, reboiler, and the associated piping,

b) accumulators and liquid outlet piping,

c) feed pipeline,

d) storage tanks and outlet piping, and

e) series of heat exchangers and associated piping.

Once the liquid inventory groups are established, the inventory for each component is added to obtain the total group inventory. The liquid inventory determined in this manner is used for each component in the group.

3.A.3.3.3 Vapor Inventory

Common equipment and piping groups for vapor systems include:

a) the top half of the distillation column, overhead piping, and the overhead condenser, and

b) vent header line, KO pot, and exit line.

The inventory for vapor systems is governed by the flow or charge rate through the system rather than inventory. A method for determining inventory is to use the flow rate for a specified time (e.g. 60 minutes) to calculate release mass. If this rate is not known, the upstream group liquid inventory can be used since flashing occurs from the liquid system. Using the upstream group liquid inventory will result in a conservative inventory calculation.

3.A.3.3.4 Two-phase Systems

Two-phase systems can be modeled as a liquid or vapor. The conservative assumption is that the release occurs in the lower portion of the component and results in a liquid release. If the upstream system is primarily liquid, only the liquid inventory can be calculated and this limits the conservativeness of modeling a two-phase system as liquid. Conversely, if the upstream inventory is primarily vapor, the vapor inventory can be calculated with an adjustment for the liquid portion.

3.A.3.4 Determination of the Release Type (Instantaneous or Continuous)

Different analytical models and methods are used to estimate the effects of an instantaneous versus a continuous type of release. The COF can differ greatly, depending on the analytical model chosen to represent a release. Therefore, it is very important that a release is properly categorized into one of the two release types.

An example of the importance of proper model selection is a vapor cloud explosion (VCE). A review of historical data on fires and explosions shows that *unconfined* VCEs are more likely to occur for an instantaneous vapor release than a continuous release. An instantaneous release is defined as the release of more than 10,000 lb (4,536 kg) of mass in a short period of time. Using this definition for a continuous release reflects the tendency for mass released in a short period of time, less than 10,000 lb (4,536 kg), to result in a flash fire rather than a VCE.

In the Level 1 consequence procedure, the continuous release model uses a lower probability for a VCE following a leak and the probability of a VCE is a function of release type, not release rate. Level 1 consequence procedure event probabilities are provided in Tables 3.A.3.3 through 3.A.3.6. The Level 2 procedure determines event probabilities as a function of release type and release rate (see Part 3, Section 5.8.1 for determining event probabilities for a Level 2 consequence procedure).

3.A.3.5 Determination of Flammable and Explosive Consequences

3.A.3.5.1 Overview

Consequence is measured in terms of the area affected by the ignition of a flammable release. There are several potential consequence outcomes for any release involving a flammable material; however, a single combined COF is calculated as the probability weighted average of all possible consequence outcomes. The probability of a consequence outcome is different from, and should not be confused with, the POF discussed in Part 2, which involves evaluation of the component damage state that affects equipment integrity.

The probability of a consequence outcome is the probability that a specific physical phenomenon (outcome) will be observed after the release has occurred. Potential release consequence outcomes for flammable materials are:

a) safe dispersion,

b) jet fire,

c) VCE,

d) flash fire,

e) fireball, and

f) liquid pool fire.

A description of each event outcome is provided in Part 3, Section 5.8.

3.A.3.5.2 Assumptions and Limitations

The consequence procedure is a simplified approach to a relatively complex discipline. A large number of assumptions are implicit in the procedure in addition to the assumptions that would be part of a more in-depth analysis. This section is intended to highlight a few of the more important assumptions related to the simplified approach but does not attempt a comprehensive discussion.

a) The consequence area does not reflect where the damage occurs. Jet and pool fires tend to have damage areas localized around the point of the release, but VCE and flash fires may result in damage far from the release point.

b) The use of a fixed set of conditions for meteorology and release orientations was chosen to represent a conservative basis for the consequence modeling. Meteorological and release orientations are site and situation specific. Quantitative risk assessment calculations allow for customization due to actual site condition since it significantly impacts the results.

c) The probabilities associated with potential release event outcomes can be situation and site specific. Standardized event trees, including ignition probabilities, were chosen to reflect typical conditions expected for the refining and petrochemical industries. Quantitative risk assessment calculations allow for customization of event probabilities since they significantly impact the results.

3.A.3.5.3 Basis for Flammable Consequence Area Tables

3.A.3.5.3.1 General

For representative fluids shown in Table 3.A.3.1, flammable consequences are determined by using the equations presented in lookup tables, allowing the RBI analyst to establish approximate consequence measures using the following information:

a) representative fluid and properties,

b) release type (continuous or instantaneous) and phase of dispersion, and

c) release rate or mass, depending on the type of dispersion and the effects of detection, isolation, and mitigation measures.

3.A.3.5.3.2 Predicting Probabilities of Flammable Outcomes

Each flammable event outcome is the result of a chain of events. Event trees, as shown in Figure 3.A.3.1, are used to visually depict the possible chain of events that lead to each outcome. The event trees also are used to show how various individual event probabilities should be combined to calculate the probability for the chain of events.

For a given release type, the two main factors that define the outcome of the release of flammable material are the probability of ignition and the timing of ignition. The three possibilities depicted in the outcome event trees are no ignition, early ignition, and late ignition. The event tree outcome probabilities used in the Level 1 consequence analysis for all release types are presented in Tables 3.A.3.3 through 3.A.3.6 according to the release type and representative fluid. Each row within the tables contains probabilities for the potential outcome, according to the representative fluid. Event trees developed for standard risk analyses were used to develop the relative outcome probabilities. Ignition probabilities were based on previously developed correlations. In general, ignition probabilities are a function of the following fluid parameters:

a) AIT,

b) flash temperature,

c) NFPA Flammability Index, and

d) flammability range (difference between upper and lower flammability limits).

Fluids that are released well above their AITs will have markedly different ignition probabilities (Table 3.A.3.3 and Table 3.A.3.4) than those released near or below their AITs (Table 3.A.3.5 and Table 3.A.3.6).

3.A.3.5.3.3 Calculating Consequences for Each Outcome

A set of materials were run through a hazards analysis screening to determine the consequence areas for all potential outcomes. The consequence areas were then plotted as a function of release rate or mass to generate graphs. When plotted on a log/log scale, the consequence curves formed straight lines that were fit to an equation relating consequence area to the release rate or mass. The consequence equations are presented in the following generic form:

$$CA_{\mathrm{f}} = x(rate)^{y} \quad \text{for a continuous release} \qquad (3.A.2)$$

$$CA_{\mathrm{f}} = x(mass)^{y} \quad \text{for an instantaneous release} \qquad (3.A.3)$$

The consequence of a release of flammable materials is not strongly dependent on the duration of the release because most fluids reach a steady state size, or footprint, within a short period of time if released into the atmosphere. The only exception to this generalization is a pool fire resulting from the continuous release of a liquid. If flammable liquids are released in a continuous manner, the consequences associated with a pool fire will depend on the duration and the total mass of the release.

3.A.3.5.3.4 Calculation of the Combined Consequence Area

An equation that represents a single consequence area for the combination of possible outcomes can be derived for each of the four combinations of release types and final phase cases. The combined consequence area is determined by a two-step process.

a) Step 1—Multiply the consequence area for each outcome [calculated from Equation (3.A.2)] by the associated event tree probabilities (taken from the appropriate Tables 3.A.3.3 through 3.A.3.6). If the impact criterion uses only a portion of the consequence area (for instance, flash fires use only 25 % of the area within the LFL for equipment damage), include this in the probability equation.

b) Step 2—Sum all of the consequence-probability products found in Step 1.

The equation that summarizes the result of the process is as follows:

$$CA_{\mathrm{f,comb}} = \sum p_i CA_{\mathrm{f},i} \qquad (3.A.4)$$

The procedure for combining consequence equations for all the potential outcomes was performed for a set of representative fluids (see Table 3.A.3.1). The results of this exercise are the equations given in Part 3, Tables 4.8 and 4.9.

3.A.3.5.3.5 Consequence Analysis Dispersion Modeling

The computer modeling necessary to determine consequence areas associated with cloud dispersion (flash fires, VCEs, toxic releases) requires specific input regarding meteorological and release conditions. For the Level 1 consequence analysis, meteorological conditions representative of the Gulf Coast annual averages were used. These conditions can also be used when performing a Level 2 consequence analysis. The meteorological input assumptions were as follows:

c) atmospheric temperature 70 °F (21 °C),

d) RH 75 %,

e) wind speed 8 mph (12.9 km/h),

f) Stability Class D, and

g) surface roughness parameter 1.2 in. (30.5 mm) for typical for processing plants.

Additional constants were used as part of the Level 1 consequence analysis as follows:

a) initial pressure typical of medium-pressure processing conditions with a refinery 100 psig (0.69 MPa),

b) initial temperatures representing a range from low-temperature [below autoignition, i.e. 68 °F (20 °C)] to high-temperature (near autoignition) conditions,

c) range of release hole sizes from 0.25 in. to 16 in. (6.35 mm to 406 mm) diameter for continuous events,

d) range of release masses from 100 lb to 100,000 lb (45.4 kg to 453,592 kg), and

e) both vapor and liquid releases from a component containing saturated liquid, with release orientation horizontal downwind at an elevation of 10 ft over a concrete surface.

Analysis has shown that these assumptions are satisfactory for a wide variety of plant conditions. Where these assumptions are not suitable, the analyst should consider performing a Level 2 consequence analysis.

3.A.3.6 Determination of Toxic Consequences

3.A.3.6.1 Overview

As with the flammable consequence analysis, dispersion analysis has been performed to evaluate the consequence areas associated with the release of toxic fluids to the atmosphere. The assumptions made for the cloud dispersion modeling are as described in Section 3.A.3.5.3.5. Toxic consequences are determined by using the equations presented in lookup tables similar to the flammable consequence analysis described in Section 3.A.3.5.

3.A.3.6.2 Background for Calculation of Toxic Consequences

The development of the toxic consequence area equations for the Level 1 consequence analysis considers exposure time and concentration. These two components combine to result in an exposure that is referred to as the toxic dose. The degree of injury from a toxic release is directly related to the toxic dose. Level 1 consequence methodology relates dose to injury using probits.

For toxic vapor exposure, the probit (a shortened form of probability unit) is represented as follows:

$$Pr = A + B \cdot \ln\left[C^n t\right] \tag{3.A.5}$$

Example constants for the probit equation are provided in Part 3, Table 4.14 for various toxic fluids. A single fixed probability of fatality (50 % probability of fatality) is used to determine the toxic impact. This level corresponds to a probit value of 5.0.

3.A.3.6.3 Toxic Continuous Releases

A cloud dispersion model is used to analyze a continuous release (plume model) to the atmosphere. The cloud footprint or plan area is approximated as the shape of an ellipse, as shown in Figure 3.A.3.2, and is calculated using Equation (3.A.6).

$$A = \pi ab \tag{3.A.6}$$

3.A.3.6.4 Toxic Instantaneous Releases

For instantaneous releases (puff model), the dispersion of the cloud over time is shown in Figure 3.A.3.3. The plan area covered by the cloud is conservatively assumed to be an ellipse, except that the y-distance (a) is taken as one-half of the maximum cloud width as determined from the dispersion results. As part of a Level 2 consequence methodology, cloud dispersion modeling software exists that provides a more accurate plot area as a function of concentration than the elliptical area assumptions made above.

3.A.3.6.5 Development of Toxic Consequence Areas for HF Acid

3.A.3.6.5.1 General

HF is typically stored, transferred, and processed in liquid form. However, the toxic impact associated with a release of liquid HF into the atmosphere is due to the dispersion of the toxic vapor cloud. A toxic vapor cloud of HF can be produced by flashing of the liquid upon release or evaporation from a liquid pool. For the Level 1 consequence analysis, the initial state of HF is assumed to be liquid; the models for calculating the toxic impact areas for HF liquid releases take into account the possibility of flashing and pool evaporation. For HF releases, the Level 1 consequence analysis uses the following guidelines to determine the release rate or mass of mixtures containing HF.

a) The mass fraction of HF is calculated if the released material contains HF as a component in a mixture.

b) The liquid release rate (or mass) of the HF component is used to calculate the toxic impact area.

c) The release rate is calculated for a continuous release of the fluid using the closest matching representative fluid and with the equations provided in Part 3, Section 4.3. If the released fluid contains a toxic component, the toxic release rate is calculated as the product of the toxic component mass fraction and the release rate for the mixture.

A consequence analysis software program (PHAST) was used to generate a range of release rates and durations to obtain graphs of toxic consequence areas. Release durations of instantaneous (less than 3 minutes), 5 minutes (300 seconds), 10 minutes (600 seconds), 30 minutes (1800 seconds), 40 minutes (2400 seconds), and 1 hour (3600 seconds) were evaluated to obtain toxic consequence areas for varying release rates. Toxic impact criteria used was for a probit value of 5.0 using the probit Equation (3.A.5) and probit values listed in Part 3, Table 4.14 for HF.

3.A.3.6.5.2 Continuous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.7).

$$CA_f = C_8 \cdot 10^{\left(c \cdot \log_{10}\left[C_4 \cdot rate\right]+d\right)} \tag{3.A.7}$$

For continuous releases, the values of the constants c and d are functions of the release duration and provided for HF in Part 3, Table 4.11.

3.A.3.6.5.3 Instantaneous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.4 could be correlated as functions of release mass for instantaneous releases in accordance with Equation (3.A.8).

$$CA_f = C_8 \cdot 10^{\left(c \cdot \log_{10}\left[C_4 \cdot mass\right]+d\right)} \tag{3.A.8}$$

For instantaneous releases, the values of the constants c and d are provided for HF and H_2S in Part 3, Table 4.11.

3.A.3.6.6 Development of Toxic Consequence Areas for H_2S

3.A.3.6.6.1 General

H_2S is processed as a vapor or when processed under high pressures, quickly flashes upon release due to its low boiling point. In either case, the release of H_2S to the atmosphere results in the quick formation of a toxic vapor cloud. For H_2S releases, the Level 1 consequence analysis uses the following guidelines to determine the release rate or mass of mixtures containing H_2S.

a) If the released material contains H_2S as a component in a mixture, the mass fraction of H_2S is obtained, and If the initial state of the material is a vapor, the mass fraction of H_2S is used to obtain the vapor discharge rate (or mass) of only H_2S; this rate (or mass) is used to determine the impact area.

b) If the initial state of the material is a liquid, the mass fraction of H_2S is used to obtain the vapor flash rate (or mass) of only the H_2S; this rate (or mass) is used to determine the impact.

c) If the initial phase of a material being released is 1 wt % H_2S in gas oil, the material has the potential for both toxic and flammable outcomes from the vapor and flammable outcomes from the liquid. Therefore, the following procedure is followed, using C_{17}–C_{25} as the representative material.

   1) Calculate the liquid discharge rate for C_{17}–C_{25} as described in Part 3, Section 4.3.

   2) When estimating flammable consequences, calculate the potential flammable consequence areas as in Part 3, Section 4.3 and take the worst case between:

      i) the flammable effects of C_{17}–C_{25} using 100 % of the release rate,

      ii) the flammable effects of H_2S based on 1 % of the release rate.

   3) Calculate the toxic effects of H_2S, using 1 % of the release rate.

For instantaneous releases, use the above procedure, substituting inventory mass for release rate.

The release durations used to model the consequences of the H_2S release were identical to those assumed for HF acid as discussed in Section 3.A.3.6.5.2.

3.A.3.6.6.2 Continuous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.7).

The values of the constants c and d are functions of the release duration and provided for H_2S in Part 3, Table 4.11.

3.A.3.6.6.3 Instantaneous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.4 could be correlated as functions of release mass for instantaneous releases in accordance with Equation (3.A.8).

For instantaneous releases, the values of the constants c and d are provided for H_2S in Part 3, Table 4.11.

3.A.3.6.7 Development of Toxic Consequence Areas for Ammonia

3.A.3.6.7.1 General

To estimate the consequence area for ammonia, the dispersion analyses was performed using a saturated liquid at ambient temperature [5 °F (24 °C)], with liquid being released from a low pressure storage tank. The tank head was set at 10 ft (3.05 m).

3.A.3.6.7.2 Continuous Releases

To determine an equation for the continuous area of a release of ammonia, four release hole sizes ($^1/_4$ in., 1 in., 4 in., and 16 in.) were run for various release durations (10, 30, and 60 minutes). Again, toxic consequences were calculated using a software package containing atmospheric dispersion routines.

Toxic impact criteria used was for a probit value of 5.0 using the probit Equation (3.A.5) and probit values listed in Part 3, Table 4.17 for ammonia. The results showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.9).

$$CA_f = e(rate)^f \tag{3.A.9}$$

For continuous releases, the values of the constants e and f are functions of the release duration and provided for ammonia in Part 3, Table 4.12.

3.A.3.6.7.3 Instantaneous Releases

For instantaneous release cases, four release masses of ammonia were modeled (10 lb, 100 lb, 1,000 lb, and 10,000 lb), and the relationship between release mass and consequence area to a probit value of 5.0 were correlated. The results in ft^2 for ammonia are provided in Equation (3.A.10).

$$CA_f = 14.17(mass)^{0.9011} \tag{3.A.10}$$

3.A.3.6.8 Development of Toxic Consequence Areas for Chlorine

3.A.3.6.8.1 General

To estimate the consequence area for chlorine, the dispersion analyses were performed using the identical procedure for ammonia as described in Section 3.A.3.6.7.1 and Section 3.A.3.6.7.2.

3.A.3.6.8.2 Continuous Releases

The results of the cloud modeling for chlorine showed that the consequence areas could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.9).

For continuous releases, the values of the constants e and f are functions of the release duration and provided for chlorine in Part 3, Table 4.12.

3.A.3.6.8.3 Instantaneous Releases

For instantaneous release cases, the consequence areas in ft^2 for chlorine could be correlated using Equation (3.A.11).

$$A = 14.97(mass)^{1.117} \tag{3.A.11}$$

3.A.3.6.9 Development of Toxic Consequence Areas for Common Chemicals

3.A.3.6.9.1 General

Procedures to perform Level 1 consequence analysis have been completed for 10 additional toxic chemicals:

a) aluminum chloride ($AlCl_3$),

b) carbon monoxide (CO),

c) hydrogen chloride (HCl),

d) nitric acid,

e) nitrogen dioxide (NO_2),

f) phosgene,

g) toluene diisocyanate (TDI),

h) ethylene glycol monoethyl ether (EE),

i) ethylene oxide (EO), and

j) propylene oxide (PO).

The Level 1 consequence analysis equations for these chemicals have been developed using the same approach as for ammonia and chlorine, described in Section 3.A.3.6.7 and Section 3.A.3.6.8.

3.A.3.6.9.2 Continuous Releases

For continuous releases, the consequence area can be approximated as a function of duration using Equation (3.A.9) with the constants e and f provided in Part 3, Table 4.12.

3.A.3.6.9.3 Instantaneous Releases

Toxic consequences of an instantaneous release for the toxic chemicals listed in Section 3.A.3.6.9.1 estimated smaller (or 0) affected areas than equivalent continuous releases. A conservative curve was calculated using a short duration continuous release toxic consequence curve instead of a less conservative instantaneous release area.

3.A.3.7 Nomenclature

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

A	is a constant for the probit equation
a	is one-half of the cloud width (minor axis), taken at its largest point (within the 50 % probability of fatality dose level)
B	is a constant for the probit equation
b	is one-half of the downwind dispersion distance (major axis), taken at the 50 % probability of fatality dose level
C	is the toxic concentration in the probit equation, ppm
CA_f	is the consequence area, ft^2 (m^2)
$CA_{f,comb}$	is the combined/probability weighted consequence area, ft^2 (m^2)
$CA_{f,i}$	is the individual outcome consequence area for the i^{th} event outcome, ft^2 (m^2)
c	is a constant for the specific consequence area equations for HF acid and H_2S
d	is a constant for the specific consequence area equations for HF acid and H_2S
e	is the constant for the specific consequence area equations for ammonia and chlorine
f	is the exponent for the specific consequence area equations for ammonia and chlorine
$mass$	is the release mass, lb (kg)
n	is the exponent in the probit equation
Pr	is the probit value, typically 5.0, which is defined as 50 % probability
p_i	is the specific event probability for the i^{th} event outcome; see Tables 3.A.3.3, 3.A.3.4, 3.A.3.5, or 3.A.3.6
$rate$	is the release rate, lb/s (kg/s)
t	is the toxic dosage in the probit equation, seconds
x	is the constant for the generic consequence area equation
y	is the exponent for the generic consequence area equation

3.A.3.8 Tables

Table 3.A.3.1—List of Representative Fluids Available for Level 1 Consequence Methodology

Representative Fluid	Examples of Applicable Materials	MW	NBP		AIT	
			°C	°F	°C	°F
C_1–C_2	Methane, ethane, ethylene, LNG, fuel gas	23	−125	−193	558	1,036
C_3–C_4	Propane, butane, isobutane, LPG	51	−21	−6.3	369	696
C_5	Pentane	72	36	97	284	544
C_6–C_8	Gasoline, naphtha, light straight run, heptane	100	99	210	223	433
C_9–C_{12}	Diesel, kerosene	149	184	364	208	406
C_{13}–C_{16}	Jet fuel, kerosene, atmospheric gas oil	205	261	502	202	396
C_{17}–C_{25}	Gas oil, typical crude	280	344	651	202	396
C_{25+}	Residuum, heavy crude, lube oil, seal oil	422	527	981	202	396
Water	Water	18	100	212	N/A	N/A
Steam	Steam	18	100	212	N/A	N/A
Acid	Acid, caustic	18	100	212	N/A	N/A
H_2	Hydrogen only	2	−253	−423	400	752
H_2S	Hydrogen sulfide only	34	−59	−75	260	500
HF	Hydrogen fluoride	20	20	68	17,760	32,000
CO	Carbon monoxide	28	−191	−312	609	1,128
DEE	Diethyl ether	74	35	95	160	320
HCl	Hydrogen chloride	36	−85	−121	N/A	N/A
Nitric acid	Nitric acid	63	121	250	N/A	N/A
NO_2	Nitrogen dioxide	90	135	275	N/A	N/A
Phosgene	Phosgene	99	83	181	N/A	N/A
TDI	Toluene diisocyanate	174	251	484	620	1,148
Methanol	Methanol	32	65	149	464	867
PO	Propylene oxide	58	34	93	449	840
Styrene	Styrene	—	—	—	—	—
EEA	Ethylene glycol monoethyl ether acetate	132	156	313	379	715
EE	Ethylene glycol monoethyl ether	90	135	275	235	455
EG	Ethylene glycol	62	197	387	396	745
EO	Ethylene oxide	44	11	51	429	804

Table 3.A.3.2—Assumptions Used when Calculating Liquid Inventories Within Equipment

Equipment Description	Component Type	Examples	Default Liquid Volume (LV) %
Process columns (may be treated as two or three items) — top half — middle section — bottom half	COLTOP COLMID COLBTM	Distillation columns, FCC main fractionator, splitter tower, debutanizer, packed columns (see Note 1), liquid/liquid columns (see Note 2)	25 % 25 % 37 % These default values are typical of trayed distillation columns and consider liquid holdup at the bottom of the vessel as well as the presence of chimney trays in the upper sections
Accumulators and drums	DRUM	Overhead accumulators, feed drums, high-pressure/ low-pressure (HP/LP) separators, nitrogen storage drums, steam condensate drums, three-phase separators (see Note 3)	50 % liquid Typically, two-phase drums are liquid level controlled at 50 %
KO pots and dryers	KODRUM	Compressor KOs, fuel gas KO drums, flare drums, air dryers (see Note 5)	10 % liquid Much less liquid inventory expected in KO drums
Compressors	COMPC COMPR	Centrifugal and reciprocating compressors	Negligible, 0 %
Pumps	PUMP1S PUMP2S PUMPR	Pumps	100 % liquid
Heat exchangers	HEXSS HEXTS	Shell and tube exchangers	50 % shellside, 25 % tubeside
Fin fan air coolers	FINFAN TUBE FINFAN HEADER	Total condensers, partial condensers, vapor coolers, and liquid coolers (see Note 4)	25 % liquid
Filters	FILTER		100 % full
Piping	PIPE-xx		100 % full, calculated for Level 2 methodology
Reactors	REACTOR	Fluid reactors (see Note 6), fixed-bed reactors (see Note 7), mole-sieves	15 % liquid

NOTE 1 Packed columns will typically contain much less liquid traffic than trayed columns. Typical LV percentages for packed columns are 10 % to 15 %.

NOTE 2 For liquid/liquid columns, such as amine contactors, caustic contactors, and lube or aromatics extractors, where a solvent or other fluid is brought into direct contact with the process fluid (e.g. TEG and BTX in an aromatics extractor), the LV % will be much higher. Consideration should be given to the amount of each fluid in the vessel and whether or not the fluid composition includes both fluids in the mixture composition.

NOTE 3 For three-phase separators, such as desalters and overhead drums with water boots, the LV % may be lower than 50 %, depending on how much of the second liquid phase (typically water) is present and whether or not the fluid composition includes both liquid phases in the mixture composition.

NOTE 4 Most air coolers are two-phase and only partially condense vapors. Even A/Cs that totally condense the vapor stream require the majority of the heat transfer area (and volume) to cool the vapors to their dew point and condense to liquid. Typically, only the final pass (less rows of tubes than other passes) will be predominately liquid. A LV % of 25 % should still be conservative for all A/Cs except liquid coolers where a LV of 100 % should be used.

NOTE 5 For flue gas KO drums and air dryers, the LV % is typically negligible. Consideration should be given to reducing LV % to 0 %.

NOTE 6 Fluidized reactors can have up to 15 % to 25 % of the available vessel volume taken up by catalyst. The remaining available volume is predominately vapor. A LV % of 15 % should still be conservative.

NOTE 7 Fixed-bed reactors can have up to 75 % of the available vessel volume taken up by hardware and catalyst. The remaining volume will typically be 50 % liquid and 50 % vapor. An assumed LV of 15 % of the overall available vessel volume should still be conservative.

Table 3.A.3.3—Specific Event Probabilities—Continuous Release Autoignition Likely

Final Liquid State—Processed Above AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2						
C_3–C_4						
C_5						
C_6–C_8	1				1	
C_9–C_{12}	1				1	
C_{13}–C_{16}	1				0.5	0.5
C_{17}–C_{25}	1				0.5	0.5
C_{25+}	1					1
H_2						
H_2S						
Styrene	1				1	
Final Gas State—Processed Above AIT						
Fluid	**Probability of Ignition**	**Probabilities of Outcome**				
		VCE	**Fireball**	**Flash Fire**	**Jet Fire**	**Pool Fire**
C_1–C_2	0.7				0.7	
C_3–C_4	0.7				0.7	
C_5	0.7				0.7	
C_6–C_8	0.7				0.7	
C_9–C_{12}	0.7				0.7	
C_{13}–C_{16}						
C_{17}–C_{25}						
C_{25+}						
H_2	0.9				0.9	
H_2S	0.9				0.9	
Styrene	1				1	

NOTE 1 Shaded areas represent outcomes that are not possible.

NOTE 2 Must be processed at least 80 °F (27 °C) above AIT.

Table 3.A.3.4—Specific Event Probabilities—Instantaneous Release Autoignition Likely

Final Liquid State—Processed Above AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2	0.7		0.7			
C_3–C_4	0.7		0.7			
C_5	0.7		0.7			
C_6–C_8	0.7		0.7			
C_9–C_{12}	0.7		0.7			
C_{13}–C_{16}						
C_{17}–C_{25}						
C_{25+}						
H_2	0.9		0.9			
H_2S	0.9		0.9			
Styrene	1					1
Final Gas State—Processed Above AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2	0.7		0.7			
C_3–C_4	0.7		0.7			
C_5	0.7		0.7			
C_6–C_8	0.7		0.7			
C_9–C_{12}	0.7		0.7			
C_{13}–C_{16}						
C_{17}–C_{25}						
C_{25+}						
H_2	0.9		0.9			
H_2S	0.9		0.9			
Styrene	1		1			

NOTE 1 Shaded areas represent outcomes that are not possible.
NOTE 2 Must be processed at least 80 °F (27 °C) above AIT.

Table 3.A.3.5—Specific Event Probabilities—Continuous Release Autoignition Not Likely

Final Liquid State—Processed Below AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2						
C_3–C_4						
C_5	0.1				0.02	0.08
C_6–C_8	0.1				0.02	0.08
C_9–C_{12}	0.05				0.01	0.04
C_{13}–C_{16}	0.05				0.01	0.04
C_{17}–C_{25}	0.020				0.005	0.015
C_{25+}	0.020				0.005	0.015
H_2						
H_2S						
DEE	1.0				0.18	0.72
Methanol	0.4				0.08	0.32
PO	0.4				0.08	0.32
Styrene	0.1				0.02	0.08
EEA	0.10				0.02	0.08
EE	0.10				0.02	0.08
EG	0.10				0.02	0.08
Final Gas State—Processed Below AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2	0.2	0.04		0.06	0.1	
C_3–C_4	0.1	0.03		0.02	0.05	
C_5	0.1	0.03		0.02	0.05	
C_6–C_8	0.1	0.03		0.02	0.05	
C_9–C_{12}	0.05	0.01		0.02	0.02	
C_{13}–C_{16}						
C_{17}–C_{25}						
C_{25+}						
H_2	0.9	0.4		0.4	0.1	
H_2S	0.9	0.4		0.4	0.1	
CO	0.899	0.4		0.4	0.099	
DEE	0.899	0.4		0.4	0.099	
Methanol	0.4	0.104		0.104	0.192	
PO	0.4	0.178		0.178	0.044	
Styrene	0.1	0.026		0.026	0.048	
EEA	0.1	0.026		0.026	0.048	
EE	0.1	0.026		0.026	0.048	
EG	0.1	0.026		0.026	0.048	
EO	0.9	0.4		0.4	0.1	

NOTE 1 Shaded areas represent outcomes that are not possible.

NOTE 2 Must be processed at least 80 °F (27 °C) below AIT.

Table 3.A.3.6—Specific Event Probabilities—Instantaneous Release Autoignition Not Likely

Final Liquid State—Processed Below AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1–C_2						
C_3–C_4						
C_5	0.1					0.1
C_6–C_8	0.1					0.1
C_9–C_{12}	0.05					0.05
C_{13}–C_{16}	0.05					0.05
C_{17}–C_{25}	0.02					0.02
C_{25+}	0.02					0.02
H_2						
H_2S						
DEE	0.9					0.9
Methanol	0.4					0.4
PO	0.4					0.4
Styrene	0.1					0.1
EEA	0.1					0.1
EE	0.1					0.1
EG	0.1					0.1
Final Gas State—Processed Below AIT						
Fluid	**Probability of Ignition**	**Probabilities of Outcome**				
		VCE	**Fireball**	**Flash Fire**	**Jet Fire**	**Pool Fire**
C_1–C_2	0.2	0.04	0.01	0.15		
C_3–C_4	0.1	0.02	0.01	0.07		
C_5	0.1	0.02	0.01	0.07		
C_6–C_8	0.1	0.02	0.01	0.07		
C_9–C_{12}	0.04	0.01	0.005	0.025		
C_{13}–C_{16}						
C_{17}–C_{25}						
C_{25+}						
H_2	0.9	0.4	0.1	0.4		
H_2S	0.9	0.4	0.1	0.4		
CO	0.899	0.4	0.099	0.4		
DEE	0.899	0.4	0.099	0.4		
Methanol	0.4	0.099	0.038	0.263		
PO	0.4	0.178	0.044	0.178		
Styrene	0.101	0.025	0.01	0.066		
EEA	0.101	0.01	0.066	0.025		
EE	0.101	0.01	0.066	0.025		
EG	0.101	0.01	0.066	0.025		
EO	0.9	0.4	0.1	0.4		

NOTE 1 Shaded areas represent outcomes that are not possible.
NOTE 2 Must be processed at least 80 °F (27 °C) above AIT.

3.A.3.9 Figures

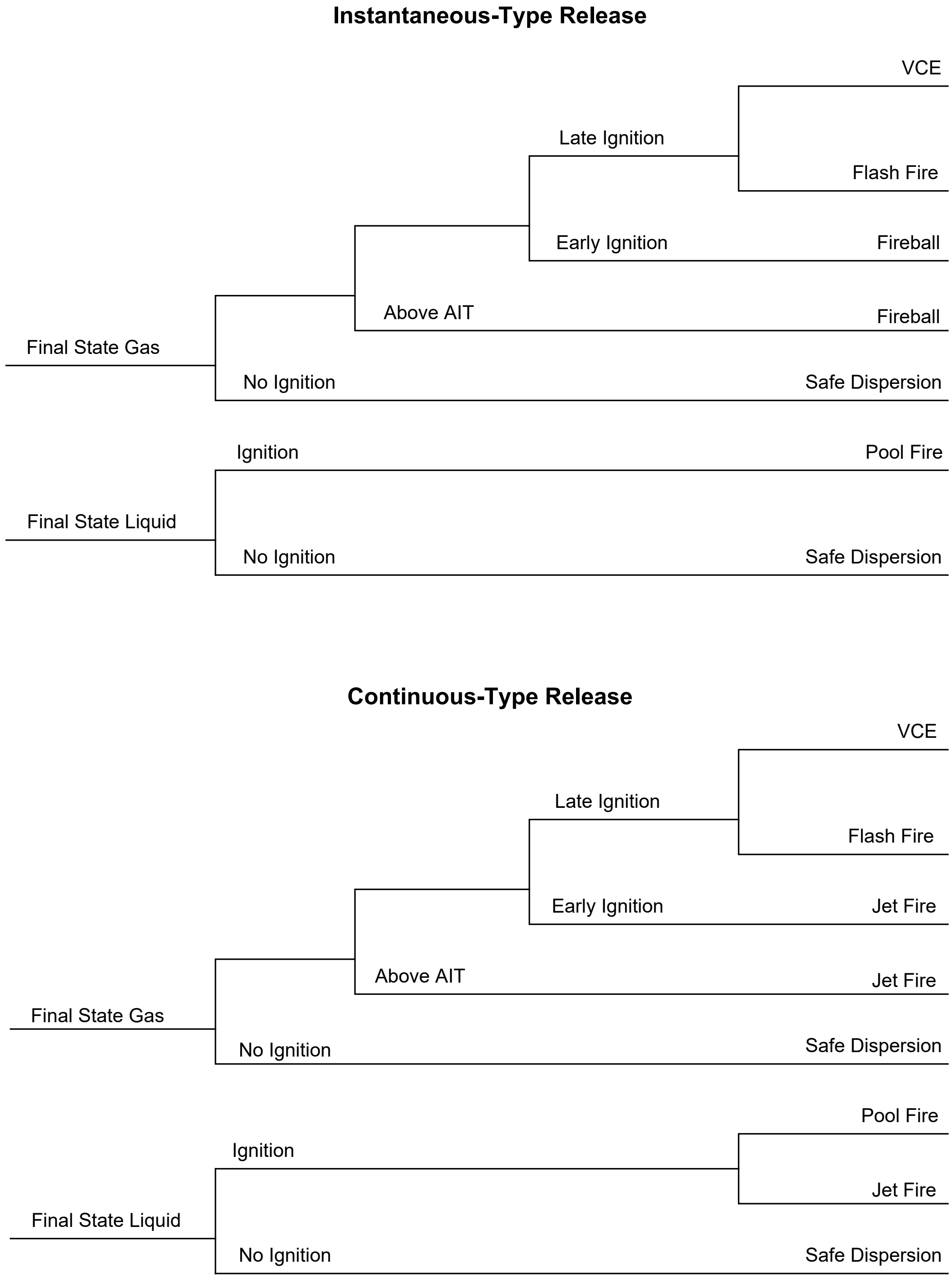

Figure 3.A.3.1—Level 1 Consequence Methodology Event Tree

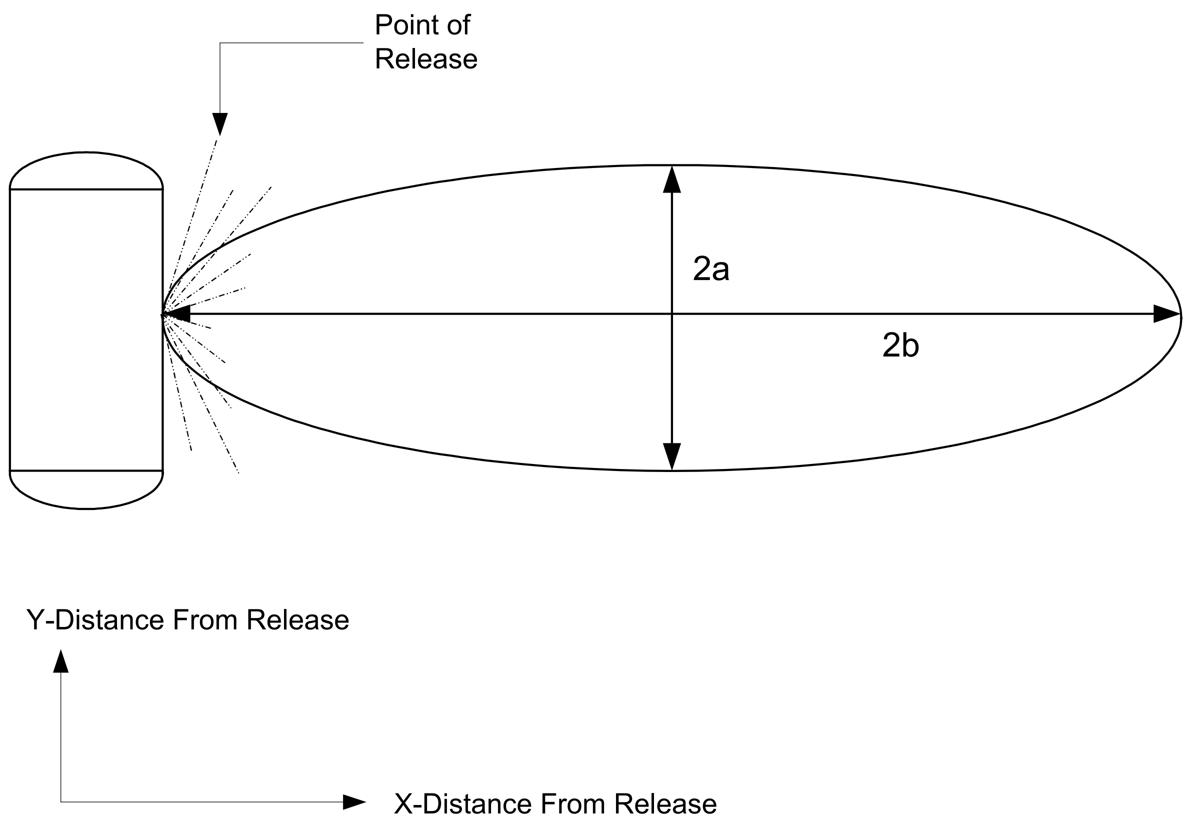

Figure 3.A.3.2—Approximated Cloud Shape for Toxic Plume from a Continuous Release

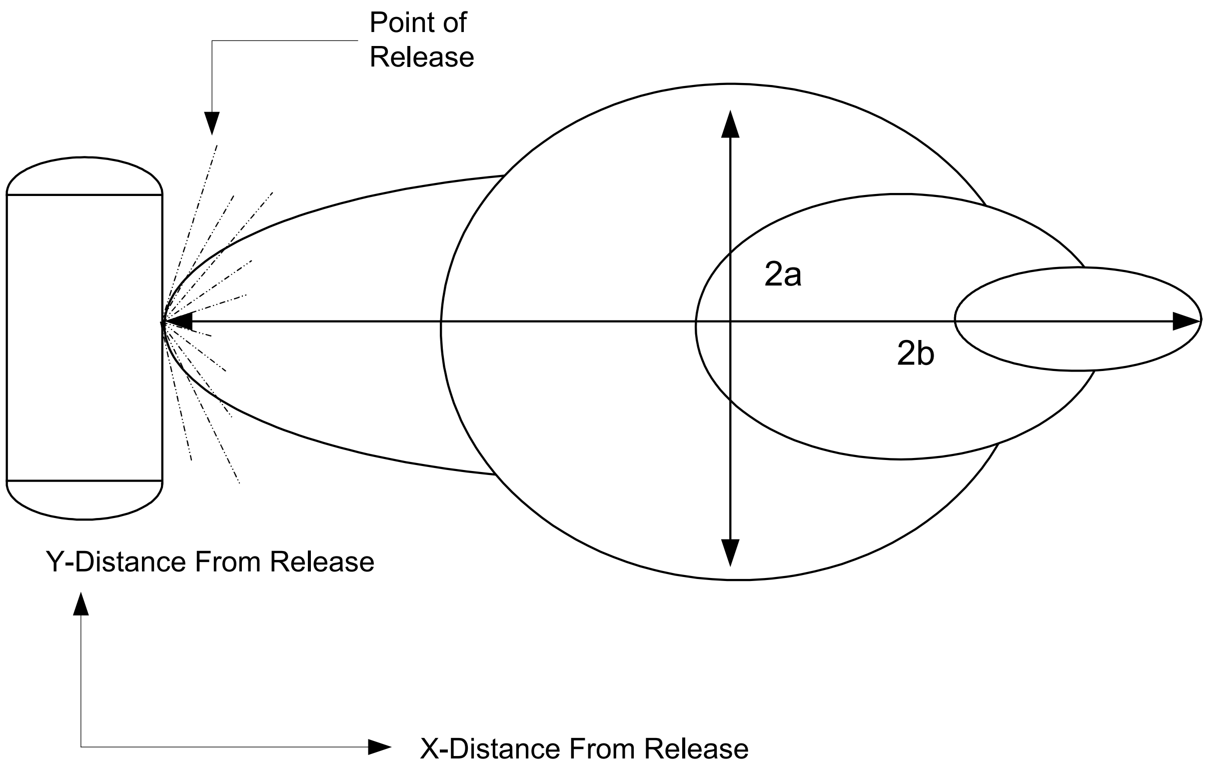

Figure 3.A.3.3—Approximated Cloud Shape for Toxic Puff from an Instantaneous Release

3.A.4 Level 2 Consequence Methodology

3.A.4.1 General

The use of event trees and semi-quantitative effects analysis forms the basis for the Level 2 consequence methodology provided in Part 3, Section 5 with the details for calculating event tree probabilities and the effects of pool fires, jet fires, flash fires, fireballs, VCEs, and BLEVEs are provided. Part 3 provides the impact of most of these events with the closed-form equations.

3.A.4.2 Cloud Dispersion Analysis

Some events, such as VCEs and flash fires, require the use of sophisticated dispersion analysis software to model how the flammable or toxic releases mix and disperse with air as they are released to the atmosphere.

There are several commercially available software packages that enable the user to perform dense gas dispersion consequence modeling. Examples include, such as SLAB, DEGADIS and PHAST, some of which are available in the public domain, while others are commercially available. A study contracted by the U.S. Department of Energy provides a comparison of many different software packages, and recommendations are provided to help select the appropriate package for a particular application.

In general, packages that perform dense gas dispersion modeling should be chosen as opposed to neutrally buoyant models because hazardous releases typically will be materials with MWs heavier than air. Even light hydrocarbons can be modeled accurately using dense gas modeling since the temperature of the releases will result in releases with densities heavier than air.

Dispersion models will provide a cloud concentration profile. For flammables releases, the concentration profile is used to assess which portions of the cloud are in the flammable range. For flash fires, the impact area at grade is determined to be the area in the cloud that has flammable concentrations between the released fluid's LFL and UFL. For VCEs, a volumetric calculation is required since the total amount of flammable volume and mass is required to assess the magnitude of the explosion.

3.A.5 Consequence Methodology for Storage Tanks

3.A.5.1 Overview

The consequence model for storage tanks is based on a modification of the Level 1 consequence analysis. Only a financial consequence analysis is provided for the storage tank bottom.

3.A.5.2 Representative Fluid and Associated Properties

A representative fluid that most closely matches the fluid contained in the storage tank system being evaluated is selected from the representative fluids shown in Part 5, Table 4.5. The required fluid properties for the consequence analysis are also contained in this table.

In addition to selecting a fluid, a soil type must also be specified because the consequence model depends on soil properties. Representative soil conditions and the associated soil properties required for the consequence analysis is provided in Part 5, Table 4.7.

3.A.5.3 GFFs and Release Holes Sizes

3.A.5.3.1 Storage Tank Bottom

The base failure frequency for the leak of an storage tank bottom was derived primarily from an analysis of a portion of the API publication *A Survey of API Members' Aboveground Storage Tank Facilities*, published in July 1994. The survey covered refining, marketing, and transportation storage tanks, each compiled separately. The survey included the years 1983 to 1993, and summary failure data are shown in Table 3.A.5.1. The base failure frequencies obtained from this survey are shown in Part 2, Table 3.1. One of the most significant findings was that tank bottom leaks contributing to soil contamination had been cut in half in the last 5 years compared to the first 5 years covered by the survey. This was attributed to an increased awareness of the seriousness of the problem and to the issuance of the API 653 standard for aboveground storage tank inspection.

A bottom leak frequency of 7.2E-03 leaks per year was chosen as the base leak frequency for an storage tank bottom. Although the leak frequency data in Part 2, Table 3.1 indicate that storage tanks less than 5 years old had a much lower leak frequency, it was decided to use the whole survey population in setting the base leak frequency. The age of the storage tank was accounted for elsewhere in the model since the percent of wall loss in the model is a function of the storage tank age, corrosion rate, and original wall thickness. The percent of wall loss was selected as the basis for the modifier on the base leak frequency; thus, a very young storage tank with minimal corrosion would have a frequency modifier of less than 1, which lowers the leak frequency accordingly.

It should be noted that the DF for storage tank bottoms in Part 2 was originally developed based on a GFF of equal to 7.2E-03, which equates to a range in DFs from less than 1 to 139. In order to be consistent with the other components in Part 2, the range of DFs was adjusted to a range of 1 to 1390. This adjustment in the DF required a corresponding change of the GFF to a value of 7.2E-04, and this is the value shown in Part 2, Table 3.1.

The survey did not report the size of leaks, but a survey of the sponsors for the storage tank RAP project indicated that leak sizes of less than or equal to $^{1}/_{2}$ in. in diameter would adequately describe the vast majority of tank bottom leaks. An $^{1}/_{8}$-in. release hole size is used if a RPB is present, and a $^{1}/_{2}$-in. hole size is used for storage tank bottoms without an RPB. A GFF of 7.2E-04 is assigned to this hole size in the consequence analysis. In addition, the number of release holes in an storage tank bottom is determined as a function of the storage tank bottom area; see Part 5, Table 4.9.

3.A.5.3.2 Tank Courses

The generic failure rate for rapid shell failures was determined based on actual incidents. A review of literature produced reports of two rapid shell failures in the U.S. petroleum industry over the last 30 years:

a) 1971 (location unknown), brittle fracture caused loss of 66,000 bbl crude oil;

b) 1988 Ashland Oil, PA, brittle fracture caused loss of 96,000 bbl diesel.

The number of tanks that provided the basis for the two failures was estimated from the literature to be about 33,300 large storage tanks. This value was based on a 1989 study carried out for API by Entropy Ltd. In this case, large is defined as having a capacity greater than 10,000 bbl. The number of tanks represents the United States total for the refining, marketing, transportation, and production sectors, thus the total number of tank years was found to be approximately 1,000,000. Dividing the number of failures by the number of tank years yields a rapid shell failure frequency of 2E-06 per tank year. API 653 requires tank evaluations for susceptibility to brittle fracture. A hydrostatic test or re-rating of the tank is required for continued service. As a result, API 653 provides protection against brittle fracture. Assuming that one-half of the tanks are not maintained to API 653, the base leak frequencies for rapid shell failures would be 4E-06 per tank year. Because the committee team members had no available documented cases of rapid shell failures for a tank that was operated, maintained, inspected, and altered in accordance with API 653, the failure frequency was believed to be significantly better than the calculated average result and the committee selected a frequency of 1E-07 per tank year.

The total GFF for leakage events in storage tank courses is set at 1E-04. The GFFs for the small, medium, and large holes size is determined by allocating the total GFF for leakage on a 70 %, 25 %, and 5 % basis for these release hole sizes, respectively. The resulting generic failure requires are shown in Part 2, Table 3.1.

3.A.5.4 Estimating the Fluid Inventory Available for Release

The consequence calculation requires an upper limit for the amount of fluid or fluid inventory that is available for release from a component. The total amount of fluid available for release is taken as the amount of product located above the release hole size being evaluated. Flow into and out of the storage tank is not considered in the consequence methodology.

3.A.5.5 Determination of the Release Type (Instantaneous or Continuous)

The release type for the storage tank bottom is assumed to be continuous.

3.A.5.6 Determination of Flammable and Explosive Consequences

Flammable and explosive consequences are not included in the storage tank bottom consequence methodology.

3.A.5.7 Determination of Toxic Consequences

Toxic consequences are not included in the storage tank bottom consequence methodology.

3.A.5.8 Determination of Environmental Consequences

Environmental consequences for storage tank bottoms are driven by the volume and type of product spilled, the property impacted, and the cost associated with cleanup. The consequence methodology includes the potential environmental impact to the locations shown below; see Part 5, Figure 4.1.

a) Diked Area—A release of petroleum products is contained within a diked area or other secondary containment system such as a RPB, spill catch basin, or spill tank. The “diked area” impacted media assumes the spill is of a size and physical characteristics to be contained within a system that is sufficiently impermeable to prevent migration of the spill off-site, prevent contamination of groundwater and surface water, and minimize the volume of impacted on-site soil. Minimal on-site soil impact is defined as less than 1 ft (0.30 m) depth of soil contamination in a 72-hour period. An earthen secondary containment system that contains a release of petroleum may be considered a “diked area” if the soil permeability and stored material properties are sufficient to meet the above definition. For example, a secondary containment system constructed from a uniform sandy soil containing asphalt or other heavy petroleum products would be considered “diked” because a release into the containment is not expected to impact other media (e.g. limited on-site soil impact, no off-site soil, no groundwater or surface water impacts). Conversely, the same system containing gasoline may not meet this definition.

b) On-site Soil—A release of petroleum products is limited to contaminating on-site surficial soils. On-site refers to the area within the physical property boundary limits of the facility. Surface soils refer to the upper 0.61 m (2 ft) of soil that could be readily removed in the event of a spill. The volume spilled, location of spill, site grade, size of the property, soil permeability, and stored material properties are important in determining whether a spill will be contained on-site. For example, a flange leak on a section of aboveground piping may be limited to impacting a small section of on-site soils.

c) Off-site Soil—A release of petroleum products contaminates off-site surface soils. Off-site refers to the property outside of the physical property boundary limits of the facility. Surface soils refer to the upper 2 ft (0.61 m) of soil that could be readily removed in the event of a spill. The volume released location of spill, site grade, land use of the off-site impacted property, soil permeability, and stored material properties are important in determining the impacts to off-site property.

d) Subsurface Soil—A release of petroleum products contaminates subsurface soils. Subsurface impacts may or may not be contained within the physical property boundary limits of the facility. Subsurface soils refer to soils deeper than 2 ft (0.61 m) in depth or those soils that cannot be readily removed in the event of a spill, such as soils beneath a field erected tank or building slab. The soil permeability, stored material properties, and location of the spill are important in determining the extent of the environmental consequences associated with subsurface soil impacts. For example, a release of petroleum from an storage tank bottom that rests on native clay soils will have minor subsurface impacts relative to the same storage tank that is located on native sand soil.

e) Groundwater—A release of petroleum products contaminates groundwater. Groundwater refers to the first encountered phreatic water table that may exist subsurface at a facility. Groundwater elevation may fluctuate seasonally and different groundwater tables may exist at a site (e.g. possible shallow soil water table and a deep bedrock water table). The soil permeability, stored material properties, and location of the spill are important in determining the extent of the environmental consequences associated with groundwater impacts. The nature of the subsurface soils will dictate the time required for a spill to impact the groundwater and the severity of the impact.

f) Surface Water—A release of petroleum products contaminates off-site surface water. Conveyance of spilled product to surface waters is primarily by overland flow, but may also occur through subsurface soils. Surface water refers to non-intermittent surficial waters from canals, lakes, streams, ponds, creeks, rivers, seas, or oceans and includes both fresh and salt water. Surface waters may or may not be navigable. The stored material properties, type of surface water, and response capabilities are important in determining the extent of the environmental consequences associated with surface water impacts.

The cleanup costs associated with these environmental impacts are provided in Part 5, Table 4.6 as a function of environmental sensitivity. The environmental sensitivity is given as Low, Medium, or High and determines the expected cost factor per barrel of spilled fluid for environmental cleanup in a worst-case scenario.

3.A.5.9 Tables

Table 3.A.5.1—Summary of API Members' Aboveground Storage Tank Facilities Relative to Tank Bottom Leakage

Population Description	Number of Tanks	Percent with Bottom Leaks in Last 5 Years	Number with Bottom Leaks in Last 5 Years	Tank Years (see Note)	Bottom Leak Frequency (1988 to 1993)
Tanks < 5 years old	466	0.9%	4	2,330	1.7×10^{-3}
Tanks 6 to 15 years old	628	3.8%	24	3,140	7.6×10^{-3}
Tanks > 15 years old	9,204	3.8%	345	46,020	7.5×10^{-3}
All tanks in survey	10,298	3.6%	373	51,490	7.2×10^{-3}
NOTE Tank years = number of tanks × average number of years in service.					

Part 3, Annex 3.B—SI and U.S. Customary Conversion Factors

3.B.1 General 1
3.B.2 Tables 1

Annex 3.B—SI and U.S. Customary Conversion Factors

3.B.1 General

The SI and U.S. customary unit conversion factors for equations that appear throughout Part 3 of this document are provided in Table 3.B.2.1 of this annex.

3.B.2 Tables

Table 3.B.2.1—SI and U.S. Customary Conversion Factors for Equations in Part 3

Conversion Factor	Equation Reference	SI Units	U.S. Customary Units
C_1	(3.3)	$31{,}623\ \dfrac{mm^2}{m^2}$	$12\ \dfrac{in.}{ft}$
C_2	(3.6), (3.7)	$1{,}000\ \dfrac{mm^2}{m^2}$	1
C_3		4,536 kg	10,000 lb
C_{4A}	(3.17)	$2.205\ \dfrac{1}{kg}$	$1\ \dfrac{1}{lb}$
C_{4B}	(3.109), (3.110)	$2.205\ \dfrac{s}{kg}$	$1\ \dfrac{s}{lb}$
C_5	(3.18), (3.70)	$25.2\ \dfrac{kg}{s}$	$55.6\ \dfrac{lb}{s}$
C_6	(3.23), (3.24), (3.25)	55.6 K	100 °R
C_8	(3.62), (3.63), (3.A.7), (3.A.8)	$0.0929\ m^2$	$1\ ft^2$
C_9	(3.68)	$0.123\ \dfrac{m^2 \cdot s}{kg}$	$0.6\ \dfrac{ft^2 \cdot s}{lb}$
C_{10}		$9.744\ \dfrac{m^2}{kg^{0.06384}}$	$63.32\ \dfrac{ft^2}{kg^{0.06384}}$
C_{12}	(3.89), (3.109), (3.110)	$1.8\ \dfrac{1}{K}$	$\dfrac{1}{°R}$
C_{13}	(3.90), (5.11), (5.41)	$6.29\ \dfrac{bbl}{m^3}$	$0.178\ \dfrac{bbl}{ft^3}$

Conversion Factor	Equation Reference	SI Units	U.S. Customary Units
C_{14}	(3.103), (3.138), (3.152), (3.162)	1	$3{,}600\ \frac{s}{hr}$
C_{15}	(3.105)	$4.685\ \frac{m^{0.33}}{s^{0.22}}$	$1\ \frac{in.^2}{ft^{1.67}s^{0.22}}$
C_{16}	(3.113), (3.114), (3.116), (3.117)	294.44 K	530 °R
C_{17}	(3.128), (3.129)	$0.001\ \frac{kg}{m^2 \cdot s}$	$2.048 \times 10^{-4}\ \frac{lb}{ft^2 \cdot s}$
C_{18}	(3.132)	0.0050 m	0.0164 ft
C_{19}	(3.140)	$1.085\ (kPa \cdot m)^{0.092}$	$1.015\ (psia \cdot ft)^{0.092}$
C_{20}	(3.141)	1.013 kPa	0.147 psia
C_{21}	(3.141)	5,328 K	9,590 °R
C_{22}	(3.158)	$5.8\ \frac{m}{kg^{0.333}}$	$14.62\ \frac{ft}{lb^{0.333}}$
C_{23}	(3.160)	$0.45\ \frac{s}{kg^{0.333}}$	$0.346\ \frac{s}{lb^{0.333}}$
C_{24}	(3.161)	$2.6\ \frac{s}{kg^{0.167}}$	$2.279\ \frac{s}{lb^{0.167}}$
C_{25}	(3.163)	$0.0296\ \frac{1}{kPa^{0.32}}$	$0.0549\ \frac{1}{psia^{0.32}}$
C_{26}	(3.170)	$100\ \frac{kPa}{bar}$	$14.5\ \frac{psi}{bar}$
C_{27}	(3.171)	$1\ \frac{kg^{\frac{1}{3}}}{m \cdot s^{\frac{1}{3}}}$	$0.3967\ \frac{lbm}{ft \cdot s^{\frac{1}{3}}}$
C_{28}	(3.172)	$1{,}000\ \frac{1}{kPa}$	$6{,}895\ \frac{1}{psia}$
C_{29}	(3.192)	$4.303 \times 10^{-4}\ \frac{s^2}{m^2}$	$1.85 \times 10^{-4}\ \frac{lbm}{psi \cdot ft^3}$
C_{30}	(3.195)	$2.150 \times 10^{-7}\ \frac{kg}{J}$	$6.43 \times 10^{-7}\ \frac{1}{lbf \cdot ft}$
C_{31}	(5.35)	$864\ \frac{s \cdot m}{cm \cdot day}$	$7{,}200\ \frac{s \cdot ft}{in. \cdot day}$

Conversion Factor	Equation Reference	SI Units	U.S. Customary Units
C_{32}	(5.5)	$0.543 \dfrac{s \cdot bbl}{day \cdot mm^2 \cdot m}$	$106.8 \dfrac{s \cdot bbl}{day \cdot in.^2 \cdot ft}$
C_{33}	(5.37)	$0.0815 \dfrac{s \cdot bbl}{day \cdot mm^2 \cdot m}$	$16.03 \dfrac{s \cdot bbl}{day \cdot in.^2 \cdot ft}$
C_{34}	(5.37)	$86.4 \dfrac{m}{day \cdot mm^2}$	$1.829 \times 10^5 \dfrac{ft}{day \cdot in.^2}$
C_{35}	(5.38)	$29.6195 \dfrac{bbl}{day^{0.26} \cdot mm^{0.2} \cdot m^{1.64}}$	$8.0592 \dfrac{bbl}{day^{0.26} \cdot in.^{0.2} \cdot ft^{1.64}}$
C_{36}	(5.53)	30.5 m	100 ft
C_{37}	(5.38)	$1.408 \times 10^{-8} \dfrac{m^{1.4}}{day \cdot mm^{1.8}}$	$6.995 \times 10^{-5} \dfrac{ft^{1.4}}{day \cdot in.^{1.8}}$
C_{38}	(5.39)	1.1341	403.95
C_{39}	(5.39)	3.9365	7.2622
C_{40}	(5.39)	5.9352	5.0489
C_{41}	(3.89)	32 °C	0 °F

Part 3, Annex 3.C—Bibliography

3.C.1 General **1**
3.C.2 Bibliography **1**

Risk-based Inspection Methodology
Part 3—Consequence of Failure Methodology
Annex 3.C—Bibliography

3.C.1 General

The references for Part 3 of this document are provided in Section 3.C.2 of this annex.

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Part 4—Inspection Planning Methodology

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Risk-based Inspection Methodology
Part 4—Inspection Planning Methodology

1 Scope

The calculation of risk outlined in API 581 involves the determination of a POF combined with the COF. Failure is defined as a loss of containment from the pressure boundary. Risk increases as damage accumulates during in-service operation as the risk tolerance or risk target is approached and an inspection is recommended of sufficient effectiveness to better quantify the damage state of the component. The inspection action itself does not reduce the risk; however, it does reduce uncertainty and therefore allows more accurate quantification of the damage present in the component.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Recommended Practice 580*, Elements of a Risk-Based Inspection*

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 1—Introduction to Risk-Based Inspection Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 3—Consequence of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 5—Special Equipment*

3 Inspection Planning Based on Risk

3.1 Overview

Inspection planning based on risk assumes that at some point in time, the risk as defined by Part 1, Equation (1.7) and Part 1, Equation (1.8) will reach or exceed a user-defined area or financial 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, inspection interval, 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 strategy that is appropriate for general thinning may 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 Part 1, Equation (1.7), Part 1, Equation (1.8), and Part 1, 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, Part 1, Equation (1.7), Part 1, Equation (1.8), and Part 1, Equation (1.9) can be rewritten as Equation (4.1), Equation (4.2), and Equation (4.3):

$$R(t,I_E) = P_f(t,I_E) \cdot CA_f^{area} \quad \text{for area-based risk} \tag{4.1}$$

$$R(t,I_E) = P_f(t,I_E) \cdot CA_f^{fin} \quad \text{for financial-based risk} \tag{4.2}$$

$$R(t,I_E) = P_f(t,I_E) \cdot CA_f^{inj} \quad \text{for safety-based risk} \tag{4.3}$$

3.1.1 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, C_f^{area} (ft^2/yr), financial, C_f^{fin} ($/yr), or safety, C_f^{inj} (injuries/yr) terms, based on the owner–operator preference. One or more risk targets may be set manage the mechanical integrity risk of components within defined acceptable limits.

b) POF Target—A frequency of failure or leak (#/yr) that is considered unacceptable and triggers the inspection planning process. A POF target may be set drive inspection for components with a very low COF and risk but where frequent, nuisance leaks are undesirable.

c) DF Target—A damage state that reflects an unacceptable failure frequency factor greater than the generic and triggers the inspection planning process. Similar to a POF target, a maximum DF target may be set to drive inspection for components with very low COF and risk but where frequent, nuisance leaks are undesirable. Minimum DF targets may be set by damage mechanism type to prevent inspection recommendations for components with very low DF but high COF and risk where inspection will not effectively reduce risk.

d) Minimum DF Target—A minimum DF where inspection will not effectively reduce risk. In this case, risk is consequence driven and other mitigation methods are recommended.

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

f) Thickness Target—A specific thickness, often the minimum required thickness, t_{min}, considered unacceptable, triggering the inspection planning process. A minimum thickness target may be set to drive inspection for components at a predetermined thickness (e.g. 1/2 wall or 0.100 in.), independent of DF, POF, or risk.

g) 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–operator's corporate standards or may be set based on a jurisdictional requirement. A maximum inspection interval may be set to require an inspection be performed at a specified maximum interval, independent of DF, POF, or risk.

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

3.1.2 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 (see API 579-1/ASME FFS-1) and understood. Using examples and guidance for inspection effectiveness provided in Part 2, Annex 2.F, 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. VT, UT, RT, 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 (4.1), Equation (4.2), or Equation (4.3).

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.F. 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–operator to create, adopt, and document their own specific levels of inspection effectiveness tables.

3.1.3 Calculation of Inspection Plan

The following procedure is used to determine the inspection required to achieve risk target prior to the plan date.

NOTE This procedure applies to pressure vessels, piping, and storage tanks. The inspection planning process for heat exchanger bundles and PRDs are provided in Part 5, Section 5 and Section 6, respectively.

a) Step 1—Assign dates to define the plan period.

    1) Define the RBI date (normally set to current date).

    2) Define the plan date (normally the RBI date + 10 years or two turnaround periods).

    3) Cracking inspection date (normally set to the midpoint between the RBI date and plan date or next turnaround).

b) Step 2—Assign one or more targets as criteria for risk calculation and inspection recommendations (see Part 1, Section 4.3.1). If more than one target is used, indicate the priority of target analysis.

    1) Risk Target.

        i) Area risk in ft²/yr, $R(t)_{\text{area-target}}$.

ii) Financial risk in $/yr, $R(t)_{\text{fin-target}}$.

iii) Safety risk in injuries/yr, $R(t)_{\text{inj-target}}$.

2) POF Target, $P_f(t)_{\text{target}}$.

3) DF Target.

i) Maximum DF target, $D_{\text{f-total,Max}}$.

ii) Minimum DF target.

— $D_{\text{f-min}}^{\text{thin}}$.

— $D_{\text{f-min}}^{\text{scc}}$.

— $D_{\text{f-min}}^{\text{extd}}$.

4) Thickness Target, t_{target}.

5) Maximum Inspection Interval, $Intvl_{\text{target}}$.

c) Step 3—Determine age_{tk} for each active damage mechanism and t_{rdi} for thinning and/or t_{rde} external for external damage mechanisms.

d) Step 4—Calculate age_{tk} at the RBI date and at 0.5 year intervals from the RBI date through the plan date starting at age_{tk} from Step 3.

e) Step 5—Using the calculation steps in Part 2, calculate the DF for each active damage mechanism at 0.5 year intervals from the RBI date through the plan date.

f) Step 6—Using the calculation steps in Part 2, calculate t_{rdi} and/or t_{rde} at 0.5 year intervals from the RBI date through the plan date.

g) Step 7—Using the calculation steps in Part 2, Section 3.4.2, calculate $D_{\text{f-total}}$ at 0.5 year intervals from the RBI date through the plan date using DFs calculated in Step 5.

Set $D_f(t)_{\text{f-total}}^{\text{woplan}} = D_f(t)_{\text{f-total}} \; @\, Plan\ Date$.

h) Step 8—Using the equations in Part 2, Section 3, calculate $P_f(t)$ at 0.5 year intervals from the RBI date to the plan date using $D_{\text{f-total}}$ calculated in Step 7 and gff_{total} from Part 2, Table 3.1.

Set $P_f(t)^{\text{woplan}} = P_f(t) \quad @\, Plan\ Date$.

i) Step 9—Using the equations in Part 1, Section 4.3, calculate the area risk over time, $R(t)_{\text{area}}$, the financial risk, $R(t)_{\text{fin}}$, and safety risk, $R(t)_{\text{inj}}$, at 0.5 year intervals from the RBI date to the plan date using $P_f(t)$ calculated in Step 8, C_f (Part 3, Section 4 or Section 5) and C_f^{fin} (Part 3, Section 4.12).

Set $R_f(t)_{\text{safety}}^{\text{woplan}} = R_f(t) \quad @\, Plan\ Date$ and $R_f(t)_{\text{fin}}^{\text{woplan}} = R_f(t) \quad @\, Plan\ Date$.

j) Step 10—Based on the criteria selected in Step 2, use the following logic to determine if inspection is required:

1) If $R_{\text{f}}(t)_{\text{area}}^{\text{woplan}} \leq R(t)_{\text{area-target}}$, no inspection is required based on risk. Go to next target criteria. If $R_{\text{f}}(t)_{\text{area}}^{\text{woplan}} > R(t)_{\text{area-target}}$, inspection is required based on safety risk.

   i) Calculate the target date based on the date the risk target is reached in Step 9. The target date is calculated based on interpolating between 0.5 years points where $R(t)_{\text{area-target}}$ is reached in Step 9.

2) If $R_{\text{f}}(t)_{\text{fin}}^{\text{woplan}} \leq R(t)_{\text{fin-target}}$, no inspection is required based on risk. Go to next target criteria. If $R_{\text{f}}(t)_{\text{fin}}^{\text{woplan}} > R(t)_{\text{fin-target}}$, inspection is required based on financial risk.

   i) Calculate the target date based on the date the risk target is reached in Step 9. The target date is calculated based on interpolating between 0.5 years points where $R(t)_{\text{fin-target}}$ is reached in Step 9.

3) If $R_{\text{f}}(t)_{\text{inj}}^{\text{woplan}} \leq R(t)_{\text{inj-target}}$, no inspection is required based on risk. Go to next target criteria. If $R_{\text{f}}(t)_{\text{inj}}^{\text{woplan}} > R(t)_{\text{inj-target}}$, inspection is required based on injury risk.

   i) Calculate the target date based on the date the risk target is reached in Step 9. The target date is calculated based on interpolating between 0.5 years points where $R(t)_{\text{inj-target}}$ is reached in Step 9.

4) If $P_{\text{f}}(t)^{\text{woplan}} \leq P(t)_{\text{target}}$, no inspection is required based on risk. Go to next target criteria. If $P_{\text{f}}(t)^{\text{woplan}} > P(t)_{\text{target}}$, inspection is required based on POF.

   i) Calculate the target date based on the date that $P_{\text{f}}(t)_{\text{target}}$ is reached in Step 8. The target date is calculated based on interpolating between 0.5 years points where $P_{\text{f}}(t)_{\text{target}}$ is reached in Step 8.

5) If $D_{\text{f}}(t)_{\text{f-total}}^{\text{woplan}} \leq D_{\text{f-total,Max}}$, no inspection is required based on risk. Go to next target criteria. If $D_{\text{f}}(t)_{\text{f-total}}^{\text{woplan}} > D_{\text{f-total,Max}}$, inspection is required based on DF.

   i) Calculate the target date based on the date that $D_{\text{f-total,Max}}$ is reached in Step 7. The target date is calculated based on interpolating between 0.5 years points where $D_{\text{f-total,Max}}$ is reached in Step 7.

6) If $t_{\text{rdi}} @ \mathit{Plan\ Date} > t_{\text{target}}$, no inspection during plan period is required. Go to next target criteria. If $t_{\text{rdi}} \leq t_{\text{target}}$, inspection is required based on thickness.

   i) Calculate the target date based on the date that t_{rdi} is reached in Step 6. The target date is calculated based on interpolating between 0.5 years points where t_{target} is reached in Step 6.

ii) Calculate the date for inspection based on the remaining life fraction from the target date.

7) If $age_{\text{tk}} @ Plan\ Date \leq Intvl_{\text{target}}$, no inspection during plan period is required. Go to next target criteria.. If $age_{\text{tk}} @ Plan\ Date > Intvl_{\text{target}}$, a user defined inspection is required based on interval and go to Step 12.

   i) Calculate the target date based on the date that $Intvl_{\text{target}}$ is reached in Step 4. The target date is calculated based on interpolating between 0.5 years points where $Intvl_{\text{target}}$ is reached in Step 4.

8) If the component passes all of the applicable above criteria, set:

   i) $R_{\text{f}}(t)_{\text{area,plan}} = R_{\text{f}}(t)^{\text{woplan}}_{\text{area}}$;

   ii) $R_{\text{f}}(t)_{\text{fin,plan}} = R_{\text{f}}(t)^{\text{woplan}}_{\text{fin}}$;

   iii) $R(t)_{\text{inj-target}} = R_{\text{f}}(t)^{\text{woplan}}_{\text{inj}}$;

   iv) $P_{\text{f}}(t)_{\text{plan}} = P_{\text{f}}(t)^{\text{woplan}}$;

   v) $D^{\text{plan}}_{\text{f-total}} = D^{\text{woplan}}_{\text{f-total}}$.

   Go to Step 14.

k) Step 11— Calculate inspection requirements during plan period.

1) If $D^{\text{thin}}_{\text{f-gov}} \leq D^{\text{thin}}_{\text{f-min}}$, $D^{\text{scc}}_{\text{f-gov}} \leq D^{\text{scc}}_{\text{f-min}}$, and $D^{\text{extd}}_{\text{f-gov}} \leq D^{\text{extd}}_{\text{f-min}}$, risk is consequence driven and inspection will not effectively mitigate risk. Another mitigation method is recommended, go to Step 13.

2) Select the highest DF for each active damage mechanism type from Step 5 and calculate DF, $D_{\text{f-gov}}$, $P(t)^{\text{plan}}$, $R_{\text{f}}(t)_{\text{area,plan}}$, $R_{\text{f}}(t)_{\text{fin,plan}}$, and $R(t)_{\text{inj,plan}}$, assuming a C level inspection will be conducted at the target date. If the damage mechanism is an SCC mechanism, use age_{tk} calculated using the cracking inspection date from Step 1.

   i) If $D^{\text{thin}}_{\text{f-gov}} \leq D^{\text{thin}}_{\text{f-min}}$, $D^{\text{scc}}_{\text{f-gov}} \leq D^{\text{scc}}_{\text{f-min}}$, and $D^{\text{extd}}_{\text{f-gov}} \leq D^{\text{extd}}_{\text{f-min}}$, no further inspection mitigation is required, go to Step 13.

   ii) If $R_{\text{f}}(t)^{\text{plan}}_{\text{area}} \leq R(t)_{\text{area-target}}$, $R_{\text{f}}(t)^{\text{plan}}_{\text{fin}} \leq R(t)_{\text{fin-target}}$, $R_{\text{f}}(t)^{\text{plan}}_{\text{inj}} \leq R(t)_{\text{inj-target}}$, and $D_{\text{f-total}} < D_{\text{f-min}}$, the inspection is sufficient to satisfy the target and go to Step 13.

3) Select the $D_{\text{f-gov}}$ of the active damage mechanism type from the previous calculation and repeat the calculation with a C level inspection or next highest inspection category. Calculate $D_{\text{f-total}}$, $P(t)^{\text{plan}}$, $R_{\text{f}}(t)_{\text{area,plan}}$, $R_{\text{f}}(t)_{\text{fin,plan}}$, and $R_{\text{f}}(t)_{\text{inj,plan}}$ assuming the inspection will performed at the target date. If the damage mechanism is an SCC mechanism, use age_{tk} calculated using the cracking inspection date from Step 1.

   i) If $D_{\text{f}}^{\text{thin}} \le D_{\text{f-min}}^{\text{thin}}$, $D_{\text{f}}^{\text{scc}} \le D_{\text{f-min}}^{\text{scc}}$, and $D_{\text{f}}^{\text{extd}} \le D_{\text{f-min}}^{\text{extd}}$, no further inspection mitigation is required, go to Step 12.

   ii) If $R_{\text{f}}(t)_{\text{area}}^{\text{plan}} \le R(t)_{\text{area-target}}$, $R_{\text{f}}(t)_{\text{fin}}^{\text{plan}} \le R(t)_{\text{fin-target}}$, $R_{\text{f}}(t)_{\text{inj}}^{\text{plan}} \le R(t)_{\text{inj-target}}$, and $D_{\text{f-total}} < D_{\text{f-min}}$, the inspection is sufficient to satisfy the target and go to Step 13.

4) Repeat the calculation procedure above for the $D_{\text{f-gov}}$ of the active damage mechanism type from the previous step and calculate $R_{\text{f}}(t)_{\text{area}}^{\text{plan}} \le R(t)_{\text{area-target}}$, $R_{\text{f}}(t)_{\text{fin}}^{\text{plan}} \le R(t)_{\text{fin-target}}$, $R_{\text{f}}(t)_{\text{inj}}^{\text{plan}} \le R(t)_{\text{inj-target}}$, and $D_{\text{f-total}} < D_{\text{f-min}}$ until the inspection is sufficient to satisfy the target or an A level inspection has been reached for each active mechanism.

5) Apply the highest level of inspection identified for the $D_{\text{f-gov}}$ of all active damage mechanisms types.

l) Step 12—Calculate $D_{\text{f-gov}}$, $P(t)^{\text{plan}}$, $R_{\text{f}}(t)_{\text{area,plan}}$, $R_{\text{f}}(t)_{\text{fin,plan}}$, and $R_{\text{f}}(t)_{\text{inj,plan}}$ for all active damage mechanism types after applying the inspection defined in Step 11.

m) Step 13—Calculate, $D_{\text{f-total}}^{\text{plan}}$, $P(t)^{\text{plan}}$, $R(t)_{\text{area}}^{\text{plan}}$, $R(t)_{\text{fin}}^{\text{plan}}$, and $R(t)_{\text{inj}}^{\text{plan}}$ at the plan date using the inspection recommended in Step 11, performed at the target date.

n) Step 14—Calculate the final target date:

   1) If no inspection is required, set $Target\ Date = Plan\ Date$.

   2) If inspection is required, use the recommended inspection plan (A, B, or C inspection effectiveness) and target date defined in Step 11 for the applicable criteria using the minimum date for the applicable criteria in Steps 4 and 6 through 10.

3.1.4 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 4.1, 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 4.2, the risk at the start time of the RBI analysis, or RBI date, exceeds the risk target. An inspection is recommended as soon as practical. The plan should be sufficient to reduce the risk so that the risk after inspection remains below the risk target at the plan date. In addition, elevated risk levels should be communicated with management and a risk mitigation plan should be developed and implemented within an acceptable time period.

c) Case 3—Risk at the Plan Date Does Not Exceed the Risk Target—As shown in Figure 4.3, 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 4.1. 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 In Figure 4.1, a C Level inspection at the target date would not have been sufficient to satisfy the risk target criteria.

3.2 Nomenclature

age_{tk}	is the time since the last A or B effective lining inspection
C_{f}	is the COF, ft^2 (m^2), $ or injuries
$C_{\mathrm{f}}^{\mathrm{area}}$	is the consequence impact area, ft^2 (m^2)
$C_{\mathrm{f}}^{\mathrm{fin}}$	is the financial consequence, $
$C_{\mathrm{f}}^{\mathrm{inj}}$	is the safety consequence, injuries
$D_{\mathrm{f\text{-}gov}}^{\mathrm{extd}}$	is the governing DF external damage
$D_{\mathrm{f\text{-}gov}}^{\mathrm{scc}}$	is the governing DF for SCC
$D_{\mathrm{f\text{-}gov}}^{\mathrm{thin}}$	is the governing DF for thinning
$D_{\mathrm{f\text{-}min}}^{\mathrm{extd}}$	is the governing external DF minimum target for inspection planning
$D_{\mathrm{f\text{-}min}}^{\mathrm{scc}}$	is the governing DF SCC minimum target for inspection planning
$D_{\mathrm{f\text{-}min}}^{\mathrm{thin}}$	is the governing DF thinning minimum target for inspection planning
$D_{\mathrm{f\text{-}total}}$	is total DF for POF calculation
$D_{\mathrm{f\text{-}total}}^{\mathrm{plan}}$	is the DF at the plan date with inspection
$D_{\mathrm{f\text{-}total,Max}}$	is maximum total DF target for inspection planning
$D_{\mathrm{f}}\left(t\right)$	is the DF as a function of time, equal to $D_{\mathrm{f\text{-}total}}$ evaluated at a specific time
$D_{\mathrm{f}}^{\mathrm{SCC}}$	is the DF for stress corrosion cracking
$D_{\mathrm{f}}\left(t\right)_{\mathrm{f\text{-}total}}^{\mathrm{woplan}}$	is the DF at the plan date without inspection

gff_{total}	is the total GFF, failures/yr
$Intvl_{\text{target}}$	is the interval target for inspection planning
plan date	is the date set by the owner–operator that defines the end of plan period
$P_{\text{f}}(t)$	is the POF as a function of time, failures/yr
$P_{\text{f}}(t)_{\text{plan}}$	is the POF at the plan date before the planned inspection, failures/yr
$P_{\text{f}}(t)_{\text{target}}$	is the POF target for inspection planning, failures/yr
$P_{\text{f}}(t)^{\text{woplan}}$	is the POF at the plan date after the planned inspection, failures/yr
$P_{\text{f}}(t, I_{\text{E}})$	is the POF as a function of time and inspection effectiveness, failures/yr
RBI date	is date set by the owner–operator that defines the start of a plan period
$R_{\text{f}}(t)_{\text{area,plan}}$	is the safety risk at the plan date before the planned inspection, ft^2/yr (m^2/yr)
$R_{\text{f}}(t)^{\text{woplan}}_{\text{area}}$	is the safety risk at the plan date after the planned inspection, ft^2/yr (m^2/yr)
$R(t)$	is the risk as a function of time, ft^2/yr (m^2/yr), \$/yr, or injuries/yr
$R(t)_{\text{area}}$	is the area risk as a function of time, ft^2/yr (m^2/yr)
$R(t)_{\text{area-target}}$	is the level of acceptable safety risk that triggers the inspection planning process, ft^2/yr (m^2/yr)
$R_{\text{f}}(t)_{\text{fin,plan}}$	is the financial risk at the plan date before the planned inspection, \$/yr
$R(t)_{\text{fin-target}}$	is the level of acceptable financial risk that triggers the inspection planning process, \$/yr
$R_{\text{f}}(t)^{\text{woplan}}_{\text{fin}}$	is the financial risk at the plan date after the planned inspection, \$/yr
$R(t)_{\text{inj}}$	is the safety risk as a function of time, injuries/yr
$R(t)_{\text{inj-target}}$	is the level of acceptable safety risk that triggers the inspection planning process, injuries/yr
$R_{\text{f}}(t)_{\text{inj,plan}}$	is the safety risk at the plan date before the planned inspection, injuries/yr
$R_{\text{f}}(t)^{\text{woplan}}_{\text{inj}}$	is the safety risk at the plan date after the planned inspection, injuries/yr

$R(t)_{\text{fin}}$ is the financial risk as a function of time, \$/yr

$R(t, I_{\text{E}})$ is the risk as a function of time and inspection effectiveness, ft^2/yr (m^2/yr), \$/yr, injuries/yr

target date is the date where the risk target is expected to be reached and is the date at or before the recommended inspection should be performed

t_{rde} is the measured thickness reading from previous inspection with respect to wall loss associated with external corrosion

t_{rdi} the furnished thickness, t, or measured thickness reading from previous inspection, only if there is a high level of confidence in its accuracy, with respect to wall loss associated with internal corrosion

t_{target} is the thickness target for inspection planning

3.3 Figures

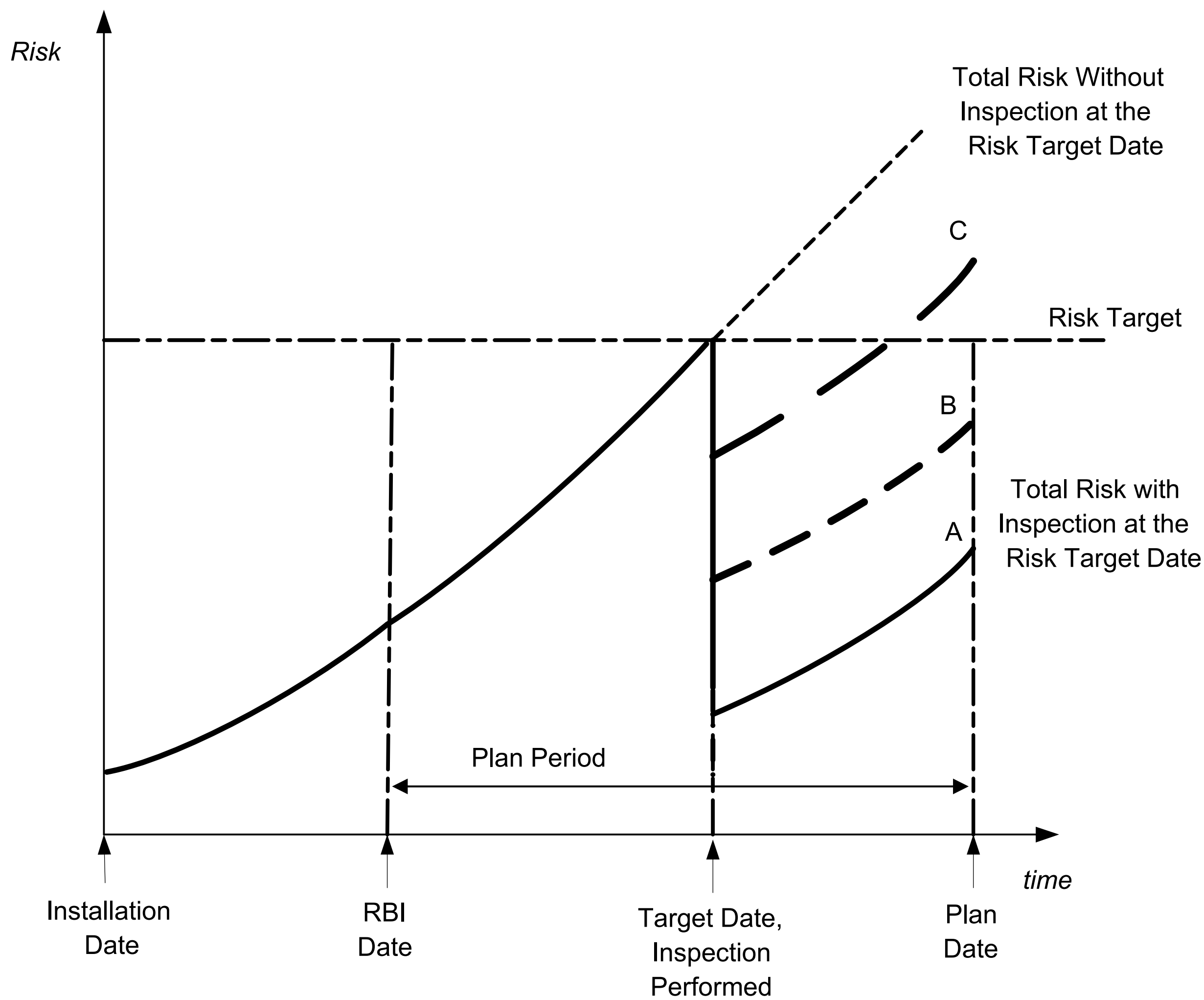

Figure 4.1—Case 1: Inspection Planning when the Risk Target Is Exceeded During the Plan Period

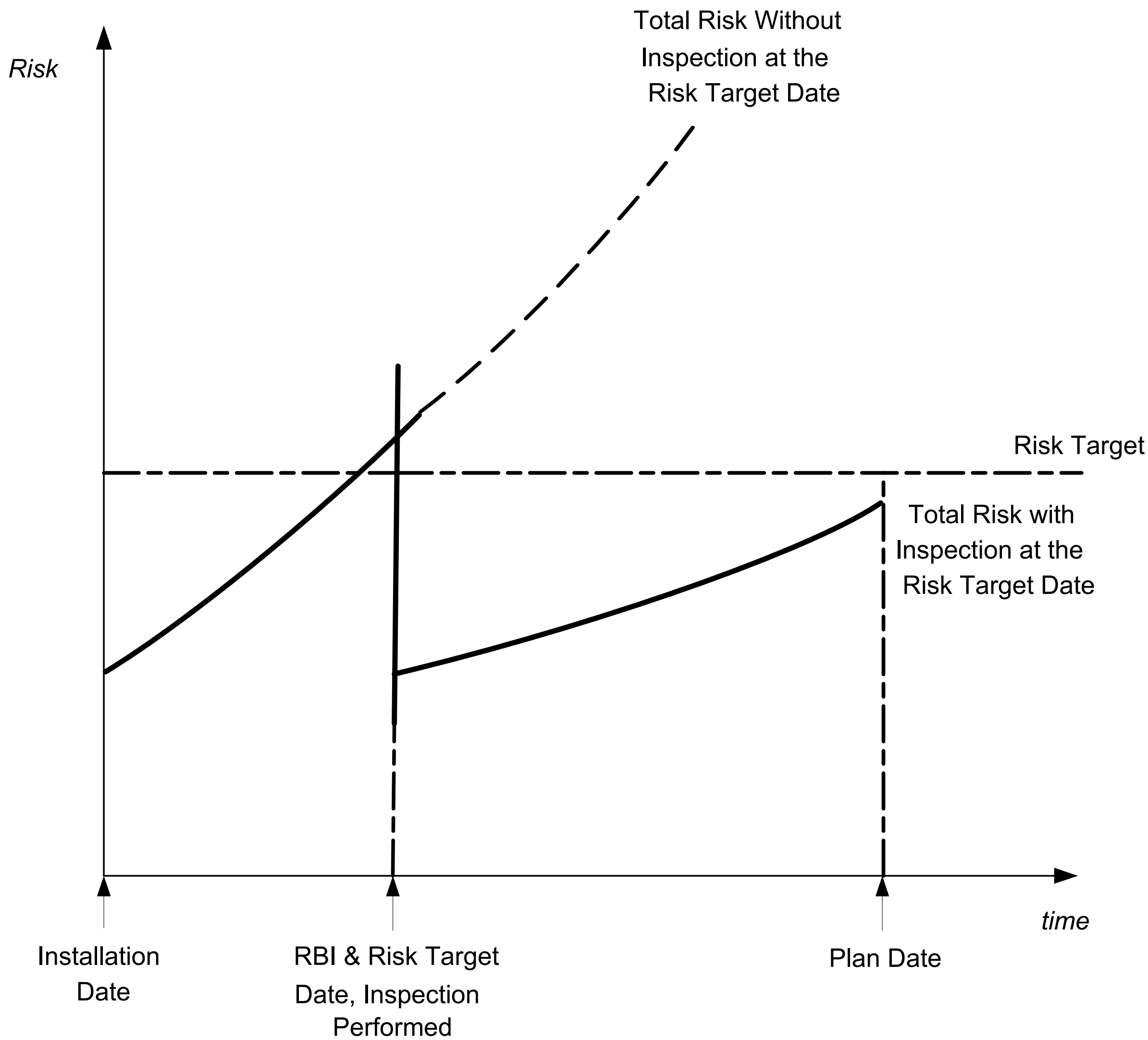

Figure 4.2—Case 2: Inspection Planning when the Risk Target Has Been Exceeded at or Prior to the RBI Date

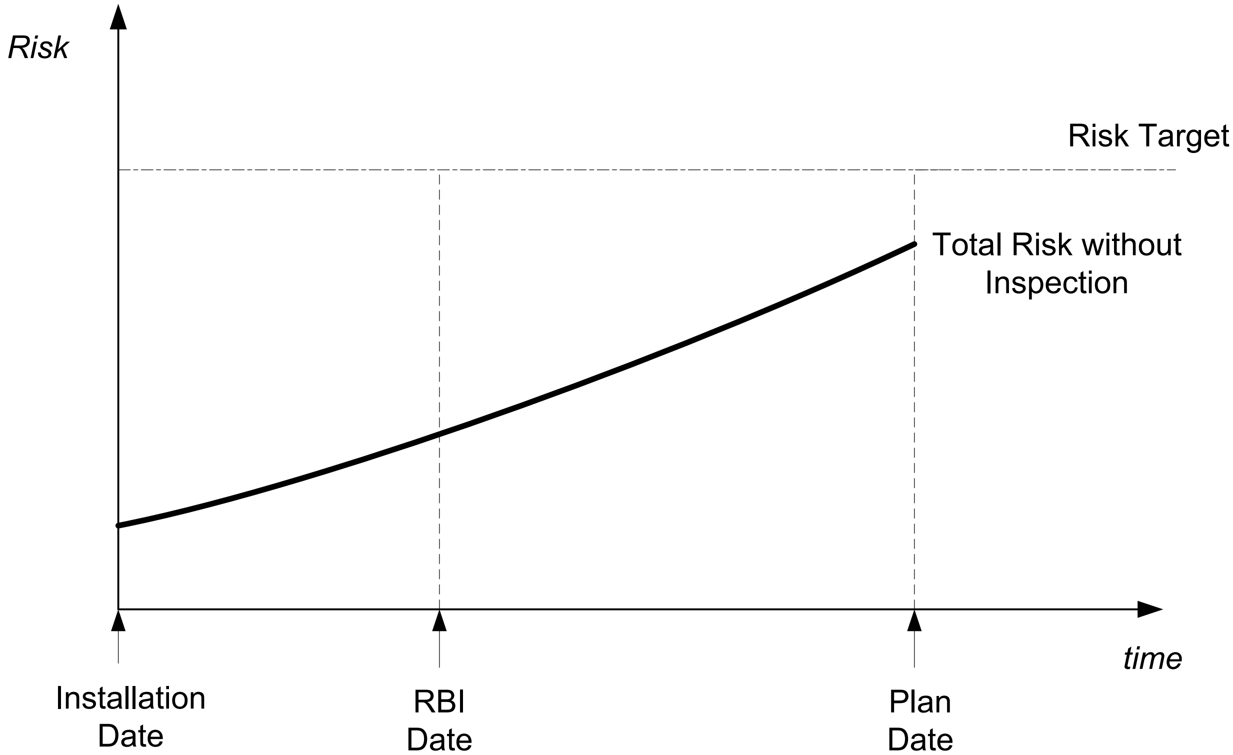

Figure 4.3—Case 3: Inspection Planning when Risk Target Is Not Exceeded During the Plan Period

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Risk-based Inspection Methodology
Part 5—Special Equipment

1 Scope

1.1 Purpose

This recommended practice, API 581, provides semiquantitative procedures to establish an inspection program using risk-based methods for pressurized fixed equipment, including pressure vessel, piping, tankage, PRDs, and heat exchanger tube bundles. API 580, *Risk-Based Inspection*, provides guidance for developing RBI programs on fixed equipment in refining, petrochemical, chemical process plants, and oil and gas production facilities. The intent is for API 580 to introduce the principles and present minimum general guidelines for RBI, while the API 581 recommended practice provides semiquantitative calculation methods to calculate risk and develop an inspection plan.

1.2 Introduction

The calculation of risk outlined in API 581 involves the determination of a probability of failure (POF) combined with the consequence of failure (COF). Failure is defined as a loss of containment from the pressure boundary resulting in leakage to the atmosphere or rupture of a pressurized component. Risk increases as damage accumulates during in-service operation as the risk tolerance or risk target is approached and an inspection is recommended of sufficient effectiveness to better quantify the damage state of the component. The inspection action itself does not reduce the risk; however, it does reduce uncertainty and therefore allows more accurate quantification of the damage present in the component.

1.3 Risk Management

In most situations, once risks have been identified, alternate opportunities are available to reduce them. However, nearly all major commercial losses are the result of a failure to understand or manage risk. In the past, the focus of a risk assessment has been on-site safety-related issues. Presently, there is an increased awareness of the need to assess risk resulting from:

a) on-site risk to employees,

b) off-site risk to the community,

c) business interruption risks, and

d) risk of damage to the environment.

Any combination of these types of risks may be factored into decisions concerning when, where, and how to inspect equipment.

The overall risk of a plant may be managed by focusing inspection efforts on the process equipment with higher risk. API 581 provides a basis for managing risk by making an informed decision on inspection frequency, level of detail, and types of NDE. It is a consensus document containing methodology that owner–operators may apply to their RBI programs. In most plants, a large percent of the total unit risk will be concentrated in a relatively small percent of the equipment items. These potential higher risk components may require greater attention, perhaps through a revised inspection plan. The cost of the increased inspection effort can sometimes be offset by reducing excessive inspection efforts in the areas identified as having lower risk. Inspection will continue to be conducted as defined in existing working documents, but priorities, scope, and frequencies can be guided by the methodology contained in API 581.

This approach can be made cost-effective by integration with industry initiatives and government regulations, such as *Process Safety Management of Highly Hazardous Chemicals* (OSHA 29 *CFR* 1910.119) or the EPA risk management programs for chemical accident release prevention.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Recommended Practice 580*, Elements of a Risk-Based Inspection*

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 1—Introduction to Risk-Based Inspection Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 3—Consequence of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 4—Inspection Planning Methodology*

3 Pressure Vessels and Piping

3.1 POF

The procedures for POF calculations to be used are provided in Part 2. The POF as a function of time and inspection effectiveness is determined using a GFF, a management systems factor, and DFs for the applicable active damage mechanisms as described in Section 4.1.

3.2 COF

COF calculation procedures for two levels of consequence analysis are provided in Part 3, as described in Section 4.2. In both methods, the consequence analysis may be determined in consequence area or in financial consequence. Consequences from flammable and explosive events, toxic releases, and nonflammable and nontoxic events are considered based on the process fluid and operating conditions.

3.3 Risk Analysis

Risk as a function of time is calculated in accordance with Section 4.3.1. The distribution of risks for different components may be plotted on a risk matrix or iso-risk plot, as described in Section 4.3.2 and Section 4.3.2.3, respectively.

3.4 Inspection Planning Based on Risk Analysis

The procedure to determine an inspection plan is provided in Part 4. This procedure may be used to determine both the time and type of inspection to be performed based on the process fluid and design conditions, component type and materials of construction, and the active damage mechanisms.

4 Storage Tanks

4.1 General

The calculation of the consequence of a leak or rupture of an API 620 low-pressure and API 650 atmospheric storage tank bottom, edge, and course components are covered in this section. The primary liquid container should be evaluated for risk with the secondary container purpose as leak isolation for API 620 double-walled tanks (tank-in-tank systems). The DF and POF calculation use a methodology similar to the approach outlined in Part 2. The methodology for consequence analysis specialized for storage tanks is provided for the COF calculation. The background on the GFFs for tank bottoms and courses are provided in Part 3, Section 3.A.5.3.1.

4.2 POF

POF calculation procedures for storage tank bottom components are provided in this section. Follow calculating procedures outlined in Part 2 for tank course POF. The tank bottom component POF as a function of time and inspection effectiveness is determined using a GFF, a management systems factor, and DFs for the applicable active damage mechanisms.

The soil-side plates of the tank bottom edge (under-shell) may have a different corrosive environment and foundation conditions than the remainder of the bottom component in tanks with annular rings. Product-side corrosion in the perimeter area of the tank may be different than the remainder of the tank bottom due to the as-built or settled profile, edge sump(s), mixers, or other appurtenances. In addition, the stresses in the tank bottom edge differs from the tank bottom and the t_{min} calculation in the critical zone are calculated using API 620 and API 650.

4.3 Determination of the Tank Bottom DF

4.3.1 General

The calculation procedure for the tank bottom component thinning DF calculation is provided in this section. DFs for other active damage mechanisms are calculated using Part 2, Section 5 through Section 24.

4.3.2 Determination of the Tank Bottom Thinning DF

a) Step 1.1—Determine the furnished thickness, t, and age, age, for the tank component from the installation date. If the tank has an internal liner, determine the liner age, age_{liner} from the liner installation date.

b) Step 1.2—Determine the corrosion rate for the base material, $C_{r,\text{bm}}$, based on the material of construction and process environment, using guidance from Part 2, Section 4.5.2 and examples in Part 2, Annex 2.B for establishing corrosion rates.

c) Step 1.3—Determine the inspection effectiveness, $N_{\text{A}}^{\text{Thin}}$, $N_{\text{B}}^{\text{Thin}}$, $N_{\text{C}}^{\text{Thin}}$, and $N_{\text{D}}^{\text{Thin}}$, for the last inspection performed using Part 2, Section 4.5.6 for guidance.

d) Step 1.4—Determine the time in service, age_{tk}, since the last inspection known thickness, t_{rdi}, where t_{rdi} is the starting thickness with respect to wall loss associated with internal corrosion (see Part 2, Section 4.5.5).

   1) Determine the date of the last inspection with a measured thickness and calculate the service age since the inspection, age_{tk}, and the measured thickness, t_{rdi}. If no measured thickness is available, set $t_{\text{rdi}} = t$ and $age_{\text{tk}} = age$.

   2) For tank components with internal liners, determine the lining type and age using Table 4.1 or using the remaining life of the internal liner, condition of liner, F_{LC}, at last inspection using Table 4.2, and

online monitoring factor, F_{OM}, using Equation (5.1). If component does not contain an internal liner, $age_{rc} = 0$.

$$age_{f,rc} = \frac{age_{rc}}{F_{LC}} \cdot F_{OM} \tag{5.1}$$

Online monitoring adjustment factor, F_{OM}—Some lined components have monitoring to allow early detection of a leak or other failure of the lining. The monitoring allows orderly shutdown of the component before failure occurs. If online monitoring is used and it is known to be effective at detecting lining deterioration, F_{OM} = 0.1; otherwise, F_{OM} = 1.0. Examples of monitoring systems include thermography or heat sensitive paint (refractory linings), weep holes with detection devices (loose alloy linings), and electrical resistance detection (glass linings).

e) Step 1.5—Determine t_{min} using one of the following methods:

   1) For the API 620 and API 650 tank courses, determine the allowable stress, S and weld joint efficiency, E, and calculate the minimum required thickness, t_{min}, using component type in Part 2, Table 4.2, geometry type in Part 2, Table 4.3, and per the original construction code or API 579-1/ASME FFS-1 [24] or API 620, as applicable.

   2) API 650 tank bottoms can be modeled with two components. If the component type is Tank650 TANKBOTTOM, use $t_{min} = 0.1$ in. if the storage tank does not have an RPB or $t_{min} = 0.05$ in. if the storage tank has an RPB, in accordance with API 653 [2]. If the component is a Tank650 TANKBOTEDGE, use the minimum thickness for an annular ring or the critical zone (for tanks without annular rings), whichever is applicable, in accordance with API 653.

   3) API 620 tank bottom t_{min} is determined by using API 620. If the component is a Tank620 TANKBOTEDGE, use the minimum thickness for an annular ring or the critical zone (for tanks without annular rings), whichever is applicable, in accordance with API 653.

   4) A specific t_{min} calculated by another method and documented in the asset management program may be used at the owner–operator's discretion.

f) Step 1.6—Determine the tank bottom component A_{rt} parameter using Equation (5.2) based on t from Step 1, $C_{r,bm}$ from Step 1.2, and age_{tk} and t_{rdi} from Step 1.4.

   NOTE The age parameter in these equations is equal to age_{tk} from Step 1.4.

   1) For tank courses, go to Steps 7 through 15 in Part 2, Section 4.5.7 and skip to Step 1.8.

   2) For tank bottom components, calculate the A_{rt} parameter using Equation (5.2).

$$A_{rt} = \max\left[\left(1 - \frac{t_{rdi} - \left(C_{r,bm} \cdot \left(age_{tk} - age_{f,rc}\right)\right)}{t_{min} + CA}\right),\ 0.0\right] \tag{5.2}$$

g) Step 1.7—For tank bottom components, determine the base DF for thinning, D_{fB}^{thin}, using Table 4.3 and based on the A_{rt} parameter from Step 1.6 and inspection effectiveness from Step 1.3.

h) Step 1.8—Determine the DF for thinning, $D_f^{Tank,Thin}$, using Equation (5.3).

$$D_f^{Tank,Thin} = \max\left[\left(D_{fB}^{Thin} \cdot F_{WD} \cdot F_{AM} \cdot F_{SM}\right),\ 0.1\right] \tag{5.3}$$

The adjustment factors in are determined as described below.

1) Adjustment for Welded Construction, F_{WD}—If the component is welded (i.e. not riveted), then $F_{WD} = 1$; otherwise, $F_{WD} = 10$.

2) Adjustment for Maintenance in Accordance with API 653, F_{AM}—If the storage tank is maintained in accordance with API 653, then $F_{AM} = 1$; otherwise, $F_{AM} = 5$.

3) Adjustment for Settlement, F_{SM}—It is determined based on the following criteria.

— Recorded settlement exceeds API 653 criteria—$F_{SM} = 2$.

— Recorded settlement meets API 653 criteria—$F_{SM} = 1$.

— Settlement never evaluated—$F_{SM} = 1.5$.

— Concrete foundation, no settlement—$F_{SM} = 1$.

4.3.3 Determination of the SCC DFs

Follow calculating procedures outlined in Part 2, Section 5 through Section 14 for SCC of storage tank courses, if applicable.

4.3.4 Determination of the External DFs

Follow calculating procedures outlined in Part 2, Section 15 through Section 18 for external damage of storage tank courses, if applicable.

4.3.5 Determination of the Brittle Fracture DFs

Follow calculating procedures outlined in Part 2, Section 21 for brittle fracture of storage tank courses, if applicable.

4.3.6 DF Combination for Multiple Damage Mechanisms

Follow calculating procedures outlined in Part 2, Section 3.4.2 for combining DFs or multiple damage mechanisms of storage tank courses.

4.4 COF

The COF is calculated in terms of affected area or in financial consequence. Consequences from flammable and explosive events, toxic releases, and nonflammable/nontoxic events are considered in both methods based on the process fluid and operating conditions. Financial consequences from component damage, product loss, financial impact, and environmental penalties are considered.

The COF methodology is performed to aid in establishing a ranking of equipment items on the basis of risk. The consequence measures are intended to be used for establishing priorities for inspection programs. Methodologies for two levels of analysis are provided. A special COF methodology is provided for low-pressure and atmospheric storage tanks and is covered in this section.

4.5 COF Methodology for Storage Tank Courses

The COF associated with storage tanks is concerned primarily with the financial losses due to leakage and/or rupture of a storage tank course. Safety/area-based consequences are addressed for the courses following the Level 1 or Level 2 consequence analysis methods provided in Part 3, Section 4 or Section 5. Detailed procedures for calculating the financial COF for courses are provided in Section 2.5 through Section 2.16.

The procedure for determining COF of storage tank course components includes calculations for both area- and financial-based methods.

4.6 Required Properties at Storage Conditions

4.6.1 General

Fluid properties should be determined for the COF calculation. When calculating the safety COF area for tank courses, see Part 3, Section 5.1.2 Level 1 or 2 COF methodology. See Part 3, Section 5.1.2 for detailed description of required properties at storage conditions. The financial COF for fluids other than those in Table 4.5 may be modeled if the stored as liquid data required in Table 4.5 and Part 3, Table 4.2 are provided by the user.

NOTE The flammable COF would be calculated based on the equation constants in Part 3, Table 4.8 and Part 3, Table 4.9 for the fluid closest matching the MW and NBP.

Fluid properties at storage conditions are necessary to calculate the financial- and area-based Level 1 and Level 2 COF. Refer to the following sections for a detailed description of the required properties at storage conditions for tank course components.

a) Level 1 COF methodology, see Part 3, Section 4.1.2.

b) Level 2 COF methodology see Part 3, Section 5.1.2.

4.6.2 Required Properties at Flashed Conditions

Fluid properties are determined for a safety based COF for use in the Level 1 or 2 COF methodology. See Part 3, Section 5.1.3 for detailed description of required properties at flashed conditions.

4.7 Release Hole Size Selection

4.7.1 General

A discrete set of release events or release hole sizes are used for consequence analysis as outlined in Table 4.4.

4.7.2 Calculation of Release Hole Sizes

The following procedure may be used to determine the release hole size and the associated GFFs.

a) Step 2.1—Determine the release hole size, $d_n = 1$, from Table 4.4 for storage tank courses.

b) Step 2.2—Determine the generic failure frequency, gff_n, for the d_n release hole size and the total generic failure frequency from Part 2, Table 3.1 or from Equation (5.4).

$$gff_{\text{total}} = \sum_{n=1}^{4} gff_n \tag{5.4}$$

4.8 Release Rate Calculation

4.8.1 General

Release rate calculations are provided for a leak in a storage tank course. The liquid head of the product is assumed to be constant over time, and the leak is to atmospheric pressure for a course leak.

4.8.2 Storage Tank Course

The discharge of a liquid through a sharp-edged orifice in a storage tank course with a liquid height above the orifices may be calculated using Equation (5.5).

$$W_n = C_{32} \cdot C_{\text{d}} \cdot A_n \sqrt{2 \cdot g \cdot LHT_{\text{above},i}} \tag{5.5}$$

In Equation (5.5), the discharge coefficient, C_{d}, for fully turbulent liquid flow from sharp-edged orifices is in the range of $0.60 \le C_{\text{d}} \le 0.65$. A value of $C_{\text{d}} = 0.61$ is recommended.

4.8.3 Calculation of Storage Tank Course Release Rate

a) Step 3.1—Determine the height of the liquid, h_{liq}, above the release hole size, d_n, for each hole size.

b) Step 3.2—Determine the hole area, A_n, for each hole size using Equation (5.6).

$$A_n = \frac{\pi d_n^2}{4} \tag{5.6}$$

c) Step 3.3—Determine the liquid height above the i^{th} course where h_{liq} is the maximum fill height in the tank and CHT is the height of each course.

$$LHT_{\text{above},i} = \left[h_{\text{liq}} - (i-1) \cdot CHT\right] \tag{5.7}$$

d) Step 3.3—Determine the flow rate, W_n, for each hole size using Equation (5.5) based on h_{liq} from Step 3.1 and A_n from Step 3.2.

4.9 Estimate the Inventory Volume and Mass Available for Release

4.9.1 General

The inventory in the storage tank available for release depends on the component being evaluated. The available inventory for courses is a function of the location of the release hole and is calculated as the volume of fluid above the release hole.

4.9.2 Calculation of Storage Tank Course Inventory Mass

The amount of fluid inventory used in the course consequence analysis is the amount of fluid that is above the lower elevation of the course under evaluation.

a) Step 4.1—Determine the liquid height above the i^{th} course where h_{liq} is the maximum fill height in the tank and CHT is the height of each course.

$$LHT_{\text{above},i} = \left[h_{\text{liq}} - (i-1) \cdot CHT\right] \tag{5.8}$$

b) Step 4.2—Determine the volume above the course being evaluated.

$$Lvol_{\text{above},i} = \left(\frac{\pi D_{\text{tank}}^{2}}{4}\right) \cdot LHT_{\text{above},i} \tag{5.9}$$

c) Step 4.3—Calculate the available volume of the release.

NOTE The release hole should be assumed to be at the bottom of the course.

$$Lvol_{\text{avail},n} = Lvol_{\text{above},i} \tag{5.10}$$

d) Step 4.4—Calculate the storage tank volume in barrels using Equation (5.11).

$$Bbl_{\text{avail},n} = Lvol_{\text{avail},n} \cdot C_{13} \tag{5.11}$$

e) Step 4.5—Calculate the storage tank mass using liquid density, ρ_{l}, from Table 4.5 and using Equation (5.12).

$$mass_{\text{avail},n} = Lvol_{\text{avail},n} \cdot \rho_{\text{l}} \tag{5.12}$$

4.10 Determine the Type of Release

The type of release for a storage tank is assumed to be continuous.

4.11 Estimate the Impact of Detection and Isolation Systems on Release Magnitude

Detection and isolation systems are not accounted for in a storage tank course consequence analysis.

4.12 Determine the Release Rate and Volume for the COF Analysis

4.12.1 General

The storage tank course release is assumed to be continuous and the release rate is calculated from Equation (5.13), where W_n is determined in Section 2.7.2.

$$rate_n = W_n \tag{5.13}$$

4.12.2 Calculation for Storage Tank Course Release Volume

A step-by-step methodology for determining the release rate and volume is in accordance with the modeling in Part 3, Section 4 for Level 1 COF and Part 3, Section 5 for Level 2 COF with the following differences.

— The pool fire area should not exceed the area of the dike.

— The release volume should be calculated with the following steps.

a) Step 5.1—Determine the release rate, $rate_n$, for each hole size in bbl/day using Equation (5.13) where the release rate, W_n, is from Step 3.3.

b) Step 5.2—Determine the leak detection time, t_{ld}, as follows:

$$t_{ld} = 7 \text{ days for } d_n \le 0.125 \text{ in. } (3.17 \text{ mm})$$

$$t_{ld} = 1 \text{ day for } d_n > 0.125 \text{ in. } (3.17 \text{ mm})$$

c) Step 5.3—Calculate the leak duration, ld_n, of the release for each hole size using Equation (5.14) based on the release rate, $rate_n$, from Step 5.1, the leak detection time, t_{ld}, from Step 5.2, and the storage tank volume, $Bbl_{avail,n}$, from Step 4.4.

$$ld_n = \min\left[\left\{\frac{Bbl_{avail,n}}{rate_n}\right\},\ 7 \text{ days}\right] \qquad \text{for } d_n \le 0.125 \text{ in. } (3.17 \text{ mm}) \tag{5.14}$$

d) Step 5.4—Calculate the release volume from leakage, Bbl_n^{leak}, for each hole size using Equation (5.15) based on the release rate, $rate_n$, from Step 5.1, the leak duration, ld_n, from Step 5.3, and available volume, $Bbl_{avail,n}$, from Step 4.4.

$$Bbl_n^{leak} = \min\left[\left\{rate_n \cdot ld_n\right\},\ Bbl_{avail,n}\right] \tag{5.15}$$

e) Step 5.5—Calculate the release mass from leakage, $mass_n^{leak}$, for each hole size using Equation (5.16) based on the available volume, Bbl_n^{leak}, from Step 5.4.

$$mass_n^{leak} = Bbl_n^{leak} \tag{5.16}$$

f) Step 5.6—Calculate the release volume from a rupture, $Bbl_n^{rupture}$, for each hole size using Equation (5.17) based on the available volume, $Bbl_{avail,n}$, from Step 4.4.

$$Bbl_n^{rupture} = Bbl_{avail,n} \tag{5.17}$$

g) Step 5.7—Calculate the mass from a rupture, $mass_n^{rupture}$, for each hole size using Equation (5.18) based on the available volume, $Bbl_n^{rupture}$, from Step 5.6.

$$mass_n^{rupture} = Bbl_n^{rupture} \tag{5.18}$$

4.13 Determine Flammable and Explosive Consequences for Storage Tank Courses

4.13.1 General

Flammable and explosive consequences for storage tanks courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

4.13.2 Calculation of Flammable and Explosive Consequences

The step-by-step procedure for determining the flammable and explosive consequences are in accordance with the level of consequence analysis; see Part 3, Section 4.8 for Level 1 analysis and Part 3, Section 5.8.9 for Level 2 COF analysis.

4.14 Determine Toxic Consequences for Storage Tank Courses

4.14.1 General

Toxic consequences for storage tank courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

4.14.2 Calculation of Toxic Consequences for Storage Tank Courses

The step-by-step methodology for determining the toxic consequences are in accordance with the Level 1 and 2 consequence analysis; see Part 3, Section 4.9 and Part 3, Section 5.9.8.

4.15 Determine Nonflammable, Nontoxic Consequences

Nonflammable, nontoxic consequences are not determined for storage tanks.

4.16 Determine Component Damage and Personnel Injury Consequences for Storage Tank Courses

4.16.1 General

Flammable and explosive consequences for storage tank courses are determined using a similar approach as implemented for Level 1 and 2 consequence analysis.

4.16.2 Calculation for Component Damage and Personnel Injury Consequences

The step-by-step procedure for determining the flammable and explosive consequences are in accordance with the Level 1 COF in Part 3, Section 4.8 and Level 2 COF in Part 3, Section 5.11.5.

4.17 Determine the Financial Consequences

4.17.1 General

The financial consequence is determined in accordance with the Level 1 COF in Part 3, Section 4.12.

4.17.2 Calculation of Storage Tank Course Financial Consequence

The step-by-step procedure for estimating the financial consequence is in accordance with Section 4.12.7, except when calculating the environmental financial consequence. The storage tank course financial consequence can be calculated following the approach in sections defined below using the hole sizes defined in Table 4.8.

— Component damage cost in accordance with Section 4.12.2.

— Damage cost to surrounding equipment in accordance with Section 4.12.3.

— Business interruption costs in accordance with Section 4.12.4.

— Potential injury costs in accordance with Section 4.12.5.

The storage tank environmental financial consequence for courses is calculated following the steps provided below.

a) Step 6.1—Determine the following parameters.

1) P_{lvdike}—percentage of fluid leaving the dike.

2) P_{onsite}—percentage of fluid that leaves the dike area but remains on-site.

3) P_{offsite}—percentage of fluid that leaves the dike area but does not enter nearby water.

b) Step 6.2—Determine the environmental sensitivity used to establish C_{indike}, $C_{\text{ss-onsite}}$, $C_{\text{ss-offsite}}$, and C_{water} from Table 4.6.

c) Step 6.3—Determine the probability weighted total barrels of fluid released by leakage, $Bbl_{\text{release}}^{\text{leak}}$.

$$Bbl_{\text{release}}^{\text{leak}} = \frac{\sum_{n=1}^{3}\left(Bbl_n^{\text{leak}} \cdot gff_n\right)}{gff_{\text{total}}} \tag{5.19}$$

d) Step 6.4—Calculate the total barrels of fluid within the dike from leakage, $Bbl_{\text{indike}}^{\text{leak}}$, the total barrels of fluid in the on-site surface soil, $Bbl_{\text{ss-onsite}}^{\text{leak}}$, the total barrels of fluid in the off-site surface soil, $Bbl_{\text{ss-offsite}}^{\text{leak}}$, and the total barrels of fluid that reach water, $Bbl_{\text{water}}^{\text{leak}}$, using Equation (5.20) through Equation (5.23), respectively.

$$Bbl_{\text{indike}}^{\text{leak}} = Bbl_{\text{release}}^{\text{leak}}\left(1 - \frac{P_{\text{lvdike}}}{100}\right) \tag{5.20}$$

$$Bbl_{\text{ss-onsite}}^{\text{leak}} = \frac{P_{\text{onsite}}}{100}\left(Bbl_{\text{release}}^{\text{leak}} - Bbl_{\text{indike}}^{\text{leak}}\right) \tag{5.21}$$

$$Bbl_{\text{ss-offsite}}^{\text{leak}} = \frac{P_{\text{offsite}}}{100}\left(Bbl_{\text{release}}^{\text{leak}} - Bbl_{\text{indike}}^{\text{leak}} - Bbl_{\text{ss-onsite}}^{\text{leak}}\right) \tag{5.22}$$

$$Bbl_{\text{water}}^{\text{leak}} = Bbl_{\text{release}}^{\text{leak}} - \left(Bbl_{\text{indike}}^{\text{leak}} + Bbl_{\text{ss-onsite}}^{\text{leak}} + Bbl_{\text{ss-offsite}}^{\text{leak}}\right) \tag{5.23}$$

e) Step 6.5—Calculate the financial environmental cost from leakage, $FC_{\text{environ}}^{\text{leakage}}$.

$$FC_{\text{environ}}^{\text{leak}} = Bbl_{\text{indike}}^{\text{leak}} \cdot C_{\text{indike}} + Bbl_{\text{ss-onsite}}^{\text{leak}} \cdot C_{\text{ss-onite}} + Bbl_{\text{ss-offsite}}^{\text{leak}} \cdot C_{\text{ss-offite}} + Bbl_{\text{water}}^{\text{leak}} \cdot C_{\text{water}} \tag{5.24}$$

f) Step 6.6—Determine the total barrels of fluid released by a course rupture, $Bbl_{\text{release}}^{\text{rupture}}$.

$$Bbl_{\text{release}}^{\text{rupture}} = \frac{Bbl_n^{\text{rupture}} \cdot gff_4}{gff_{\text{total}}} \tag{5.25}$$

g) Step 6.7—Calculate the total barrels of fluid within the dike from a rupture, $Bbl_{\text{indike}}^{\text{rupture}}$, the total barrels of fluid in the on-site surface soil, $Bbl_{\text{ss-onsite}}^{\text{rupture}}$, the total barrels of fluid in the off-site surface soil, $Bbl_{\text{ss-offsite}}^{\text{rupture}}$, and the total barrels of fluid that reach water, $Bbl_{\text{water}}^{\text{leak}}$, using Equation (5.26) through Equation (5.29), respectively.

$$Bbl_{\text{indike}}^{\text{rupture}} = Bbl_{\text{release}}^{\text{rupture}} \left(1 - \frac{P_{\text{lvdike}}}{100}\right) \tag{5.26}$$

$$Bbl_{\text{ss-onsite}}^{\text{rupture}} = \frac{P_{\text{onsite}}}{100}\left(Bbl_{\text{release}}^{\text{rupture}} - Bbl_{\text{indike}}^{\text{rupture}}\right) \tag{5.27}$$

$$Bbl_{\text{ss-offsite}}^{\text{rupture}} = \frac{P_{\text{offsite}}}{100}\left(Bbl_{\text{release}}^{\text{rupture}} - Bbl_{\text{indike}}^{\text{rupture}} - Bbl_{\text{ss-onsite}}^{\text{rupture}}\right) \tag{5.28}$$

$$Bbl_{\text{water}}^{\text{rupture}} = Bbl_{\text{release}}^{\text{rupture}} - \left(Bbl_{\text{indike}}^{\text{rupture}} + Bbl_{\text{ss-onsite}}^{\text{rupture}} + Bbl_{\text{ss-offsite}}^{\text{rupture}}\right) \tag{5.29}$$

h) Step 6.8—Calculate the financial environmental cost for a course rupture, $FC_{\text{environ}}^{\text{rupture}}$.

$$FC_{\text{environ}}^{\text{rupture}} = Bbl_{\text{indike}}^{\text{rupture}} \cdot C_{\text{indike}} + Bbl_{\text{ss-onsite}}^{\text{rupture}} \cdot C_{\text{ss-onite}} + Bbl_{\text{ss-offsite}}^{\text{rupture}} \cdot C_{\text{ss-offite}} + Bbl_{\text{water}}^{\text{rupture}} \cdot C_{\text{water}} \tag{5.30}$$

i) Step 6.9—Calculate the total financial environmental cost from a leak and a rupture, FC_{environ}, where $FC_{\text{environ}}^{\text{leak}}$ is from Step 12.5 and $FC_{\text{environ}}^{\text{rupture}}$ is from Step 12.8.

$$FC_{\text{environ}} = FC_{\text{environ}}^{\text{leak}} + FC_{\text{environ}}^{\text{rupture}} \tag{5.31}$$

j) Step 6.10—Calculate the total financial COF, FC_{total}, using Equation (5.32).

$$FC_{\text{total}} = FC_{\text{environ}} + FC_{\text{cmd}} + FC_{\text{prod}} + FC_{\text{affa}} + FC_{\text{inj}} \tag{5.32}$$

4.18 Determination of Safety Consequences

Safety consequences, SC_{f}, for storage tank courses are calculated the approach outlined in Part 3, Section 5.13. The injury area, CA_{inj}, for a course release is outlined in Section 3.15.1.

4.19 COF Methodology for Storage Tank Bottoms

4.19.1 General

The COF associated with storage tanks is concerned primarily with the financial losses due to loss of containment and leakage through the storage tank bottoms. Area-based consequences are not calculated for storage tank bottoms. Detailed procedures for calculating the financial COF for bottom plates are provided in this section.

The procedure for determining the COF for storage tank bottom components consists of calculations for financial COF based on environmental consequences, component damage cost, and business interruption cost. storage tank consequence analysis for flammable and/or explosive or toxic are not calculated for storage tank bottoms.

4.19.2 Required Properties at Storage Conditions

The tank bottom financial COF is calculated using one of the following approaches.

a) Select the representative fluid from Table 4.5 that most closely matches the stored fluid.

b) Determine the dynamic viscosity and density of the stored fluid.

4.19.3 Hydraulic Conductivity for Storage Tank Bottom

The amount and rate of leakage from storage tank bottoms is dependent on the type of soil and its properties as well as whether or not the storage tank bottom has an RBP. A list of soil types and properties used in the storage tank consequence analysis routine is shown in Table 4.7.

The fundamental soil property required in the analysis is the soil hydraulic conductivity, k_{h}. The hydraulic conductivity as a function of soil type is provided in Table 4.7 based on water. The hydraulic conductivity for other fluids can be estimated based on the hydraulic conductivity, density, and dynamic viscosity of water, denoted as $k_{\text{h,water}}$, ρ_{w}, and μ_{w}, respectively, and the density and dynamic viscosity of the actual fluid using Equation (5.33).

$$k_{\text{h,prod}} = k_{\text{h,water}} \left(\frac{\rho_{\text{l}}}{\rho_{\text{w}}} \right) \left(\frac{\mu_{\text{w}}}{\mu_{\text{l}}} \right) \tag{5.33}$$

4.19.4 Fluid Seepage Velocity for Storage Tank Bottom

The seepage velocity of the fluid in the storage tank bottom or product through the soil is given by Equation (5.34), where k_{h} is the soil hydraulic conductivity and p_{s} is the soil porosity.

$$vel_{\text{s,prod}} = \frac{k_{\text{h,prod}}}{p_{\text{s}}} \tag{5.34}$$

4.19.5 Calculation of Fluid Seepage Velocity for Storage Tank Bottom

a) Step 7.1—Determine properties including density, ρ_{l}, and dynamic viscosity, μ_{l}, of the stored fluid. If a Level 1 analysis is being performed, select the representative fluid properties from Table 4.5.

b) Step 7.2—Calculate the hydraulic conductivity for water by averaging the upper and lower bound hydraulic conductivities provided in Table 4.7 for the soil type selected using Equation (5.35).

$$k_{\text{h,water}} = C_{31} \frac{\left(k_{\text{h,water-lb}} + k_{\text{h,water-ub}} \right)}{2} \tag{5.35}$$

c) Step 7.3—Calculate the fluid hydraulic conductivity, $k_{\text{h,prod}}$, for the fluid stored in the storage tank using Equation (5.33) based on the density, ρ_{l}, and dynamic viscosity, μ_{l}, from Step 7.1 and the hydraulic conductivity for water, $k_{\text{h,water}}$, from Step 7.2.

d) Step 7.4—Calculate the product seepage velocity, $vel_{\text{s,prod}}$, for the fluid stored in the storage tank using Equation (5.34) based on fluid hydraulic conductivity, $k_{\text{h,prod}}$, from Step 7.3 and the soil porosity provided in Table 4.7.

4.20 Release Hole Size Selection

4.20.1 General

A discrete set of release events or release hole sizes are used for consequence analysis as outlined in Table 4.8.

4.20.2 Calculation of Release Hole Sizes

The following procedure may be used to determine the release hole size and the associated GFFs.

a) Step 8.1—Determine the release hole size, d_n, from Table 4.8 for storage tank bottoms.

b) Step 8.2—Determine the generic failure frequency, gff_n, for the d_n release hole size and the total generic failure frequency from Part 2, Table 3.1 or from Equation (5.36).

$$gff_{\text{total}} = \sum_{n=1}^{4} gff_n \tag{5.36}$$

4.21 Release Rate Calculation

4.21.1 General

Release rate calculations are provided for a leak in a storage tank bottom plate. The liquid head is assumed to be constant in time, and the leak is into the ground that is modeled as a continuous porous media approximated by soil properties typically used for storage tank foundations.

4.21.2 Storage Tank Bottom Release Rate

The product leakage flow rate through a small hole in the storage tank bottom is a function of the soil and fluid properties as well as the liquid head (fill height) above the bottom. The flow rate equations can be found in Rowe [3]. The flow rate through a storage tank bottom into a porous media is calculated using the Bernoulli in Equation (5.37), Giroud in Equation (5.38), or Equation (5.39) based on the hydraulic conductivity, $k_{\text{h,prod}}$, and release hole size, d_n.

$$W_n = C_{33} \cdot \pi \cdot d_n^2 \sqrt{2 \cdot g \cdot h_{\text{liq}}} \cdot n_{\text{rh},n} \qquad \text{for } k_{\text{h,prod}} > C_{34} \cdot d_n^2 \tag{5.37}$$

$$W_n = C_{35} \cdot C_{\text{qo}} \cdot d_n^{0.2} \cdot h_{\text{liq}}^{0.9} \cdot k_{\text{h,prod}}^{0.74} \cdot n_{\text{rh},n} \qquad \text{for } k_{\text{h,prod}} \le C_{37} \cdot \left[\frac{d_n^{1.8}}{C_{\text{qo}} \cdot h_{\text{liq}}^{0.4}} \right]^{\frac{1}{0.74}} \tag{5.38}$$

$$W_n = C_{38} \cdot 10^{2 \cdot \log\left(d_n\right) + 0.5 \cdot \log\left(h_{\text{liq}}\right) - 0.74 \cdot \left(\frac{C_{39} + 2 \cdot \log\left(d_n\right) - \log\left(k_{\text{h,prod}}\right)}{m} \right)^m} \cdot n_{\text{rh},n} \qquad \text{for all other cases} \tag{5.39}$$

where

$$m = C_{40} - 0.4324 \cdot \log\left(d_n\right) + 0.5405 \cdot \log\left(h_{\text{liq}}\right).$$

In Equation (5.38), the parameter C_{qo} is an adjustment factor for degree of contact with soil and ranges from $C_{qo} = 0.21$ for good contact to $C_{qo} = 1.15$ for poor contact. A value of $C_{qo} = 0.21$ is recommended in the consequence analysis.

If the storage tank bottom has an RBP, then the liquid height, h_{liq}, to be used in the flow rate calculations is set to 0.25 ft (0.0762 m). If the storage tank does not have an RPB, the liquid height, h_{liq}, to be used in the flow rate calculations is the actual height of the stored product.

The number of release holes, $n_{rh,n}$, for each release hole size is a function of the storage tank diameter and is shown in Table 4.9.

4.21.3 Calculation for Storage Tank Bottom Release Hole Size

a) Step 9.1—For each release hole size, determine the number of release holes, $n_{rh,n}$, from Table 4.9.

b) Step 9.2—Determine the hole area, A_n, for each hole size from Step 8.1 using Equation (5.6).

c) Step 9.3—Determine the hydraulic conductivity of the stored liquid, $k_{h,prod}$, from Step 1.4.

d) Step 9.4—For each release hole size, determine the flow rate, W_n, using Equation (5.37), Equation (5.38), or Equation (5.39), as applicable. The liquid height, h_{liq}, to use in this calculation is determined as follows.

   1) The storage tank has an RPB: $h_{liq} = 0.25 \text{ ft } (0.0762 \text{ m})$.

   2) The storage tank does not have an RPB: $h_{liq} = Actual\ Product\ Height$.

4.22 Inventory Volume and Mass Available for Release

4.22.1 General

The amount of inventory in the storage tank available for release depends on the component being evaluated. The available inventory is the entire contents of the storage tank for bottom components unless the tank has an RPB.

4.22.2 Calculation of Storage Tank Bottom Inventory Mass

The amount of fluid available for release through storage tank bottoms is the fluid level up to the storage tank design fill height or the operating fill height.

a) Step 10.1—Calculate liquid volume in the storage tank in ft^3 (m^3) using Equation (5.40).

$$Lvol_{total} = \left(\frac{\pi D_{tank}^2}{4}\right) \cdot h_{liq} \tag{5.40}$$

b) Step 10.2—Calculate the total storage tank volume in barrels using Equation (5.41).

$$Bbl_{total} = Lvol_{total} \cdot C_{13} \tag{5.41}$$

c) Step 10.3—Calculate the storage tank mass using Equation (5.42).

$$mass_{total} = Lvol_{total} \cdot \rho_l \tag{5.42}$$

4.23 Type of Release

The type of release for the storage tank bottom is assumed to be continuous.

4.24 Impact of Detection and Isolation Systems on Release Magnitude

Detection and isolation systems are not accounted for in the storage tank consequence analysis.

4.25 Release Rate and Volume for the COF Analysis

4.25.1 General

The release for the storage tank is assumed to be continuous, and the release rate is calculated from Equation (5.43) where W_n is determined in Step 9.4.

$$rate_n = W_n \tag{5.43}$$

4.25.2 Storage Tank Bottom Release Volume

A step-by-step procedure for determining the release rate and volume is as follows.

a) Step 11.1—Determine the release rate, $rate_n$, for each release hole size using Equation (5.43) where the release rate, W_n, is from Step 9.4.

b) Step 11.2—Determine the leak detection time, t_{ld}, as follows:

   1) t_{ld} = 7 days for a storage tank on a concrete or asphalt foundation, or

   2) t_{ld} = 30 days for a storage tank with an RPB, or

   3) t_{ld} = 360 days for a storage tank without an RPB.

c) Step 11.3—Calculate the leak duration, ld_n, for each release hole size using Equation (5.44) based on the release rate, $rate_n$, from Step 11.1, the leak detection time, t_{ld}, from Step 11.2, and the total volume, Bbl_{total}, from Step 10.2

$$ld_n = \min\left[\left\{\frac{Bbl_{\text{total}}}{rate_n}\right\},\ t_{\text{ld}}\right] \tag{5.44}$$

d) Step 11.4—Calculate the release volume from leakage, Bbl_n^{leak}, for each release hole size using Equation (5.45) based on the release rate, $rate_n$, from Step 11.1, the leak duration, ld_n, from Step 11.3, and the total volume, Bbl_{total}, from Step 10.2.

$$Bbl_n^{\text{leak}} = \min\left[\left\{rate_n \cdot ld_n\right\},\ Bbl_{\text{total}}\right] \tag{5.45}$$

e) Step 11.5—Calculate the release volume from a rupture, Bbl_n^{rupture}, for each release hole size using Equation (5.46) based on the total volume, Bbl_{total}, from Step 10.2.

$$Bbl_n^{\text{rupture}} = Bbl_{\text{total}} \tag{5.46}$$

4.26 Determine the Financial Consequences

4.26.1 General

The step-by-step procedure for estimating the financial consequence is in accordance with Section 4.12.7. The financial consequences for the storage tank bottom are calculated with the steps provided below.

— Damage cost to surrounding equipment in accordance with Section 4.12.3 is not applicable for storage tank bottom component.

— Business interruption costs in accordance with Section 4.12.4.

— Potential Injury costs in accordance to Section 4.12.5 is not applicable for storage tank bottom component.

4.26.2 Calculation of Storage Tank Bottom Financial Consequence

The step-by-step procedure for determining financial COF is as follows.

a) Step 12.1—Determine the following parameters.

   1) P_{lvdike} —percentage of fluid leaving the dike.

   2) $P_{\text{lvdike-onsite}}$ —percentage of fluid that leaves the dike area but remains on-site.

   3) $P_{\text{lvdike-offsite}}$ —percentage of fluid that leaves the site area, but does not enter nearby water.

   4) The storage tank environmental financial consequence for the bottom can be calculated following the steps provided below.

b) Step 12.2—Determine the environmental sensitivity to establish C_{indike}, $C_{\text{ss-onsite}}$, $C_{\text{ss-offsite}}$, C_{water}, C_{subsoil}, and $C_{\text{groundwater}}$ from Table 4.6.

c) Step 12.3—Determine the seepage velocity of the product, $vel_{\text{s-prod}}$, using Equation (5.34).

d) Step 12.4—Determine the total distance to the groundwater underneath the storage tank, s_{gw}, and the time to initiate leakage to the groundwater, t_{gl}.

$$t_{\text{gl}} = \frac{s_{\text{gw}}}{vel_{\text{s,prod}}} \tag{5.47}$$

e) Step 12.5—Determine the volume of the product for each hole size in the subsoil and groundwater where the leak detection time, t_{ld}, is determined in Step 11.2.

$$Bbl^{\text{leak}}_{\text{groundwater},n} = Bbl^{\text{leak}}_{n}\left(\frac{t_{\text{ld}} - t_{\text{gl}}}{t_{\text{ld}}}\right) \qquad \text{for } t_{\text{gl}} < t_{\text{ld}} \tag{5.48}$$

$$Bbl^{\text{leak}}_{\text{groundwater},n} = 0 \qquad \text{for } t_{\text{gl}} \geq t_{\text{ld}} \tag{5.49}$$

$$Bbl^{\text{leak}}_{\text{subsoil},n} = Bbl^{\text{leak}}_{n} - Bbl^{\text{leak}}_{\text{groundwater},n} \tag{5.50}$$

f) Step 12.6—Determine the environmental financial consequence of a leak, $FC^{\text{leak}}_{\text{environ}}$, for each hole size.

$$FC^{\text{leak}}_{\text{environ}} = \frac{\sum_{n=1}^{3}\left(Bbl^{\text{leak}}_{\text{groundwater},n} \cdot C_{\text{groundwater}} + Bbl^{\text{leak}}_{\text{subsoil},n} \cdot C_{\text{subsoil}}\right) gff_n}{gff_{\text{total}}} \tag{5.51}$$

g) Step 12.7—Determine the total barrels of fluid released by a storage tank bottom rupture, $Bbl^{\text{rupture}}_{\text{release}}$.

$$Bbl^{\text{rupture}}_{\text{release}} = \frac{Bbl_{\text{total}} \cdot gff_4}{gff_{\text{total}}} \tag{5.52}$$

h) Step 12.8—Calculate the total barrels of fluid within the dike from a rupture, $Bbl^{\text{rupture}}_{\text{indike}}$, the total barrels of fluid in the on-site surface soil, $Bbl^{\text{rupture}}_{\text{ss-onsite}}$, the total barrels of fluid in the off-site surface soil, $Bbl^{\text{rupture}}_{\text{ss-offsite}}$, and the total barrels of fluid that reach water, $Bbl^{\text{leak}}_{\text{water}}$, using Equation (5.26) through Equation (5.29), respectively.

i) Step 12.9—Calculate the financial environmental cost for a storage tank bottom rupture, $FC^{\text{rupture}}_{\text{environ}}$, using Equation (5.30) where $Bbl^{\text{rupture}}_{\text{indike}}$, $Bbl^{\text{rupture}}_{\text{ss-onsite}}$, $Bbl^{\text{rupture}}_{\text{ss-offsite}}$, and $Bbl^{\text{leak}}_{\text{water}}$ are from Step 12.8.

j) Step 12.10—Calculate the total financial environmental cost from a leak and a rupture, FC_{environ}, using Equation (5.51) where $FC^{\text{leak}}_{\text{environ}}$ is from Step 12.6 and $FC^{\text{rupture}}_{\text{environ}}$ is from Step 12.9.

k) Step 12.11—Calculate the component damage cost, FC_{cmd}, using Equation (5.53) with the release hole size damage costs from Part 3, Table 4.15 and GFFs for the release hole sizes from Step 2.3. The material cost factor, *matcost*, is obtained from Part 3, Table 4.16.

$$FC_{\text{cmd}} = \left(\frac{\sum_{n=1}^{3} gff_n \cdot holecost_n + gff_4 \cdot holecost_4 \cdot \left(\frac{D_{\text{tank}}}{C_{36}}\right)^2}{gff_{\text{total}}}\right) \cdot matcost \tag{5.53}$$

The parameter, $\left(\frac{D_{\text{tank}}}{C_{36}}\right)^2$, is a cost adjustment factor for a storage tank bottom replacement. The cost factor included in Part 3, Table 4.15 is normalized for a storage tank with a diameter of 100 ft (30.5 m), and this factor corrects the cost for other storage tank diameters.

l) Step 12.12—Calculate the total financial COF, FC_{total}, using Equation (5.54).

$$FC_{\text{total}} = FC_{\text{environ}} + FC_{\text{cmd}} + FC_{\text{prod}} \tag{5.54}$$

4.27 Nomenclature

The following lists the nomenclature used in Section 2. The coefficients C_1 through C_{36}, which provide the metric and U.S conversion factors for the equations, are provided in Part 3, Annex 3.B.

A_n	is the hole area associated with the n^{th} release hole size, in.^{2} (mm^2)
A_{rt}	is the component wall loss fraction since last inspection thickness measurement or service start date
age	is the in-service time that the damage is applied, years
$age_{f,rc}$	is the final remaining life of the internal liner after adjusting for liner age factors, years
age_{rc}	is the remaining life of the internal liner associated with the date of the starting thickness, years
age_{tk}	is the component in-service time since the last inspection thickness measurement or service start date, years
$Bbl_{avail,n}$	is the available product volume for the n^{th} release hole size due to a leak, barrels
$Bbl_{groundwater}^{leak}$	is the total product volume in the groundwater due to a leak, barrels
$Bbl_{groundwater,n}^{leak}$	is the product volume for the n^{th} release hole size due to a leak in the groundwater, barrels
Bbl_{indike}^{leak}	is the total product volume in the dike due to a leak, barrels
$Bbl_{indike}^{rupture}$	is the product volume in the dike due to a rupture, barrels
Bbl_{n}^{leak}	is the product volume for the n^{th} release hole size due to a leak, barrels
$Bbl_{n}^{rupture}$	is the product volume for the n^{th} release hole size due to a rupture, barrels
$Bbl_{release}^{leak}$	is the total product volume released due to a leak, barrels
$Bbl_{release}^{rupture}$	is the product volume in released due to a rupture, barrels
$Bbl_{ss\text{-}offsite}^{leak}$	is the total product volume released on the surface located off-site due to a leak, barrels
$Bbl_{ss\text{-}offsite}^{rupture}$	is the product volume on the surface located off-site due to a rupture, barrels
$Bbl_{ss\text{-}onsite}^{leak}$	is the total product volume released on the surface located on-site due to a leak, barrels
$Bbl_{ss\text{-}onsite}^{rupture}$	is the product volume on the surface located on-site due to a rupture, barrels

$Bbl_{\text{subsoil}}^{\text{leak}}$	is the total product volume in the subsoil due to a leak, barrels
$Bbl_{\text{subsoil},n}^{\text{leak}}$	is the product volume for the n^{th} release hole size due to a leak in the subsoil, barrels
Bbl_{total}	is the product volume in the storage tank, barrels
$Bbl_{\text{water}}^{\text{leak}}$	is the total product volume in the water due to a leak, barrels
$Bbl_{\text{water}}^{\text{rupture}}$	is the total product volume in the water due to a rupture, barrels
CHT	is the course height of the storage tank, ft (m)
C_{d}	is the discharge coefficient
C_{indike}	is the environmental cost for product in the dike area, \$/bbl
$C_{\text{groundwater}}$	is the environmental cost for product in the groundwater, \$/bbl
C_{subsoil}	is the environmental cost for product in the subsoil, \$/bbl
$C_{\text{ss-offsite}}$	is the environmental cost for product on the surface located off-site, \$/bbl
$C_{\text{ss-onsite}}$	is the environmental cost for product on the surface located on-site, \$/bbl
C_{water}	is the environmental cost for product in water, \$/bbl
C_{qo}	is the adjustment factor for degree of contact with soil
$C_{\text{r,bm}}$	is the corrosion rate for the base material, in./yr (mm/yr)
CA	is the corrosion allowance, in. (mm)
$D_{\text{f}}^{\text{Tank,Thin}}$	is the DF for thinning
$D_{\text{fB}}^{\text{Thin}}$	is the base value of the DF for thinning
D_{tank}	is the storage tank diameter, ft (m)
d_n	is the diameter of the n^{th} release hole, in. (mm)
E	is the weld joint efficiency or quality code from the original construction code
F_{AM}	is the DF adjustment for AST maintenance per API 653
F_{LC}	is the DF adjustment for lining condition
F_{OM}	is the DF adjustment for online monitoring
F_{SM}	is the DF adjustment for settlement
F_{WD}	is the DF adjustment for welded construction

FC_{affa}	is the financial consequence because of damage to the 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 because of serious personnel injury, $
$FC_{\text{environ}}^{\text{leak}}$	is the financial consequence of environmental cleanup for leakage, $
$FC_{\text{environ}}^{\text{rupture}}$	is the financial consequence of environmental cleanup for leakage, $
FC_{prod}	is the financial consequence of lost production on the unit, $
FC_{total}	is the total financial consequence, $
g	is the acceleration due to gravity on earth at sea level = 32.2 ft/s^2 (9.81 m/s^2)
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_{liq}	is the maximum fill height in the storage tank, ft (m)
k_{h}	is the soil hydraulic conductivity, ft/day (m/day)
$k_{\text{h,prod}}$	is the soil hydraulic conductivity based on the storage tank product, ft/day (m/day)
$k_{\text{h,water}}$	is the soil hydraulic conductivity based on water, ft/day (m/day)
$k_{\text{h,water-lb}}$	is the lower bound soil hydraulic conductivity based on water, in./s (cm/s)
$k_{\text{h,water-ub}}$	is the upper bound soil hydraulic conductivity based on water, in./s (cm/s)
$LHT_{\text{above},i}$	is the liquid height above the i^{th} storage tank course, ft (m)
$Lvol_{\text{above},i}$	is the total liquid volume above the i^{th} storage tank course, ft^3 (m^3)
$Lvol_{\text{above},n}$	is the total liquid volume for the n^{th} release hole size, ft^3 (m^3)
$Lvol_{\text{total}}$	is the total liquid volume in the storage tank, ft^3 (m^3)
ld_n	is the actual leak duration of the release based on the available mass and the calculated release rate, associated with the n^{th} release hole size, day
$mass_{\text{avail},n}$	is the available mass for release for each of the release hole sizes selected, associated with the n^{th} release hole size, lb (kg)
$mass_n^{\text{leak}}$	is the release mass from leakage associated with the n^{th} hole size, bbl/day
$mass_n^{\text{rupture}}$	is the release mass from a rupture associated with the n^{th} hole size, bbl/day
$mass_{\text{total}}$	is the available mass for release, barrels
$matcost$	is the material cost factor
$N_{\text{A}}^{\text{Thin}}$	is the number of A level inspections

N_{B}^{Thin}	is the number of B level inspections
N_{C}^{Thin}	is the number of C level inspections
N_{D}^{Thin}	is the number of D level inspections
n^{th}	is the representative holes sizes
$n_{rh,n}$	is the number of release holes for each release hole size as a function of the storage tank diameter
P_{lvdike}	is the percentage of fluid leaving the dike
$P_{offsite}$	is the percentage of fluid that leaves the dike area, remains off-site, and remains out of nearby water
P_{onsite}	is the percentage of fluid that leaves the dike area but remains on-site
p_{s}	is the soil porosity
$rate_{n}$	is the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, bbl/day
S	is the allowable stress, psi (MPa)
s_{gw}	is the distance to the groundwater underneath the storage tank, ft (m)
t	is the furnished thickness of the component calculated as the sum of the base material and cladding/weld overlay thickness, as applicable, in. (mm)
t_{gl}	is the time required for the product to reach the groundwater through a leak in the storage tank bottom, days
t_{ld}	is the leak detection time, days
t_{min}	is the minimum required thickness based on the applicable construction code, in. (mm)
t_{rdi}	the furnished thickness, t, or measured thickness reading from previous inspection, only if there is a high level of confidence in its accuracy, with respect to wall loss associated with internal corrosion, in. (mm)
$vel_{s,prod}$	is the seepage velocity, ft/day (m/day)
W_{n}	is the discharge rate of the storage tank product through a hole in the course, bbl/day
μ_{l}	is the dynamic viscosity, (lbf-s)/ft^2 [(N-s)/m^2]
μ_{w}	is the dynamic viscosity of water at storage or normal operating, (lbf-s)/ft^2 [(N-s)/m^2)]
ρ_{l}	is the liquid density at storage or normal operating conditions, lb/ft^3 (kg/m^3)
ρ_{w}	is the density of water at storage or normal operating conditions, lb/ft^3 (kg/m^3)

4.28 Tables

Table 4.1—Internal Liner Types

Internal Liner	Lining Resistance	Expected Age
Alloy strip liner	Subject to failure at seams	5 to 15 years
Organic coating—low-quality immersion grade coating (spray applied, to 40 mils)	Limited life	1 to 3 years
Organic coating—medium-quality immersion grade coating (filled, trowel applied, to 80 mils)	Limited life	3 to 5 years
Organic coating—high-quality immersion grade coating (reinforced, trowel applied, ≥ 80 mils)	Limited life	5 to 10 years
Thermal resistance service: castable refractory plastic refractory refractory brick ceramic fiber refractory refractory/alloy combination	Subject to occasional spalling or collapse	1 to 5 years
Thermal resistance service: castable refractory ceramic tile	Limited life in highly abrasive service	1 to 5 years
Glass liners	Complete protection, subject to failure due to thermal or mechanical shock	5 to 10 years
Acid brick	Partial protection. The brick provides thermal protection but is not intended to keep the fluid away from the base material.	10 to 20 years

Table 4.2—Lining Condition Adjustment

Qualitative Condition	Description	Adjustment Multiplier, F_{LC}
Poor	The lining has either had previous failures or exhibits conditions that may lead to failure in the near future. Repairs to previous failures are not successful or are of poor quality.	3
Average	The lining is not showing signs of excessive attack by any damage mechanisms. Local repairs may have been performed, but they are of good quality and have successfully corrected the lining condition.	2
Good	The lining is in “like new” condition with no signs of attack by any damage mechanisms. There has been no need for any repairs to the lining.	1

Table 4.3—Thinning DFs for Storage Tank Bottom Components

A_{rt}	Inspection Effectiveness				
	E	1 Inspection			
		D	C	B	A
0.00	0.1	0.1	0.1	0.1	0.1
0.05	4	1	0.5	0.4	0.3
0.10	14	3	1	0.7	0.5
0.15	32	8	2	1	0.7
0.20	56	18	6	2	1
0.25	87	32	11	4	3
0.30	125	53	21	9	6
0.35	170	80	36	16	12
0.40	222	115	57	29	21
0.45	281	158	86	47	36
0.50	347	211	124	73	58
0.55	420	273	173	109	89
0.60	500	346	234	158	133
0.65	587	430	309	222	192
0.70	681	527	401	305	270
0.75	782	635	510	409	370
0.80	890	757	638	538	498
0.85	1005	893	789	696	658
0.90	1126	1044	963	888	856
0.95	1255	1209	1163	1118	1098
1.00	1390	1390	1390	1390	1390

Table 4.4—Release Hole Sizes and Areas—Storage Tank Courses

Release Hole Number	Release Hole Size	Range of Hole Diameters (in.)	Release Hole Diameter (in.)
1	Small	0 to $^1/_8$	$d_1 = 0.125$
2	Medium	$>$ $^1/_8$ to $^1/_4$	$d_2 = 0.25$
3	Large	$>$ $^1/_4$ to 2	$d_3 = 2$
4	Rupture	> 2	$d_4 = 12\left(\frac{D_{tank}}{4}\right)$

Table 4.4M—Release Hole Sizes and Areas—Storage Tank Courses

Release Hole Number	Release Hole Size	Range of Hole Diameters (mm)	Release Hole Diameter (mm)
1	Small	0 to 3.175	$d_1 = 3.175$
2	Medium	$>$ 3.175 to 6.35	$d_2 = 6.35$
3	Large	$>$ 6.35 to 50.8	$d_3 = 50.8$
4	Rupture	> 50.8	$d_4 = 1000\left(\frac{D_{tank}}{4}\right)$

Table 4.5—Fluids and Fluid Properties for Storage Tank Consequence Analysis

Fluid	Level 1 Consequence Analysis Representative Fluid	MW	Liquid Density (lb/ft^3)	Liquid Dynamic Viscosity ($lbf\text{-}s/ft^2$)
Gasoline	C_6–C_8	100	42.702	8.383E-05
Light diesel oil	C_9–C_{12}	149	45.823	2.169E-05
Heavy diesel oil	C_{13}–C_{16}	205	47.728	5.129E-05
Fuel oil	C_{17}–C_{25}	280	48.383	7.706E-04
Crude oil	C_{17}–C_{25}	280	48.383	7.706E-04
Heavy fuel oil	C_{25+}	422	56.187	9.600E-04
Heavy crude oil	C_{25+}	422	56.187	9.600E-04

Table 4.5M—Fluids and Fluid Properties for Storage Tank Consequence Analysis

Fluid	Level 1 Consequence Analysis Representative Fluid	MW	Liquid Density (kg/m^3)	Liquid Dynamic Viscosity ($N\text{-}s/m^2$)
Gasoline	C_6–C_8	100	684.018	4.01E-03
Light diesel oil	C_9–C_{12}	149	734.011	1.04E-03
Heavy diesel oil	C_{13}–C_{16}	205	764.527	2.46E-03
Fuel oil	C_{17}–C_{25}	280	775.019	3.69E-02
Crude oil	C_{17}–C_{25}	280	775.019	3.69E-02
Heavy fuel oil	C_{25+}	422	900.026	4.60E-02
Heavy crude oil	C_{25+}	422	900.026	4.60E-02

Table 4.6—Cost Parameters Based on Environmental Sensitivity

Location [1]	Description	Environmental Sensitivity		
		Low (US$/bbl)	**Medium** (US$/bbl)	**High** (US$/bbl)
1	C_{indike} —Environmental cost for product located in the dike area	10	10	10
2	$C_{ss\text{-}onsite}$ —Environmental cost for product located in surface soil located on-site	50	50	50
3	$C_{ss\text{-}offsite}$ —Environmental cost for product located in surface soil located off-site	100	250	500
4	$C_{subsoil}$ —Environmental cost for product located in subsoil	500	1,500	3,000
5	$C_{groundwater}$ —Environmental cost for product located in groundwater	1,000	5,000	10,000
6	C_{water} —Environmental cost for product in surface water	500	1,500	5,000

NOTE 1 See Figure 4.1.

NOTE 2 The values shown above are estimates. The end user should decide if these values are appropriate for the specific application.

Table 4.7—Soil Types and Properties for Storage Tank Consequence Analysis

Soil Type	Hydraulic Conductivity for Water Lower Bound (in./s)	Hydraulic Conductivity for Water Upper Bound (in./s)	Soil Porosity
Gravel	3.94E-01	3.94	0.40
Coarse sand	3.94E-03	3.94E-02	0.33
Fine sand	3.94E-04	3.94E-03	0.33
Very fine sand	3.94E-06	3.94E-04	0.33
Silt	3.94E-07	3.94E-06	0.41
Sandy clay	3.94E-08	3.94E-07	0.45
Clay	3.94E-09	3.94E-08	0.50
Concrete-asphalt	3.94E-12	3.94E-11	0.3

Table 4.7M—Soil Types and Properties for Storage Tank Consequence Analysis

Soil Type	Hydraulic Conductivity for Water Lower Bound (cm/s)	Hydraulic Conductivity for Water Upper Bound (cm/s)	Soil Porosity
Gravel	1.00E00	1.00E01	0.40
Coarse sand	1.00E-02	1.00E-01	0.33
Fine sand	1.00E-03	1.00E-02	0.33
Very fine sand	1.00E-05	1.00E-03	0.33
Silt	1.00E-06	1.00E-05	0.41
Sandy clay	1.00E-07	1.00E-06	0.45
Clay	1.00E-08	1.00E-07	0.50
Concrete-asphalt	1.00E-11	1.00E-10	0.3

Table 4.8—Release Hole Sizes and Areas—Storage Tank Bottoms

Release Hole Number	Release Hole Size	RPB?	Range of Hole Diameters (in.)	Release Hole Diameter (in.)
1	Small	Yes	0 to $^1/_8$	$d_1 = 0.125$
		No	0 to $^1/_2$	$d_1 = 0.50$
2	Medium	N/A	0	$d_2 = 0$
		N/A	0	
3	Large	N/A	0	$d_3 = 0$
		N/A	0	
4	Rupture	Yes	$> {^1/_8}$	$d_4 = 12\left(\frac{D_{tank}}{4}\right)$
		No	$> {^1/_2}$	

Table 4.8M—Release Hole Sizes and Areas—Storage Tank Bottoms

Release Hole Number	Release Hole Size	RPB?	Range of Hole Diameters (mm)	Release Hole Diameter (mm)
1	Small	Yes	0 to 3.175	$d_1 = 3.175$
		No	0 to 12.7	$d_1 = 12.7$
2	Medium	N/A	0	$d_2 = 0$
		N/A	0	
3	Large	N/A	0	$d_3 = 0$
		N/A	0	
4	Rupture	Yes	> 3.175	$d_4 = 1000\left(\frac{D_{tank}}{4}\right)$
		No	> 12.7	

Table 4.9—Number of Release Holes as a Function of Storage Tank Diameter

Storage Tank Diameter [ft (m)]	Number of Release Holes with or Without an RPB		
	Small	Medium	Large
30.5 (100)	1	0	0
61.0 (200)	4	0	0
91.4 (300)	9	0	0

NOTE For intermediate storage tank diameters, the number of small release holes may be calculated using the following equation where the function nint() is defined as the nearest integer. For example, nint(3.2) = 3, nint(3.5) = 4, and nint(3.7) = 4.

$$n_{rh,1} = \max\left[\text{nint}\left[\left(\frac{D}{C_{36}}\right)^2\right],\ 1\right]$$

4.29 Figures

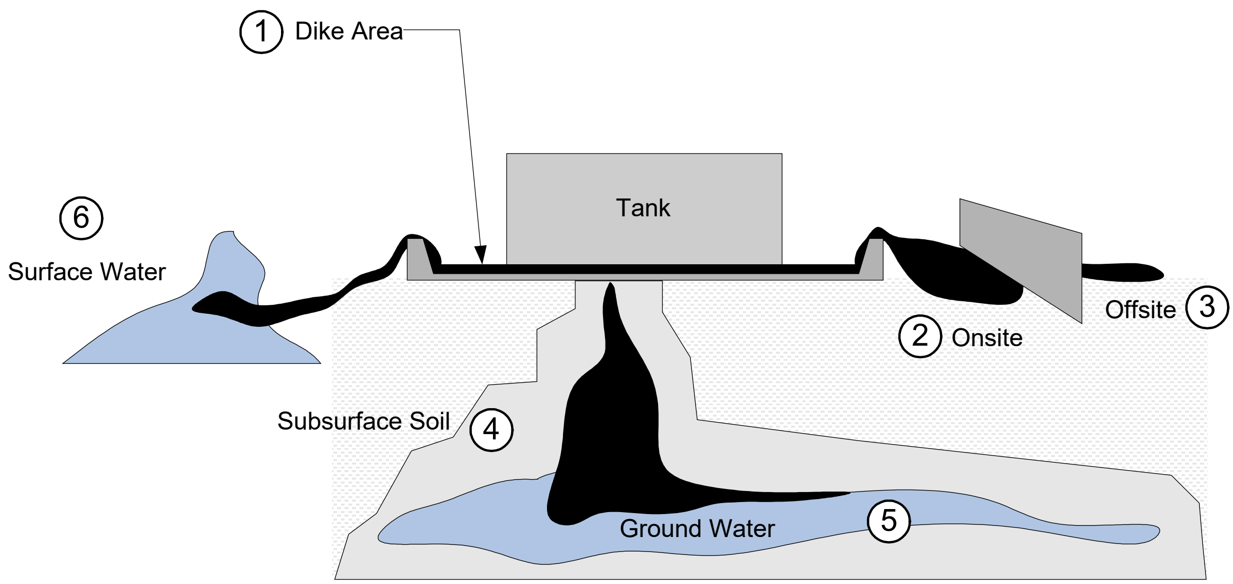


Figure 4.1—Storage Tank Consequence

5 Heat Exchanger Tube Bundles

5.1 Overview

This section describes a methodology to assess the reliability and remaining life of heat exchanger bundles. It also provides a methodology for performing cost benefit analysis to assist in making RBI and replacement decisions and to determine the optimal replacement frequency of heat exchanger bundles.

The purpose of the module is to manage heat exchanger bundle inspection and replacement cycles and to reduce annual operating and maintenance costs of heat exchanger bundles. The costs considered include bundle fabrication and installation costs, environmental impact costs, and lost opportunity costs due to unit and plant unplanned shutdowns or unit rate reductions as a result of an unplanned bundle failure.

5.2 Background

Analyzing each heat exchanger bundle service history generally does not consider the financial consequences associated with a bundle failure. Many exchangers experience few or no bundle failures, while some failures may not have occurred at the current operating conditions or practices. In addition, statistically significant data may not exist in order to make an accurate prediction of future performance or POF for the heat exchanger bundle.

5.3 Basis of Model

The application of risk principles to exchanger bundle inspection allows decisions to be made based on the consequences of bundle failure, including costs associated with lost production and environmental impact costs associated with leakage into utility systems and the replacement and maintenance costs associated with bundle replacement.

The combined experience of heat exchanger bundles of similar design and service is combined and statistically analyzed to provide a prediction of future performance. The exchanger bundle under evaluation is matched to similar bundles and statistically analyzed using a Weibayes or similar analysis to estimate the POF of the bundle. The results from the analysis are used to determine if the exchanger bundle will operate safely and reliably until the next scheduled maintenance opportunity. See Annex 5.A for an explanation on how to determine Weibull parameters.

5.4 Required Data

5.4.1 General

The data listed in Table 5.1 shows the minimum data requirements for each heat exchanger bundle.

5.4.2 Methodology Overview

Calculations for the risk and inspection for heat exchanger bundles are performed following the flow chart shown in Figure 5.1.

An overview of the steps for calculating risk are shown in the following steps.

a) Step 1.1—Gather and input the bundle basic input data required as defined in Table 5.1.

b) Step 1.2—Gather and input inspection historical data, if available.

c) Step 1.3—Determine the maximum acceptable POF, $P_{\mathrm{f,tgt}}^{\mathrm{tube}}$ based on the calculated $C_{\mathrm{f}}^{\mathrm{tube}}$ and the risk target, $Risk_{\mathrm{tgt}}$.

d) Step 1.4—Provide $MTTF$ or Weibull parameters for the bundle failure rate curve based on historical bundle failures in the same or similar service using Weibull analysis or some other statistical approach.

e) Step 1.5—Calculate the POF at the current date, RBI date, plan date, turnaround date 1, and turnaround date 2 using the Weibull data.

f) Step 1.6—Determine consequences of bundle failure, $C_{\mathrm{f}}^{\mathrm{tube}}$.

g) Step 1.7—Calculate the risk at the plan date with and without inspection.

h) Step 1.8—Define a recommended inspection plan.

i) Step 1.9—Calculate a bundle replacement frequency.

5.5 POF

5.5.1 Definition of Bundle Failure

A definition of bundle failure was established to determine the bundle life (failure) to predict the point in time at which an existing bundle will reach its end of life. A failure is defined as a tube leak for the purposes of RBI.

The current condition or remaining life of a bundle is quantified and expressed as a percent of the original wall thickness when the controlling damage mechanism for the bundle is general corrosion. Inspection data may be used to determine when failure occurred or to predict when a failure is likely to occur if inspection records documenting average remaining wall thickness are available. Other damage mechanisms, such as local corrosion, erosion, or vibration damage, are not easily predicted based on inspection measurements. In these cases, a predicted bundle life is based on a remaining life estimate.

Bundles are often replaced or repaired prior to failure due to a deteriorated condition. An assumed remaining bundle life (25 % remaining life is recommended) for the degraded condition provides an adjustment for a bundle replaced prior to a failure. A degraded condition is a bundle that would not be expected to make another operating cycle without expected tube failures.

5.5.2 POF Using Weibull Distribution

a) The POF for a heat exchanger bundle is expressed using a two-parameter Weibull distribution in Equation (5.55) [4].

$$P_{\mathrm{f}}^{\mathrm{tube}} = 1 - R(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{5.55}$$

where $P_{\mathrm{tgt}}^{\mathrm{tube}}$ is the POF as a function of time or the fraction of bundles that have failed at time t, β is the Weibull shape factor that is unitless, η is the Weibull characteristic life in years, and t is the independent variable time in years.

The time to reach a specified POF is calculated by using Equation (5.55) and solving for t, as shown in Equation (5.56).

$$t = \eta \cdot \left(-\ln\left[1 - P_{\mathrm{f}}^{\mathrm{tube}}\right]\right)^{\frac{1}{\beta}} \tag{5.56}$$

b) POF is calculated as a function of in-service duration using one of the methods below.

1) Method 1, Specified Weibull Parameters (see Part 2, Section 5.5.3.1)—The Weibull β and η parameters for the exchanger bundle are provided and used for the POF calculation. A statistical analysis such as Weibayes or other statistical analysis is used to establish the Weibull β and η parameters from an exchanger bundle reliability library or available bundle failure data. Annex 5.A shows an example of calculating Weibull parameters from an exchanger bundle reliability library.

2) Method 2, Specified $MTTF$ (see Part 2, Section 5.5.3.2)—An $MTTF$ for the bundle is provided for the POF calculation. This approach uses the $MTTF$ to calculate a Weibull η parameter using a β value of 3.0. As an option, the Weibull β parameter in addition to the $MTTF$ is specified.

3) Method 3, Specific Bundle Inspection History (see Part 2, Section 5.5.3.3)—Statistical approaches are outlined to calculate the η parameter for the bundle if sufficient inspection history is available.

5.5.3 POF Calculation

5.5.3.1 POF Using the Supplied Weibull Parameters

The β and η parameters for the exchanger bundle are provided from a statistical analysis and used in Equation (5.55) to determine the POF for the bundle as a function of time.

5.5.3.2 POF Using the Supplied MTTF

An MTTF is calculated if sufficient inspection information exists for a bundle using a Weibull distribution with a known β parameter (default to 3.0 if unknown) and η parameter using the gamma function in Equation (5.57).

$$MTTF = \eta \cdot \Gamma\left[1+\frac{1}{\beta}\right] \tag{5.57}$$

POF is calculated using Equation (5.55) for β and η.

5.5.3.3 POF Calculated Using Specific Bundle History

5.5.3.3.1 General

Information gained from inspection of the tube bundle is used to assess the actual condition of the bundle and adjust the POF rate. Inspection provides two benefits:

a) a reduction in uncertainty due to the effectiveness of the inspection providing a more accurate assessment of the bundle condition and failure rate;

b) improved knowledge of the true condition of the bundle by using measured tube wall thicknesses to make an estimate of the remaining life.

Inaccuracies and biases are addressed with uncertainty, as shown in Part 2, Annex C, Table 2.C.4.1. Uncertainty is reduced and the POF decreases through bundle inspection. The level of uncertainty decreases as more effective inspection techniques are used and risk reduction through inspection results in more rigorous inspection techniques as the bundle reaches end of life. Inspection effectiveness is discussed in more detail in Part 2, Annex 2.C. The bundle may reach a time in life when inspection (more data) does little or nothing to lower the risk and repair, replace, coat, or other recommendations are more appropriate. This is typically because it is actually at or near end of life.

5.5.3.3.2 Specific Bundle History

Inspection provides knowledge of the current condition of the bundle. Inspection determines if the bundle is in better or worse condition than predicted by using data from similar service bundles.

If general corrosion is the primary damage mechanism, average measured tube thickness data is used to predict the bundle failure date. When other damage mechanisms (such as vibration or tube end thinning) or when measured thickness data does not exist, a qualitative estimate of the remaining life is used to predict the bundle failure date. Two methods are provided for inspection data use in adjusting the POF calculation.

a) Calculated Failure Data Based on Measured Thickness Data—The thinning rate of the tube bundle, t_{rate}, is calculated using the average furnished wall thickness, $\overline{t}_{orig}$, and average measured wall thickness, $\overline{t}_{insp}$, from inspection, and the time in service, t_{dur}, using Equation (5.58):

$$t_{rate} = \frac{\overline{t}_{orig} - \overline{t}_{insp}}{t_{dur}} \tag{5.58}$$

The calculated rate is adjusted, $t_{\text{rate,adj}}$, in Equation (5.59) uses the probabilities and damage state factors used in the thinning DF calculation in Part 2, Section 4.5.7.

$$t_{\text{rate,adj}} = \left(t_{\text{rate1}} \cdot D_1^{\text{Bundle}}\right) + \left(t_{\text{rate2}} \cdot D_2^{\text{Bundle}}\right) + \left(t_{\text{rate3}} \cdot D_3^{\text{Bundle}}\right) \tag{5.59}$$

where t_{rate1}, t_{rate2}, and t_{rate3} are the thinning states based on the measured corrosion rate from inspection, and D_1^{Bundle}, D_2^{Bundle}, and D_3^{Bundle} are the probabilities Part 2, Table 4.5.

The calculated bundle life, PBL_{adj}, is adjusted for inspection using Equation (5.60).

$$PBL_{\text{adj}} = \frac{RWT_{\text{f}} \cdot \bar{t}_{\text{orig}}}{t_{\text{rate,adj}}} \tag{5.60}$$

where the failure point is defined as a fraction of remaining wall thickness, RWT_{f}.

b) Calculated Failure Data Based on Estimated Remaining Life—The estimated remaining life, ERL, of the bundle is used to calculate bundle life if tube wall thickness data is not available for calculation of a bundle tube thinning rate or when the damage mechanism is not general corrosion. The ERL is calculated using inspection data combined with accepted FFS calculations based on the damage mechanism known or anticipated and the time in service, t_{dur}.

$$PBL_{\text{adj}} = t_{\text{dur}} + ERL \tag{5.61}$$

5.5.3.3.3 Adjustment to Failure Rate Based on Condition of Bundle

A bundle with a recommended two or more life cycles with inspection data is used to calculate a β parameter for the matching bundle criteria (default to 3.0 if unknown) with a Weibayes analysis. The η parameter is calculated using Equation (5.62).

$$\eta = \left(\sum_{i=1}^{N} \frac{t_{\text{dur},i}^{\beta}}{r}\right)^{\frac{1}{\beta}} \tag{5.62}$$

where N is the number of past bundles, $t_{\text{dur},i}$ is the time in service for each bundle in years, r is the number of failed bundles, and β is the Weibull slope parameter. This method assumes that the current operating conditions for the bundle have not changed including changes in metallurgy, process conditions, or bundle design. POF is calculated using Equation (5.55) for β and η.

A modified characteristic life, η_{mod}, for the bundle is calculated using Equation (5.63) if the bundle life is calculated based on the last inspection using Equation (5.60) or Equation (5.63).

$$\eta_{\text{mod}} = \left(\frac{1}{r}\sum_{i=1}^{N} t_{i,\text{dur}}^{\beta}\right)^{\frac{1}{\beta}} \tag{5.63}$$

where N is the number of past bundles, $t_{\text{dur},i}$ is the time in service for each bundle in years, r is the number of failed bundles, and β is the Weibull slope parameter.

NOTE If the bundle was replaced before failure, a factor of 1.25 is applied to the service duration. This method assumes that the current operating conditions for the bundle have not changed including changes in metallurgy, process conditions, or bundle design. POF is calculated using Equation (5.55) for β and η_{mod}.

The recommended inspection interval at the target POF for the bundle is calculated using Equation (5.64):

$$t_{insp} = \eta_{mod} \cdot \left(-\ln\left[1 - P_{f,tgt}^{tube}\right]\right)^{\frac{1}{\beta}} \tag{5.64}$$

The adjusted characteristic life, and adjusted POF, $P_{f,adj}^{tube}$,of the bundle is calculated using η_{mod} from Equation (5.63) using Equation (5.65).

$$P_{f,adj}^{tube} = 1 - \exp\left[-\left(\frac{t}{\eta_{mod}}\right)^{\beta}\right] \tag{5.65}$$

5.5.3.3.4 Effects of Bundle Life Extension Efforts

Minor repairs and cleaning operations performed on bundles prior to inspection do not affect the life of the bundle. However, there are life extension methods that are often implemented during shutdowns that return the bundle to service in an improved condition. An adjustment is made to the inspection interval based on Table 4.2 for life extension methods and by determining a life extension factor, LEF. The adjusted service duration, $tadj_{dur}$, is calculated with the LEF using Equation (5.66).

$$tadj_{dur} = (1 + LEF) \cdot t_{dur} \tag{5.66}$$

NOTE The actual service duration, t_{dur} , is the time period in years between the bundle installation date and the inspection date that the life extension method was performed, as shown in Equation (5.67).

$$t_{dur} = Inspect\ Date - Install\ Date \tag{5.67}$$

The effective installation date, $Bundle\ Installation\ Date_{adj}$, is calculated using $tadj_{dur}$, as shown in Equation (5.68).

$$Bundle\ Installation\ Date_{adj} = Inspect\ Date - tadj_{dur} \tag{5.68}$$

5.6 COF

Bundle failure is defined as a tube leak. Financial COF is determined based on the bundle criticality, which includes costs associated with lost opportunity due to production downtime, environmental impact costs, and costs associated with maintenance and replacement of the bundle. The consequence of an unplanned shutdown due to a bundle tube leak is determined using Equation (5.69).

$$C_f^{tube} = \left(Unit_{prod} \cdot \frac{Rate_{red}}{100} \cdot D_{sd}\right) \cdot Outage_{mult} + Cost_{env} + \left(Cost_{bundle} \cdot matcost\right) + Cost_{maint} \tag{5.69}$$

where D_{sd} is the time in days for a planned or unplanned shutdown and $matcost$ factor is from Table 4.3.

5.7 Risk Analysis

5.7.1 General

Risk over time is calculated to determine what inspection is required to manage risk. Uncertainty exists when relevant, credible data is lacking. More relevant data reduces the amount of uncertainty in the risk calculation. Information from inspection is often needed to improve confidence in the damage states and damage rates associated with bundles. Risk for bundles is a function of time is the product of the POF and the COF in financial terms, as shown in Equation (5.70).

$$Risk_{\text{f}}^{\text{tube}} = P_{\text{f}}^{\text{tube}} \cdot C_{\text{f}}^{\text{tube}} \tag{5.70}$$

5.7.2 Risk Matrix

A risk matrix is a valuable visual tool for identifying high risk bundles. The risk of each bundle is characterized by the POF and COF categories, shown in Part 1, Section 4.3.2.2, and enables each bundle to be plotted on the risk matrix as shown in Part 1, Figure 4.2 and Figure 4.3.

The risk matrix is grouped into four areas: high risk, medium high risk, medium risk, and low risk. If an exchanger has been identified as high risk prior to the turnaround, it would require a more rigorous inspection than has been used on that bundle in the past. For example, if the bundle were determined to be a high risk on the risk matrix and past inspections for that bundle were *usually effective*, it is very likely that a *highly effective inspection* would be required at the upcoming shutdown. The benefits of the different levels of inspection are discussed in Section 5.8.

5.8 Inspection Planning Based on Risk Analysis

5.8.1 General

The inspection target date is the date at which the calculated risk using Equation (5.55) exceeds the risk target, $Risk_{\text{tgt}}$. An inspection is required prior to the target date to maintain a risk level below the risk target. The target date for the next inspection is calculated using the inspection adjusted Weibull parameters.

5.8.2 Use of Risk Target in Inspection Planning

The risk target is a function of the owner–operator's corporate philosophy for making risk decisions. Some companies are more risk adverse than others, and this will have a direct impact on the inspection planning results.

Equation (5.71) is used to calculate the target POF for a bundle as a function of the COF and using the target risk:

$$P_{\text{f,tgt}}^{\text{tube}} = \frac{Risk_{\text{tgt}}}{C_{\text{f}}^{\text{tube}}} \tag{5.71}$$

A target inspection date is calculated using Equation (5.56). The target date is the date when the bundle risk reaches the target risk.

A user-defined $P_{\text{f,tgt}}^{\text{tube}}$ is used in place of the calculated $P_{\text{f,tgt}}^{\text{tube}}$ if a lower risk or probability of bundle failure is required for inspection planning.

The target inspection time is calculated using Equation (5.72). The target time is the number of years from the installation date when the bundle risk reaches the target risk.

$$t_{\text{insp}} = \eta_{\text{tgt}} \cdot \left(-\ln\left[1 - P_{\text{f,tgt}}^{\text{tube}}\right]\right)^{\frac{1}{\beta}} \tag{5.72}$$

The target inspection date is calculated using Equation (5.73) using t_{insp} and the installation date. The target date is the date when the bundle risk reaches the target risk.

$$Target\ Inspection\ Date = Bundle\ Installation\ Date + t_{insp} \tag{5.73}$$

Bundle target characteristic life, η_{tgt}, is calculated using the $P_{f,tgt}^{tube}$ and the bundle age at the plan date as shown in Equation (5.74).

$$\eta_{tgt} = \frac{t_{plan}}{-\ln\left[1 - P_{f,tgt}^{tube}\right]^{\frac{1}{\beta}}} \tag{5.74}$$

5.8.3 Determine Inspection Recommendation

Once a decision has been made to inspect per Equation (5.74), an economic decision can be made as to the appropriate level of inspection with similar techniques as described in Section 5.9.1 by comparing the cost of the various inspection techniques to the reduction in risk expected for the level of inspection.

NOTE No inspection is required if $P_{f,plan}^{tube} \le P_{f,tgt}^{tube}$.

The target uncertainty, $AU_{tgt}\%$, is the level of uncertainty associated with an inspection required to remain below the $P_{f,tgt}^{tube}$ at the plan date from Equation (5.75).

$$AU_{tgt}\% = \frac{\eta_{tgt}}{\eta_{mod}} \tag{5.75}$$

The $AU_{tgt}\%$ is used with Table 4.5 to determine the level of inspection required to achieve target $P_{f,tgt}^{tube}$ at the plan date. The inspection plan is defined by using the target inspection date from Equation (5.71) and the recommended inspection from Equation (5.75).

5.8.4 Calculate Characteristic Life at Plan Date

The recommended inspection uncertainty is used calculate the characteristic life at the plan date after inspection using Equation (5.76).

$$\eta_{insp} = \eta_{mod} \cdot \left(\frac{1 - AU_{w/insp}\%}{1 - AU_{w/outinsp}\%} \right) \tag{5.76}$$

where η_{mod} is defined in Equation (5.62).

5.8.5 Calculation of Risk

The POF at the plan date, $P_{f,w/insp}^{tube}$, with inspection is calculated with Equation (5.55), using t_{plan} for time at the plan date, η_{insp} from Equation (5.76), and the original β value.

5.8.6 Calculation of Risk

The risk at the plan date is calculated using Equation (5.70) using $P_{f,w/insp}^{tube}$ and $C_{f,plan}^{tube}$.

5.9 Bundle Inspect/Replacement Decisions Using Cost Benefit Analysis

5.9.1 General

Weibull parameters are used to predict the optimal replacement frequency for a bundle and determine whether it makes economic sense to inspect or replace a bundle at an upcoming shutdown.

5.9.2 Decision to Inspect or Replace at Upcoming Shutdown

Risk reduction cost benefit is calculated from mitigating actions including various levels of inspection or bundle replacement. The cost benefit calculation includes the cost of the mitigating action to inspect or replace). An optional rate of return, ROR (or hurdle cost), is added to the cost of a bundle replacement to prevent excessive bundle replacement for borderline risk determinations that require action. The decision to perform a risk mitigating bundle inspection or bundle replacement at an upcoming turnaround is determined by comparing the incremental risk ($) associated with deferring the inspection or replacement to the cost associated with the performing the inspection or replacement.

Expected incremental risk, $EIR_{\text{t1}}^{\text{t2}}$, associated with deferring the inspection or replacement of a bundle to a later date is calculated using Equation (5.77).

$$EIR_{\text{t1}}^{\text{t2}} = C_{\text{f}}^{\text{tube}} \cdot \left(1 - \left[\frac{1 - P_{\text{f}}^{\text{tube}}(t_2)}{1 - P_{\text{f}}^{\text{tube}}(t_1)}\right]\right) \tag{5.77}$$

where t_1 is the service duration of the bundle at the next shutdown (turnaround date 1) and t_2 is the service duration of the bundle at the subsequent shutdown (turnaround date 2).

If the cost to inspect or replace is greater than the expected incremental risk using Equation (5.78) and Equation (5.79), that action is recommended.

$$\begin{aligned}
&\text{If } \left(Cost_{\text{insp}} + Cost_{\text{maint}}\right) \cdot (1 + ROR) < EIR_{\text{t1}}^{\text{t2}}, \text{ then inspect} \\
&\text{If } \left(Cost_{\text{insp}} + Cost_{\text{maint}} + Hurdle\ Cost\right) < EIR_{\text{t1}}^{\text{t2}}, \text{ then inspect}
\end{aligned} \tag{5.78}$$

$$\begin{aligned}
&\text{If } \left(Cost_{\text{bundle}} + Cost_{\text{maint}}\right) \cdot (1 + ROR) < EIR_{\text{t1}}^{\text{t2}}, \text{ then replace the bundle} \\
&\text{If } \left(Cost_{\text{bundle}} + Cost_{\text{maint}} + Hurdle\ Cost\right) < EIR_{\text{t1}}^{\text{t2}}, \text{ then replace the bundle}
\end{aligned} \tag{5.79}$$

The actual inspection costs should be used when available. Maintenance costs to pull the bundles for inspection should be included in the total inspection costs when using Equation (5.78) and Equation (5.79).

5.9.3 Optimal Bundle Replacement Frequency

Maintenance optimization helps to strike a balance between cost and reliability. The cost per day of a “run to failure” strategy shows low costs early in the life of the equipment and increasing costs as reliability decreases. By overlaying the costs of an associated preventative maintenance to address the failure mode, initial costs are high, but costs per unit time decrease as time progresses. This optimization occurs at a point where the total cost function (sum of the two cost functions) is at a minimum. The time at which the minimum occurs is the optimum time to perform maintenance [5].

The optimum replacement frequency is calculated comparing the cost associated with a bundle failure (increasing with increasing replacement frequency) to the replacement cost associated with periodic planned shutdowns to replace the bundle (decreasing with increasing replacement frequency). The point where the two costs reach a minimum value is the optimum replacement frequency.

The methodology in Shultz, 2001 [6] described below is recommended to determine the optimum bundle replacement frequency.

a) Increasing Risk Cost of Unplanned Outage.

A planned replacement time frequency is defined by the variable, tr_n, and the risk cost associated with an unplanned failure to replace the bundle (including business interruption and bundle replacement costs) is calculated using Equation (5.80).

$$Risk_{\text{f}}^{\text{tube}}\left(tr_n\right) = C_{\text{f,unplan}}^{\text{tube}} \cdot P_{\text{f}}^{\text{tube}}\left(tr_n\right) \tag{5.80}$$

where $C_{\text{f,plan}}^{\text{tube}}$ is defined in Equation (5.81).

$$C_{\text{f,unplan}}^{\text{tube}} = \left(Unit_{\text{prod}} \cdot \frac{Rate_{\text{red}}}{100} \cdot D_{\text{sd,unplan}}\right) \cdot Outage_{\text{mult}} + Cost_{\text{env}} + \left(Cost_{\text{bundle}} \cdot matcost\right) + Cost_{\text{maint}} \tag{5.81}$$

NOTE Equation (5.81) is similar to Equation (5.69) but uses the unplanned outage time, $D_{\text{sd,unplan}}$. The consequence of an unplanned frequency due to a tube bundle failure, $C_{\text{f}}^{\text{tube}}$, includes business interruption, the number of days required for bundle replacement during an unplanned outage, $D_{\text{sd,unplan}}$ and environmental impact, $Cost_{\text{env}}$. The risk cost due to bundle failure increases with time since the POF, $P_{\text{f}}^{\text{tube}}\left(tr_n\right)$, increases with time.

b) Decreasing Cost of Bundle Replacement.

The bundle replacement costs as a function of planned replacement frequency, tr, is calculated using Equation (5.82).

$$Cost_{\text{pbr}}\left(tr_n\right) = C_{\text{f,plan}}^{\text{tube}} \cdot \left[1 - P_{\text{f}}^{\text{tube}}\left(tr_n\right)\right] \tag{5.82}$$

where $C_{\text{f,plan}}^{\text{tube}}$ is defined in Equation (5.83).

$$C_{\text{f,plan}}^{\text{tube}} = \left(Unit_{\text{prod}} \cdot \frac{Rate_{\text{red}}}{100} \cdot D_{\text{sd,plan}}\right) \cdot Outage_{\text{mult}} + Cost_{\text{env}} + \left(Cost_{\text{bundle}} \cdot matcost\right) + Cost_{\text{maint}}$$
$$C_{\text{f,plan}}^{\text{tube}} = Cost_{\text{env}} + \left(Cost_{\text{bundle}} \cdot matcost\right) + Cost_{\text{maint}} \tag{5.83}$$

c) Optimization of Total Cost.

The total cost as a function of replacement time frequency averaged over the service bundle life is calculated using Equation (5.84).

$$Cost_{\text{total}}\left(tr_n\right) = \frac{Risk_{\text{f}}^{\text{tube}}\left(tr_n\right) + Cost_{\text{pbr}}\left(tr_n\right)}{365.25 \cdot ESL_n} \tag{5.84}$$

The estimated service life as a function of replacement time interval may be approximated using an integration technique using Equation (5.85).

$$ESL_n = ESL_{\text{f},n} + ESL_{\text{p},n} \tag{5.85}$$

where the average life of the bundles that would have been expected to fail prior to the planned replacement time, $ESL_{\text{f},n}$, and the average life of the bundles that would not have been expected to fail prior to the planned replacement time, $ESL_{\text{p},n}$ are summed, ESL_n.

The average life of the bundles that would have been expected to fail prior to the planned replacement time is:

$$ESL_{\text{f},n} = ESL_{\text{f},n-1} + tr_n \cdot \left(P_{\text{f},n}^{\text{tube}} - P_{\text{f},n-1}^{\text{tube}}\right) \tag{5.86}$$

The average life of the bundles that would have been expected to not fail prior to the planned replacement time is:

$$ESL_{\text{p},n} = tr_n \cdot \left(1 - P_{\text{f},n}^{\text{tube}}\right) \tag{5.87}$$

A planned replacement frequency is selected and the costs associated with the frequency calculated to allow optimization of the total cost. The frequency is incrementally increased and the costs are calculated for each incremental step, $n\left(n = n+1\right)$. The point where the costs reach a minimum is the optimum replacement frequency.

1) Step 2.1—Select an appropriate time step, t_{s}, in days (a value for t_{s} of 7 to 14 days should be sufficient) and an increment of n = 1. Subsequent calculations will increase the increment by 1 or $n\left(n = n+1\right)$

2) Step 2.2—Calculate the planned replacement frequency, tr_n, by multiplying the increment number, n, by the time step, t_{s}, as follows:

$$tr_n = n \cdot \frac{t_{\text{s}}}{365.25} \tag{5.88}$$

3) Step 2.3—Calculate the POF at the planned replacement frequency at increment n, $P_{\text{f},n}^{\text{tube}}\left(tr_n\right)$, using Equation (5.55), the updated Weibull parameters based on the latest inspection of the bundle and the time value to use in Equation (5.56) is tr_n obtained in Step 2.2.

   NOTE Time is reported in years.

4) Step 2.4—Calculate the average life of the bundles that would have been expected to fail prior to the planned replacement time, $ESL_{\text{f},n}$, using Equation (5.86).

5) Step 2.5—Calculate the average life of the bundles that would have not been expected to fail prior to the planned replacement time, $ESL_{\text{p},n}$, using Equation (5.87).

6) Step 2.6—Calculate the estimated service life, ESL_n, using Equation (5.83).

7) Step 2.7—Calculate the risk cost associated with bundle failure at the replacement frequency, $Risk_{\text{f}}\left(tr_n\right)$, using Equation (5.80).

8) Step 2.8—Calculate the bundle replacement cost at the replacement frequency, $Cost_{\text{pbr}}\left(tr_n\right)$, using Equation (5.82).

9) Step 2.9—Calculate the total costs at the replacement frequency averaged over the expected life of the bundle, $Cost_{\text{total}}\left(tr_n\right)$, using Equation (5.84).

10) Step 2.10—Increase the increment number by 1 $\left(n = n+1\right)$ and repeat Steps 2.2 through 2.9 until a minimum value of $Cost_{\text{total}}\left(tr_n\right)$ in Step 2.9 is obtained.

11) Step 2.11—The optimal bundle replacement frequency, t_{opt}, is where the tr_n is at the minimum $Cost_{\text{total}}\left(tr_n\right)$.

5.10 Nomenclature

$AU\%$	is the percent additional uncertainty, %
$AU_{\text{tgt}}\%$	is the additional inspection uncertainty required to remain below the $P_{\text{f,tgt}}^{\text{tube}}$ at the plan date, %
$AU_{\text{w/insp}}\%$	is the additional inspection uncertainty at the plan date after inspection, %
$AU_{\text{w/outinsp}}\%$	is the additional inspection uncertainty at the plan date before inspection, %
$C_{\text{f}}^{\text{tube}}$	is the consequence of bundle failure, $
$C_{\text{f,plan}}^{\text{tube}}$	is the consequence of bundle failure based on a planned bundle replacement, $
$C_{\text{f,unplan}}^{\text{tube}}$	is the consequence of bundle failure during an unplanned bundle replacement, $
$Cost_{\text{bundle}}$	is the replacement cost of the tube bundle, $
$Cost_{\text{env}}$	is the environmental costs due to a bundle leak, $
$Cost_{\text{insp}}$	is the cost to perform the inspection, $
$Cost_{\text{maint}}$	is the cost of maintenance for bundle inspection or replacement, $
$Cost_{\text{pbr}}\left(tr_n\right)$	is the cost per year of bundle replacement at a planned frequency, tr_n, $/yr
$Cost_{\text{prod}}$	is the production losses as a result of shutting down to repair or replace a tube bundle, $
$Cost_{\text{total}}\left(tr_n\right)$	is the total cost of a bundle replacement program at a planned frequency, tr_n, $/yr
D_{sd}	is the number of days required to shut a unit down to repair a bundle during an unplanned shutdown, days
$D_{\text{sd,plan}}$	is the number of days required to shut a unit down to repair a bundle during a planned shutdown, days

$D_{\text{sd,unplan}}$	is the number of days required to shut a unit down to repair a bundle during an unplanned shutdown, days
D_1^{Bundle}	is the probability adjustment for t_{rate1}
D_2^{Bundle}	is the probability adjustment for t_{rate3}
D_3^{Bundle}	is the probability adjustment for t_{rate4}
$EIR_{\text{t1}}^{\text{t2}}$	is the expected incremental risk between turnaround dates t_1 and t_2, \$/yr
ERL	is the estimated remaining life of the bundle, years
ESL_n	is the estimated service life of a bundle as a function of replacement time interval, years
$ESL_{\text{f},n}$	is the average life of bundles that would have failed at the replacement time interval, years
$ESL_{\text{f},n-1}$	is the average life of bundles that would have failed at the previous replacement time interval ($n-1$), years
$ESL_{\text{p},n}$	is the average life of bundles that would not have failed at the replacement time interval, years
LEF	is the bundle life extension factor
$MTTF$	is the mean time to failure, years
$matcost$	is the material cost factor for the tube bundle material of construction
N	is the number of bundles in a heat exchangers past history
$Outage_{\text{mult}}$	is the outage multiplier factor of the unit
$P_{\text{f}}^{\text{tube}}$	is the probability of the bundle failure, failures/yr
$P_{\text{f},n}^{\text{tube}}$	is the probability of bundle failure calculated for the current (n) increment of the optimization procedure, failures/yr
$P_{\text{f},n-1}^{\text{tube}}$	is the probability of bundle failure calculated for the previous ($n-1$) increment of the optimization procedure, failures/yr
$P_{\text{f,w/insp}}^{\text{tube}}$	is the probability of bundle failure at the plan date with inspection, failures/yr
$P_{\text{f,tgt}}^{\text{tube}}$	is the maximum acceptable probability of bundle failure based on the owner–operator's risk target, failures/yr
PBL_{adj}	is the predicted bundle life adjusted based on inspection, years

$R(t)$	is the risk as a function of time, ft^2/yr (m^2/yr) or \$/yr
$Risk_f^{\text{tube}}$	is the risk of failure of the tube bundle, \$/yr
$Risk_f^{\text{tube}}(tr_n)$	is the risk of failure of the tube bundle at a planned bundle replacement frequency, tr_n, \$/yr
$Rate_{\text{red}}$	is the production rate reduction on a unit as a result of a bundle being out of service, %
$Risk_{\text{tgt}}$	is the risk target, \$/yr
ROR	is the fractional rate of return or hurdle rate
RWT_f	is the failure point defined as a fraction of remaining wall thickness
r	is the number of failed bundles in a heat exchangers past history
t	is time, years
t_{dur}	is the bundle duration or time in service, years
$t_{\text{dur},i}^{\beta}$	is the time in service for the i^{th} bundle in a heat exchanger, years
t_{insp}	is the inspection interval, years
t_{plan}	is the time from the bundle installation date to the plan date, years
t_{rate}	is the thinning rate for the tube bundle, in./yr (mm/yr)
$t_{\text{rate,adj}}$	is the probability adjusted corrosion rate
t_{rate1}	is the corrosion rate for damage state 1, in./yr (mm/yr)
t_{rate2}	is the corrosion rate for damage state 2, in./yr (mm/yr)
t_{rate3}	is the corrosion rate for damage state 3, in./yr (mm/yr)
t_s	is the time step used in the optimization routine for bundle replacement frequency, days
t_1	is the service duration of the bundle at the upcoming turnaround (turnaround date 1), years
t_2	is the service duration of the bundle at the subsequent turnaround (turnaround date 2), years
$tadj_{\text{dur}}$	is the bundle duration or time in service adjusted for life extension activities, years
tr_n	is the bundle planned replacement frequency, year
$\bar{t}_{\text{insp}}$	is the average measured tube wall thickness, in. (mm)

$\bar{t}_{orig}$	is the average furnished tube wall thickness, in. (mm)
$Unit_{prod}$	is the daily production margin on the unit, \$/day
β	is the Weibull shape parameter that represents the slope of the line on a POF vs time plot
Γ	is the gamma function
η	is the Weibull characteristic life parameter that represents the time at which 62.3 % of the bundles are expected to fail, years
η_{insp}	is the Weibull characteristic life parameter at the plan date after inspection, years
η_{mod}	is the Weibull modified characteristic life parameter modified with inspection history, years
η_{tgt}	is the Weibull target characteristic life parameter based on the risk target, years

5.11 Tables

Table 5.1—Basic Data for Exchanger Bundle Risk Analysis

Bundle Remaining Life Methodology	
Specified MTTF	User-specified MTTF for bundle, years to be used in calculation
Specified Weibull, η	User-specified Weibull characteristic life (years) to be used in calculations (β should also be provided)
Specified Weibull, β	User-specified Weibull slope parameter to be used in calculations (η should also be provided)
Bundle life	The life of the bundle under evaluation, years (required for inactive bundles)
Consequences of Bundle Failure	
Financial risk target	User risk target, $/yr
Tube wall failure fraction	Wall thickness fraction that constitutes bundle failure (0 and 1.0)
Production cost	Unit production costs, $/day (should be equal to the production rate, bbl/day $\times$ margin ($/bbl)
Production impact	Production impact, e.g. none, bypass, bypass with rate reduction, shutdown
Rate reduction	Rate reduction, % (required if production impact is bypass with rate reduction)
Planned shutdown days	Number of days required to repair or replace failed exchanger bundle when the shutdown is planned, days
Unplanned shutdown days	Number of days required to repair or replace failed exchanger bundle when the shutdown is unplanned, days (should be a longer duration than a planned shutdown to allow for lead time to mobilize or to purchase a replacement bundle)
Environmental impact	Environmental costs associated with bundle failure that includes damage to cooling water system and towers
Lost opportunity cost	Additional cost beyond production losses or environmental costs as a result of bundle failure, $
Bundle cost	Cost of replacement bundle, $
Bundle installation cost	Cost of maintenance required to remove, clean, and re-install exchanger bundle, $
Hurdle cost	Additional cost above the economic breakeven point at which a decision to inspect or replace a bundle is made, $
Turnaround date 1	The date for the next scheduled turnaround from the RBI date (used as plan date for calculating risk)
Turnaround date 2	The date for the second scheduled turnaround from the RBI date (used in the cost benefit analysis to make inspection or replacement decisions)

Table 5.2—Effects of Bundle Life Extension Methods

Life Extension Method	Life Extension Factor (LEF) [3]
Plug tubes	0.10
180° bundle rotation	0.50
Partial re-tube	0.50
Total re-tube	0.90
Install spare bundle [2]	0.50
Install tube ferrules [1]	0.75

NOTE 1 This LEF is only valid when the tube ferrules are installed for protection against localized, tube-end damage due to erosion, corrosion, or impingement.

NOTE 2 The spare bundle condition is known to be good through prior inspection. If the condition of the spare bundle is known to be excellent, a higher LEF can be used.

NOTE 3 LEFs provided in this table are suggestions. It is the responsibility of the owner–operator to define life extensions for use for the bundle life extension methods.

Table 5.3—Bundle Material Cost Factors

Bundle Generic Material	Tube Material Cost Factor, M_f
Carbon steel	1.0
C-$^1/_2$ Mo	2.0
1$^1/_4$Cr	2.0
2$^1/_4$Cr	2.8
5Cr	3.2
9Cr	3.3
12Cr	3.4
70/30 CuNi	3.5
90/10 CuNi	3.5
Monel 400*	7.0
Nickel 200	8.5
304/309/310 SS	2.6
304L/321/347 SS	2.8
316 SS	3.0
316L SS	3.0
317L SS	4.2
410/439 SS	2.8
444 SS	3.2
904L	7.0
2205 duplex SS	3.0
2304 duplex SS	2.8
2507 duplex SS	4.0
AL6XN/254 SMO	7.0

Bundle Generic Material	Tube Material Cost Factor, M_f
Seacure/E-Brite*	6.0
Admiralty brass/aluminum brass/red brass/Muntz	2.5
Aluminum alloy	3.0
Alloy 20 Cb3	6.5
Alloy 600	9.5
Alloy 625	11.0
Alloy 800	7.0
Alloy 825	8.0
Alloy C276	11.0
Ferralium 255	7.0
Bimetallic	4.5
Ceramic	1.0
Plastic	1.0
Titanium Grade 2	6.0
Titanium Grade 12	10.0
Titanium Grade 16	14.0
Zeron 100	4.0
Zirconium alloy	15.0

NOTE The tube material cost factors are generic data, and the user is encouraged to set values based on current material cost factors.
* These terms are used as examples only, and do not constitute an endorsement of these products by API.

Table 5.4—Numerical Values Associated with POF and Financial-based COF Categories for Exchanger Bundles

Probability Category [1]		Consequence Category [2]	
Category	**Range**	**Category**	**Range ($)**
1	$POF \le 0.1$	A	$COF \le \$10,000$
2	$0.1 < POF \le 0.2$	B	$\$10,000 < COF \le \$50,000$
3	$0.2 < POF \le 0.3$	C	$\$50,000 < COF \le \$150,000$
4	$0.3 < POF \le 0.5$	D	$\$150,000 < COF \le \$1,000,000$
5	$0.5 < POF \le 1.0$	E	$COF > \$1,000,000$

NOTE 1 In terms of the total DF, see Part 2, Section 2.3.
NOTE 2 In terms of consequence area, see Part 3, Section 4.11.4.

Table 5.5—Inspection Effectiveness and Uncertainty

Inspection Category	Inspection Effectiveness Category	Inspection Confidence	Inspection Uncertainty
A	Highly Effective	$>$ 90 %	$<$ 10 %
B	Usually Effective	$>$ 70 % to 90 %	$<$ 30 % to 10 %
C	Fairly Effective	$>$ 50 % to 70 %	$<$ 50 % to 30 %
D	Poorly Effective	$>$ 40 % to 50 %	$<$ 60 % to 50 %
E	Ineffective	$<$ 40 %	$>$ 60 %

NOTE 1 Inspection cost numbers are not provided in this table but may be used in the methodology regarding a "repair or replace" strategy. It is the responsibility of the owner–operator to determine the cost numbers unique to their particular operation and strategy.

NOTE 2 Refer to Part 2, Annex C, Section 2.C.4 for more information.

NOTE 3 The owner–operator should consider applying confidence/uncertainty based upon the relationship between the following variables:

a) amount of the bundle inspected (percentage whole or percentage per pass),

b) examination method(s) used and degree of cleanliness,

c) metallurgy of the bundle,

d) damage mechanism(s) expected/found.

5.12 Figures

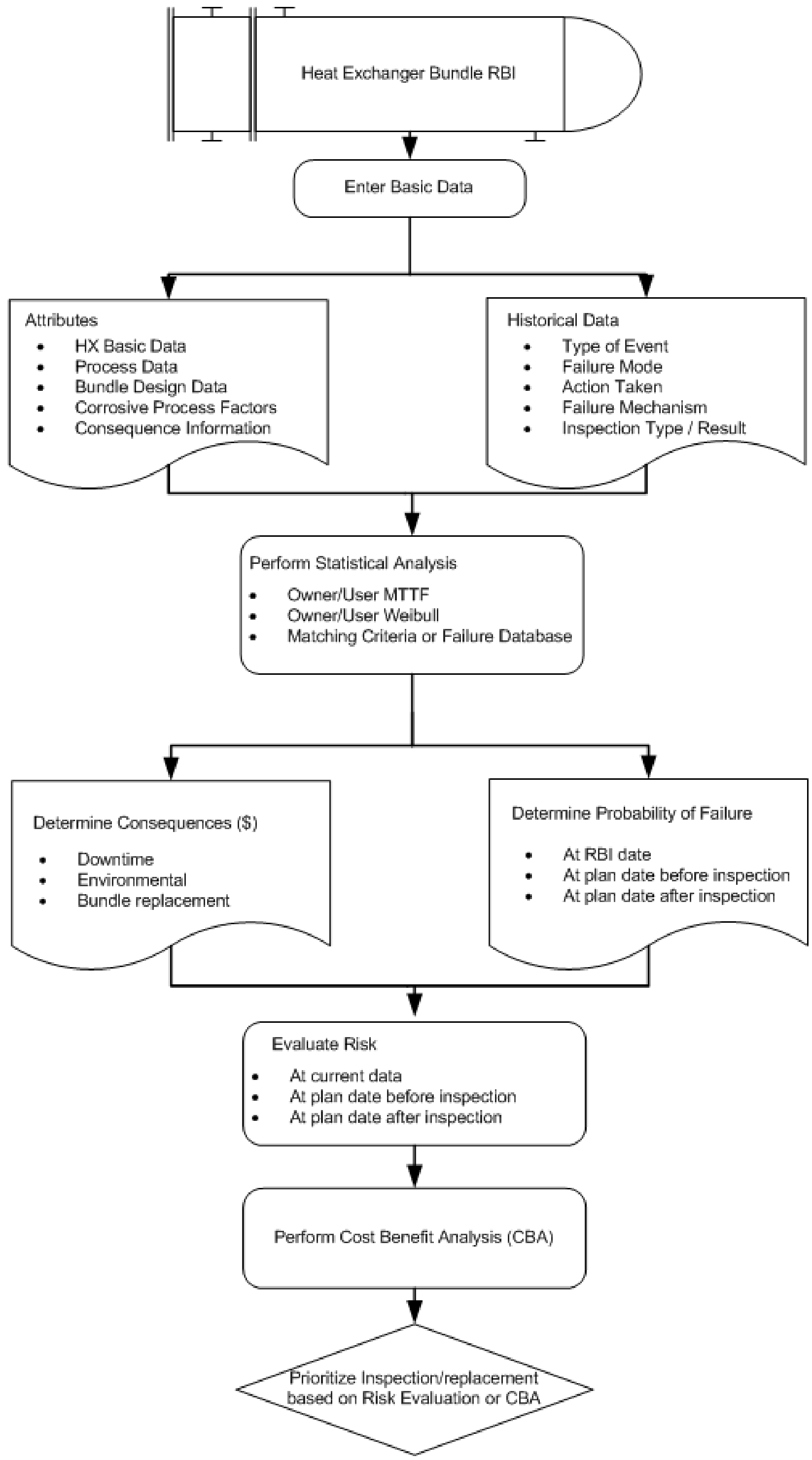


Figure 5.1—Flow Chart of Bundle Calculation Approach

6 PRDs

6.1 General

6.1.1 Overview

PRDs are routinely inspected and tested to assure that the PRDs will relieve properly in overpressure events to prevent a loss of containment of the protected component. The impact of leaks associated with PRDs is also considered.

A risk-based approach to evaluate PRD criticality is covered in this section to set inspection and test intervals. All spring-loaded and pilot-operated PRVs with and without rupture disks are covered. AST pressure/vacuum vents (P/Vs) and explosion hatches may be analyzed using this methodology provided Weibull parameter reliability data are available.

This methodology is not intended to be used to perform or check PRD design or capacity calculations. It is assumed that the owner–operator has completed due diligence and the PRDs have been designed in accordance with API 521 [7] and sized, selected, and installed in accordance with API 520 [8]. It is also assumed that minimum inspection practices in accordance with API 576 [9] are in place.

The methodology outlined uses a demand rate for the PRD combined with a probability of failure on demand (POFOD) determined from plant-specific data, if available, or using conservative default data provided. These inputs are used to generate POF as a function of time with a Weibull statistical approach. The protected component COF if the PRD fails to operate on demand is based on the methodology outlined in Part 3, substituting the operating pressure with the overpressure of each demand case combined with the consequences associated with PRD leakage. The combination of COF with a time-based POF results in an increasing risk value with time between inspection and test, allowing test intervals to be set based on risk targets.

The flow chart shown in Figure 6.1 illustrates the basic methodology required for the determination of an RBI inspection and test schedule. The basic data required for the evaluation are listed in Table 6.1.

6.1.2 Failure Modes

There are several failure modes of significance when evaluating the risks associated with PRD failure. For the PRD, the failure modes are grouped into two categories.

a) Fails to open as designed (FAIL):

    1) stuck or fails to open (FTO),

    2) device partially open (DPO),

    3) opens above set pressure (OASP).

b) Leakage failure (LEAK):

    1) leakage past device (LPD),

    2) spurious or premature opening (SPO),

    3) device stuck open (DSO).

FAIL modes generally causes the potential for the protected equipment overpressure resulting in a loss of containment. Included in FAIL modes is the case of a DPO causing a less severe equipment overpressure.

A PRD OASP is included in the FAIL failure mode. The POF curves are based on bench test data where a failure is defined as any test requiring a pressure greater than 1.3 times the set pressure. A value that opens above set pressure during a test but does not exceed 1.3 times the set pressure is considered a successful test and is not included in the FAIL case.

Consequences associated with the FAIL failure mode include the effects of fires and explosions on personnel and equipment and the exposure of personnel to toxic fluids as a result of loss of containment. These consequences and their effect on personnel and equipment are further described in Part 3.

A secondary concern is failure of a PRD to contain the process while operating at normal conditions. The API 581 methodology groups the remaining three failure modes together into the LEAK category. LPD, SPO, and DSO failures will not result in overpressure or loss of containment from the protected equipment but represent potentially unacceptable leakage from the process system. The consequences of leakage through a PRD can range from a minor nuisance, causing some loss of product, to a more severe consequence resulting in a process shutdown to repair or replace the PRD. If the PRD discharges to the atmosphere, additional consequences may be environmental impact and potential for fires, explosions, and toxic exposure.

6.1.3 Use of Weibull Curves

POFOD and the probability of leakage (POL) is expressed as a function of time for risk-based planning of inspections and tests. Weibull functions are suitable for this task with the added advantage that they may be used to evaluate large populations of data points to seek trends. In the absence of large sets of failure data, the functions are still useful as a starting point since the parameters involved describe both the manner of failure and the time to failure.

Using a two-parameter Weibull distribution [4], The cumulative failure density function, $F(t)$, sometimes referred to as unreliability, is using a two-parameter Weibull distribution as shown in Equation (5.90) and discussed in Section 6.1.2.

The Weibull characteristic life parameter, η, is equivalent to the MTTF when the Weibull β parameter is equal to 1.0. Adjustments to the η parameter are made to increase or decrease the POFOD and POF as a result of environmental factors, PRD types, or available inspection data the PRD. Adjustments to the η parameter may be viewed as an adjustment to the PRD MTTF.

Determination of the default Weibull parameters assumes that PRDs in similar services will have a similar POFOD, P_{fod}, and POL, P_l, and industry failure rate data may be used as a basis to establish the initial or default PRD POF. The POFOD is evaluated for the process and installation conditions, such as process temperature, process corrosivity, and the tendency of the process to foul, polymerize, block the PRD inlet, or prevent the PRD from reseating during operation. Rough handling during transportation and installation and excessive piping vibration are also associated with failures. In addition, increased demand rates and improper installations that result in chatter may also increase the POFOD and POL.

6.1.4 PRD Testing, Inspection, and Repair

Inspection, testing, reconditioning, or replacement of PRDs are recognized safe practices and serve to reduce the POFOD and leakage. This PRD methodology assumes that a bench test performed on a PRD in the as-received condition from a process unit will result in a true determination of the performance of the PRD on the unit.

An effective inspection program for PRDs will track the history of inspection and test of each PRD. The outlined PRD methodology adjusts the POF data for each PRD based on historical data and allows varying degrees of inspection effectiveness. Pass/fail test data are given the highest confidence inspection effectiveness level when a shop bench pre-pop test is performed. A lower confidence inspection effectiveness level is associated with the inspection if a PRD is inspected or overhauled without a pre-test.

6.1.5 PRD Shop Inspection/Overhaul or Replacement Start Date [9]

The PRD is assumed to be returned to service in the as-new condition when the PRD is overhauled in the shop. The original install date for the PRD is retained with a last inspection date reflecting the PRD overhaul date or the installation date after overhaul. As a result, the calculated inspection interval and subsequent new due date for the PRD is based on the date the PRD was most recent overhaul or the date the PRD was installed following the most recent overhaul.

The installation date and last inspection date will be the same for a PRD that is replaced rather than overhauled and the calculated inspection interval and next test due date is based on the installation date. The replaced PRD does not necessarily need to be a new valve, it could be a spare or overhauled valve.

It is important to note that there may be a delay between the time of overhaul and the time the PRD is placed in service. This time delay may occur because the PRD has a spare and is currently installed or there is a delay in recommissioning. If there is a delay in between the time of the overhaul and the time the PRD returns to service, consider using the date of return to service date to calculate the inspection interval and subsequent new due date. For example, if the last inspection date with shop inspection/overhaul was in the year 2015, and the PRD was not put back into service until 2018, then consider using 2018 to calculate the next inspection due date.

The impact on the PRDs reliability of a time delay between the testing and installation dates should be considered. Where reliability may have adversely been affected, retesting prior to the installation should be considered. The owner–operator should specify the maximum delay time after which:

a) the install date is to be used rather than the last overhaul date to calculate the next inspection date, and

b) a retest should be considered before installation.

Often PRDs are pop-tested either in the field or in the shop without overhauling the PRD. When a PRD is pop-tested in the field or in the shop without performing an overhaul, the PRD has not been returned to service in an as-new condition. The PRD is assumed to remain in the prior test condition, and the POFOD may be adjusted based on the results of the field test (i.e. credit for inspection to reduce uncertainty). In this case, the last overhaul date is unchanged and the PRD will not get the full benefit of an overhaul. In this case, the due date is determined by adding the recommended inspection interval to the last overhaul date (not the last inspection date). For example, if PRD was pop-tested and overhauled in 2005, and then pop-tested, but not overhauled in 2010, and put back into service, the next inspection date is determined by adding the recommended inspection interval (7 years) to 2005, the date of the last overhaul. The next inspection due date is therefore 2012.

6.1.6 Risk Ranking of PRDs

The PRD methodology provides individual PRD risk ranking as well as risk ranking between PRDs and other fixed equipment being evaluated.

The two key drivers for effectively risk ranking between PRDs is the:

1) specific PRD reliability for each PRD by selecting a severity of service for the PRDs, establishing a default POF, and modifying the POFOD using the inspection and test history;

2) relative importance or criticality of each PRD by defining the relief system design basis and knowledge of the overpressure demand cases applicable for each PRD. The PRD risk rank will increase based on the criticality and demand placed the PRD.

6.1.7 Link to Fixed or Protected Equipment

To effectively characterize the risk associated with PRD failure, the consequence associated with the failure of a PRD to open upon demand should be tied directly to the equipment that the PRD protects by using direct links to the fixed equipment RBI analysis as covered in Part 2 and Part 3. The risk of loss of containment from fixed equipment increases proportionately with the amount of overpressure that occurs when the PRD fails to open on demand. In addition, the calculated risk associated with damaged fixed equipment will be greater than that for undamaged equipment since the actual damage states (i.e. damage factor, D_f, see Part 2) are used in the calculations.

Although consequences associated with PRD overpressure cases are greater than those associated with the fixed equipment operating at normal pressure, it may be compensated by using realistic PRD demand rates and accurate PRD failure rate data results in a low frequency of occurrence.

6.2 Overpressure Potential for Overpressure Demand Cases

6.2.1 General

The PRD analysis should consider the overpressure demand cases applicable for each PRD. The overpressure demand cases are the potential process upsets that the PRD is designed protect against and the criticality of the protected equipment if a failure on demand occurs. The importance of the criticality of the protected equipment in addition to the PRD failure is demonstrated by the following examples.

EXAMPLE 1 A PRD that protects equipment and piping for the blocked discharge demand case downstream of a pump is less critical than a PRD that is protecting a reactor from a runaway chemical reaction. In the former case, a lower overpressure with a PRD failure to open upon demand would be expected.

EXAMPLE 2 A PRD protecting piping against thermal relief is less critical than a PRD protecting low-pressure equipment from a high-pressure gas breakthrough due to a control valve failure.

The potential overpressure resulting from a PRDs failure to open upon demand may be calculated for most of the overpressure demand cases. The logic for determining the potential overpressure for each of the overpressure demand cases is provided in Table 6.2. The potential overpressure approaches the burst pressure (defined as design margin times MAWP) of the protected equipment in cases where the overpressure demand case is not self-limiting. In other cases, such as a blocked discharge downstream of a centrifugal pump, the potential overpressure is self-limiting as it deadheads at the pump pressure of typically 1.3 times the normal discharge pressure of the pump.

Defining demand case overpressure scenarios for each PRD requires a thorough review of the unit pressure-relief study in conjunction with the P&IDs. The review should be performed by qualified personnel with experience in the design and installation of pressure-relief systems.

The determination of the potential overpressure, P_o, due to a PRDs failure to open upon demand is generally a function of the following.

a) Type of Upstream Overpressure Source—Centrifugal pumps, steam supply headers, upstream pressure vessels, etc.

b) Upstream Source Pressures—Steam supply pressure, control valve upstream pressure, pressure from the high-pressure side of a heat exchanger, and deadhead pressure for centrifugal rotating equipment. Additionally, credit for PRDs on upstream equipment can be assumed to be available to limit overpressure.

c) Heat Sources, Types, and Temperatures—Blocked-in equipment, the heat source supplying energy to the system has a significant impact on the potential overpressure. Examples, a solar heat/energy supplied in a thermal relief scenario may result in flange leaks, limiting the overpressure to the normal operating pressure of the system. Alternatively, the overpressure may increase until a rupture occurs if the heat source is a fired heater (i.e. overpressure exceeding the burst pressure of the protected equipment). Other heat sources include steam reboilers to towers and the hot side of heat exchangers.

d) Fluid Bubble Point Pressure—Pressure increase is limited by the bubble point pressure of the contained process fluid at the temperature of the heat/energy source being supplied to the process.

6.2.2 Multiple Relief PRD Installations

The probability is reduced when multiple PRDs are used to manage the relief capacity required since the likelihood that multiple failures would occur is unlikely. In this case, the component POF is lower due to the expectation that some of the PRD capacity will be available on demand and minimize the overpressure experienced. When a component is protected by multiple PRDs, the calculated POFOD of each PRD in the multiple installation does not change. This multiple PRD installation adjustment factor, F_a, adjusts the overpressure that the component is likely to experience with a multiple PRD installation to minimize the potential overpressure.

$$F_a = \sqrt{\frac{A^{prd}}{A^{prd}_{total}}} \tag{5.89}$$

The F_a is a ratio of the area of a single PRD to the total area considering all PRDs in the multiple setup. The multiple PRD installation adjustment factor has a minimum reduction value of 0.25 since PRDs in a multiple PRD installation may have common failure modes. The final component overpressure is reduced by using Equation (5.90):

$$P^{comp}_{o,j} = F_a \cdot P_{o,j} \tag{5.90}$$

The reduced overpressure should be used when determining the protected component POF but is not used for calculating the overpressure factor, F_{op}.

6.2.3 Calculation Procedure

The following procedure is used to identify the potential PRD overpressure demand case scenarios.

a) Step 1.1—Determine the list of overpressure scenarios applicable to the piece of equipment being protected by the PRD under evaluation. Table 5.3 provides a list of overpressure demand cases specifically covered. Additional guidance on overpressure demand cases and pressure-relieving system design is provided in API 521 [7].

b) Step 1.2—Determine the design margin, DM, for the protected component material of construction.

c) Step 1.3—For each overpressure demand case, estimate the amount of overpressure, $P_{o,j}$, likely to occur during the overpressure event if the PRD were to fail to open.

d) Step 1.4—Calculate the total PRD orifice area, A^{prd}_{total}, for all PRDs in a multiple PRD installation.

e) Step 1.5—Calculate the overpressure adjustment factor, F_a, using Equation (5.89).

f) Step 1.6—Calculate the final component overpressures determined in Step 1.4 using Equation (5.90).

6.3 PRD POF

6.3.1 Definition

The POF calculations are performed for each overpressure demand case identified for the PRD according to Section 5.2. Failure of a PRD is defined as:

1) failure to open during emergency or upset condition causing an overpressure of the protected component and resulting in loss of containment in failures/yr;

2) leakage through a PRD (Section 6.4).

6.3.2 Failure to Open

The calculation for the POF of a PRD failing to open is the product of an estimated overpressure demand case frequency (failures/demand), the probability of the PRD failing to open on demand (failures/demand), and the POF of the protected component at the overpressures.

A PRD protects equipment components from multiple overpressure scenarios. Guidance on overpressure demand cases and pressure relieving system design is provided in API 521 [7]. Each of these scenarios (fire, blocked discharge, etc.) may result in a multiple possible overpressure demand case scenarios, $P_{\text{o},j}$. In addition, each overpressure demand case scenario has an associated demand rate, DR_j. Demand cases are discussed in more detail in Section 6.2, Table 6.2, and Table 6.3. The POF of the PRD failing to open for each overpressure demand case scenario is defined in Equation (5.91).

$$P_{\text{f},j}^{\text{prd}} = P_{\text{fod},j} \cdot DR_j \cdot P_{\text{f},j} \tag{5.91}$$

where j is the applicable overpressure demand case scenario for the PRD, $P_{\text{f},j}^{\text{prd}}$.

The protected component POF, $P_{\text{f},j}$, is a function of time and the potential overpressure. The individual parts for the POF of a PRD failing to open in Equation (5.91) are discussed in more detail in the following sections.

a) Section 5.3.3—PRD demand rate, DR_{f}.

b) Section 5.3.4—PRD POFOD, $P_{\text{fod},j}$.

c) Section 5.3.5—POF of protected component as a result of overpressure, $P_{\text{f},j}$.

6.3.3 PRD Demand Rate

The first step in evaluating the POF of a PRD failing to open is to determine the expected demand rate (demands/yr) placed on the PRD.

a) Default Initiating Event Frequencies.

   Estimated initiating event frequencies, EF_j, are provided based on the types of overpressure demand case scenario assigned. Examples of the initiating event frequencies are provided in Table 6.3, and the background on the default initiating event frequencies is provided in Table 6.2.

b) Credit for Other Layers of Protection.

   The actual PRD demand rate is not necessarily equal to the initiating event frequency. A demand rate reduction factor, $DRRF_j$, accounts for the difference in the overpressure demand case event frequency and the PRD overpressure demand rate.

Pressure vessels often contain control systems, high integrity protective instrumentation, shutdown systems, and other layers of protection to reduce the PRD demand rate. Credit can be taken for additional layers of protection, $DRRF_j$, or operator intervention for by the to reduce the probability of overpressure. The $DRRF_j$ may be determined rigorously for the installation using a layer of protection analysis (LOPA) or use the estimated value provided in Table 6.3.

An example using the $DRRF_j$ credit is for the fire overpressure demand case with an estimated initiating event frequency of 1 every 250 years (0.004 events/yr). However, due to factors such as fire impinging on equipment rarely results in a significant pressure increase causing the PRD to open. As a result, factors reducing the actual PRD demand rate, such as fire proofing, availability of other escape paths for the process fluid, and firefighting efforts at the facility may increase the $DRRF_j$.

c) Calculation of Demand Rate.

The PRD demand rate, DR_j, is calculated as the product of the initiating event frequency and the $DRRF_j$ using Equation (5.92):

$$DR_j = EF_j \cdot DRRF_j \tag{5.92}$$

where j is the applicable overpressure demand case scenario.

A PRD typically protects equipment from several overpressure demand case scenarios, and each overpressure demand case has a unique demand rate. Default EF_j values for each of the overpressure cases are provided in Table 5.3. An overall demand rate on the PRD can be calculated in Equation (5.93):

$$DR_{\text{total}} = \sum_{j=1}^{ndc} DR_j \tag{5.93}$$

Additional guidance on overpressure demand cases and pressure relieving system design is provided in API 521 [7].

If the relief design basis of the PRD installation has not been completed, the list of applicable overpressure demand cases may not be available, and it may be more appropriate to use a simple overall average value of the demand rate for a PRD. An overall demand rate for a particular PRD may usually be estimated from past operating experience for the PRD.

d) Owner–Operator Experience.

The EF_j for the overpressure demand cases as shown in Table 6.3 are default values that may not be applicable in all situations. Owner–operators may have operating experience with a particular process system that may warrant using other event frequencies. Additionally, a PRD that protects multiple components may experience an increased demand for a particular overpressure scenario. For example, a PRD located on a crude distillation tower may also protect the desalted preheat exchanger train. Since the PRD protects equipment encompassing a much greater area of the unit, an increase in the EF_j for the fire case may be appropriate. In general, where a PRD protects multiple components, the EF_j should be evaluated to determine if an increase is justified.

6.3.4 PRD POFOD

The next step is to determine the PRD POFOD in service.

a) Categories of Service Severity.

PRD failure rates are directly related to the process severity of service. Categories of service are established for a PRD based on the process fluid tendency to result in a PRD failure caused by corrosion, fouling, plugging, or other effects. Temperature may also be a factor in determining the severity of service. The categories of service severity (mild, moderate, or severe) are associated with specific failure tendencies and default Weibull cumulative failure distribution curves, as described in Table 6.4.

It is important to note that a process fluid classified as mild service for POFOD is not necessarily a mild service for POL. For example, industry failure data show that cooling water, which is known to be a dirty/scaling service, has one of the highest POFOD rates and therefore may be classified as severe. Conversely, PRDs in cooling water service have not demonstrated a significant amount of POL failures and therefore may be classified as mild service for the POL. Steam service is another example where industry data indicate that steam should be classified as mild for a POFOD failure. Steam is classified as severe for a POL failure since steam is known to cause PRD leaks due to erosion of high-temperature steam.

b) Default POFOD vs Time in Service.

1) General.

Table 6.5 provides the default Weibull parameters for failure to open for conventional spring-loaded PRVs, balanced bellows PRVs, pilot-operated PRVs, and rupture disks. Weibull parameters provided in Table 6.5 were determined using industry failure rate data with the majority of the available data from successful performance during the PRD service interval. Successful service test points are referred to as suspensions and were included with the failure data in determination of the Weibull parameters.

Weibull parameters are provided for the three categories of PRD service severity (mild, moderate, or severe), as discussed in Section 6.3.4 a). The Weibull parameters provide the default POFOD curves for each of the PRD types listed in Table 6.5 when used in the Weibull cumulative failure density function, $F(t)$, in Equation (5.90). For example, Figure 6.2 provides the default Weibull cumulative failure distribution curves used for spring-loaded conventional PRVs using the Weibull function to describe the three categories of service severity.

NOTE The units for the POFOD data presented in Figure 6.2 are failures/demand since the data were established from actual PRD bench test results rather than continuous service data. POFOD should not be confused with POF (failures/yr) that includes the demands on the PRD (see Section 6.2) and the probability that the protected component will fail in an overpressure event (see Section 6.3.5).

The cumulative failure distribution curves shown in Figure 6.2 and the Weibull parameters presented in Figure 6.6 are the default values based on the category of service severity of the PRD being evaluated. These base values are defaults and should be replaced with owner–operator site-specific data, if available [Section 6.3.4 c) 3)].

2) Presence of an Upstream Rupture Disk.

Rupture disks are often installed in combination with PRVs to isolate the PRV from process corrosive or fouling conditions and reducing the potential for POFOD. API 520, Parts 1 and 2 provide additional information related to the use and installation of rupture disks upstream of PRVs.

A mild service for POFOD is recommended for a PRD with upstream rupture disks, regardless of the process fluid severity. Assigning a mild POFOD service assumes that the space between the rupture disk and the PRV is vented and monitored for leakage, as required by code and recommended by API 520. If the space is not vented and monitored for leakage, no credit for an upstream rupture disk is given.

3) Use of Plant-specific Failure Data.

Data collected from specific plant testing programs may be used for POFOD and POL analysis. MTTF or failure per million operating hours may be calculated in the required format using simple conversion routines.

c) Default Data for Balanced Bellows PRVs.

Balanced spring-loaded PRVs contain a bellows to isolate the back side of the disk from the effects of superimposed and built-up back pressure. The bellows isolates the PRD internals from a corrosive process fluid in the discharge system. Industry failure rate data indicates that balanced bellows PRVs have the same POFOD rates as conventional PRDs since process fluid is isolated from the PRV internals. As shown in Table 6.6, the η characteristic life for bellows PRVs is the same as for conventional PRVs.

d) Default Weibull Parameters for Pilot-operated PRVs.

To date, there is little failure rate data in the industry available for pilot-operated PRVs. One source [10] indicates that pilot-operated PRVs are 20 times more likely to fail than their spring-loaded counterparts. The Weibull parameters for the POFOD curves for conventional PRVs in Table 6.5 are used as the basis for pilot-operated PRVs with adjustment factors applied to the η characteristic life. For mild service, the η characteristic life for pilot-operated PRVs is reduced by a factor of 1.5; for moderate service, the reduction factor is 3.0; and for severe service, the reduction factor is 5.0.

e) Default Weibull Parameters for Rupture Disks.

To date, there is little failure rate data in the industry available for rupture disks. Rupture disks are simple to use and reliable. Rupture disks open at or near burst pressure unless the inlets or outlets are plugged or the disk is installed improperly. Failure of rupture disks are typically due to premature bursts. The Weibull parameters for POFOD for rupture disks are based on the mild severity curve for conventional PRVs and assuming that a rupture disk is at least as reliable as a conventional PRV. Default parameters assume that the rupture disk material is resistant to the process fluid corrosion. If the rupture disk material is resistant to the process fluid corrosion, the disk Weibull parameters should be adjusted accordingly.

f) Adjustment for Conventional PRVs Discharging to Closed System.

An adjustment factor is used to modify the base Weibull parameters for conventional PRVs discharging to a closed system or to flare. A conventional PRV characteristic life, η, is reduced by 25 % since no bellows is present to protect the bonnet housing from discharge system corrosion.

$F_c = 0.75$ for conventional valves discharging to closed system or flare

$F_c = 1.0$ for all other cases

g) Adjustment for Environmental Factors.

Environmental and installation factors that affect the reliability of PRDs include installed piping vibration, a history of chatter, or pulsing flow or cyclical service (downstream of reciprocating rotating equipment).

Other environmental factors that can significantly affect POL are operating temperature and operating ratio. The PRD operating ratio is the ratio of maximum system operating pressure to the set pressure. When the operating ratio is greater than 90 % for spring-loaded PRVs, the system pressure is close to overcoming the closing force provided by the spring on the seating surface and the PRV will be more likely to leak (simmer). The increased potential for leakage is considered by applying an environmental factor to the default leakage curve. Similarly, an environmental factor is applied when the operating margin is greater than 95 % for pilot-operated PRVs.

NOTE Some pilot-operated PRVs can function at operating ratios up to 98 % (see API 520 for guidance on operation margin).

Analysis of the industry failure rate data shows that PRDs in vibration or cyclical service generally experience higher leakage rates, but POFOD rates are not significantly affected.

PRVs in service with a history of chattering should be redesigned or modified to eliminate the chatter, as soon as possible. An adjustment factor of 0.5 is applied to the Weibull η parameters for the POFOD and POL curves of a PRD experiencing chattering in service since the effects of chatter are detrimental to the protection provided by the PRD.

Table 6.6 provides the environmental adjustment factors applied to the default POFOD and POL Weibull curves. The environmental factor, F_{env}, increases the POFOD or POL (shifting the probability curves to the left) by reducing the curve's η characteristic life, as shown in Figure 6.5.

h) Updating POFOD Based on PRD-specific Inspection and Test Data.

1) Tracking Historical Inspection and Test Data.

An inspection program should track each PRD's testing and inspection history from its initial installation. Adjustments to the PRD POFOD, P_{fod}, and POL, P_{l}, curves are made to provide credit for information during a PRD inspection and test.

Data obtained from a PRD inspection and test will increase or decrease the POFOD and POL by modifying the Weibull parameters based on the pass/fail and no-leak/leak test results for the service duration, $t_{\text{dur},i}$, since the last inspection. An increase or decrease in the POFOD and POL through inspection will increase or decrease the recommended inspection and test interval.

Modifying the POFOD based on test results alone (i.e. bench test) will be nonconservative if the inlet or outlet piping was plugged during operation, affecting the operating of the PRD. The visually inspected condition of the piping should be documented for each inspection and specifically noted if the piping is plugged. Plugged PRD piping should be considered to have failed the inspection and test, regardless of the bench test results or inspection method used. More than 25 % of the pipe is considered plugged and the PRD should fail the inspection and test.

2) Effectiveness of Inspection Programs in Confirming Failure Rates.

Inspection effectiveness is based on its ability to adequately predict the pass/fail condition of the PRD and detect/quantify damage. Definitions for PRD inspection and test effectiveness are provided in Part 2, Annex 2.C, Table 2.C.3.1.

PRD inspection and test should document the effectiveness of the inspection and test performed. The inspection effectiveness concept as described in Part 2, Section 3.4.3 for fixed equipment is similar for PRDs. In addition, PRD inspection effectiveness measures the confidence in the pass/fail/leak result of the inspection and test.

Table 6.7 provides default conditional probabilities based on expert opinion. The conditional probabilities indicate the ability of the inspection and test to reflect an accurate representation of the PRD performance in an overpressure event. For example, a 90 % effectiveness associated with passing a highly effective inspection and test indicates that there is a 90 % chance that the PRD would perform as intended in service. Conversely, there is a 10 % chance that the PRD would fail to perform as intended in service.

The conditional probabilities in Table 6.7 assign the highest confidence to a PRD passing a bench tested without any prior cleaning (i.e. as-received condition). Bench testing of PRDs that were cleaned prior to testing or testing in situ, as well as visual inspections, provide information for expected PRD performance in service but are not considered as reliable as the as-received bench test.

PRDs that fail an inspection and test are treated differently than passed test results. For PRDs that fail a highly effective bench test, the 95 % confidence indicates a 95 % chance that the PRD would have failed to perform as intended in service. A usually effective bench test or test in situ after the PRD was steamed is assigned a 95 % confidence the PRD will fail to perform as intended in service.

An ineffective test does not provide additional information about the ability of the PRD to perform as intended in service and receives no inspection and test credit. Credit is provided for an overhauled PRD and is returned to service in like-new condition. In this case the service duration, $t_{\text{dur},i}$, is calculated based on the date of the ineffective inspection and test.

3) Inspection Updating.

The initial default Weibull parameters for the listed provided process fluid services are modified as inspection and test data are provided.

The Bayesian updating approach used assumes that the Weibull β shape parameter remains constant based on historical data and modifies the η since no inspection data being available. This is analogous to evaluating a one-parameter Weibull to update the PRD performance. Bayes' theorem works best when the error rates for a test are very small; however, test effectiveness in Table 6.8 varies from 50 % to 90 %. As a result, using Bayes' theorem high levels of uncertainty generates an unrealistically high adjusted POF, particularly for a pass bench test result. A modified inspection updating method was developed to provide a more realistic modification approach to characteristic life.

A default POFOD is defined for the PRD based on service duration, $t_{\text{dur},i}$, at the time of inspection to provide a POFOD vs time. The methodology calculates a prior PRD POFOD (prior to inspection) using Equation (5.94).

$$P_{\text{f,prior}}^{\text{prd}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{mod}}}\right)^{\beta}\right] \tag{5.94}$$

The prior probability that the PRD will operate on demand (pass) is calculated using Equation (5.95).

$$P_{\text{p,prior}}^{\text{prd}} = 1 - P_{\text{f,prior}}^{\text{prd}} \tag{5.95}$$

A PRD POFOD posterior probability is calculated based on the conditional probability, or confidence factor, CF, from Table 6.7 after an inspection of a specific effectiveness is performed. The updated POFOD is the conditional POFOD and is calculated using Equation (5.96) or Equation (5.97) depending on the inspection and test result.

The conditional PRD POFOD, $P_{\text{p,cond}}^{\text{prd}}$, for a passed inspection is calculated using Equation (5.96).

$$P_{\text{p,cond}}^{\text{prd}} = \left(1 - CF_{\text{pass}}\right) \cdot P_{\text{p,prior}}^{\text{prd}} \tag{5.96}$$

The conditional PRD POFOD, $P_{\text{f,cond}}^{\text{prd}}$,for a failed inspection is calculated using Equation (5.97).

$$P_{\text{f,cond}}^{\text{prd}} = CF_{\text{fail}} \cdot P_{\text{f,prior}}^{\text{prd}} + \left(1 - CF_{\text{pass}}\right) \cdot P_{\text{p,prior}}^{\text{prd}} \tag{5.97}$$

Weighted equations were developed to increase credit for inspection and test conducted later in the characteristic life. The posterior POFOD, $P_{\text{f,wgt}}^{\text{prd}}$, is calculated using the weighted prior and conditional probability equations provided in Table 6.9.

The updated η characteristic life is calculated using Equation (5.101) based on the service duration, $t_{\text{dur},i}$, of the PRD, the known β shape parameter, and $P_{\text{f,wgt}}^{\text{prd}}$.

The weighted equations produce a gradual shift from default POFOD data to PRD-specific POFOD data with a gradual increasing η characteristic life. A significantly shorter η characteristic life results if the PRD inspection and test has resulted in repeated failures early in the service.

Additional inspection and test updating guidance are as follows.

i) Tests conducted less than 1 year apart should not be credited.

ii) The η characteristic life cannot decrease after a pass inspection and test result—if the methodology decreases the η characteristic life, the prior probability should be used for the η characteristic life.

iii) The η characteristic life cannot increase after a fail inspection and test result—if the methodology increases the η characteristic life, the prior probability should be used for the η characteristic life.

4) Updating Failure Rates After Modification to the Design of the PRD.

Design changes that improve the PRD performance may result in a failure rate change, such as upgrading to a corrosion-resistant material or installation of an upstream rupture disk. Past inspection data no longer applies after PRD design changes. A new default curve should be selected based on Figure 6.2 or PRD-specific Weibull parameters should be defined based on owner–operator experience (generating a unique PRD curve) should be used after PRD design changes.

i) Adjustment for Overpressures Higher Than Set Pressure.

As discussed in Section 6.1.2, the POFOD curves are based on bench test data where a failure is defined as any test requiring a pressure greater than 1.3 times the set pressure. Industry failure data supports that as ratio of overpressure increases, the POFOD decreases, as shown in Figure 6.4.

A conservative assumption decreases the operating failure rate, $F_{\text{op},j}$, by a factor of 5 at an overpressure of 4.0 times the set pressure and linearly interpolate between 1.3 and 4.0 at an overpressure times the set pressure, shown in Equation (5.98).

$$\begin{aligned}
F_{\text{op},j} &= 1.0 && \text{for } \frac{P_{\text{o},j}}{P_{\text{set}}} < 1.3 \\
F_{\text{op},j} &= 0.2 && \text{for } \frac{P_{\text{o},j}}{P_{\text{set}}} > 4.0 \\
F_{\text{op},j} &= 1 - \frac{1}{3.375} \cdot \left(\frac{P_{\text{o},j}}{P_{\text{set}}} - 1.3 \right) && \text{for all other cases}
\end{aligned} \tag{5.98}$$

The $F_{op,j}$ adjustment factor ranges from 0.2 and 1.0.

The overpressure factor, $F_{op,j}$, is an adjustment for overpressure scenarios higher than 1.3 times the set pressure where j is the overpressure demand case scenario.

6.3.5 Protected Equipment Failure Frequency as a Result of Overpressure

A damage adjusted POF for components evaluated with RBI is included in the PRD POF calculation (Section 6.1). The component DF increases as a function of time and is calculated based on the applicable damage mechanisms for the equipment, the inspection history, and condition of the equipment. As the PRD inspection interval is extended, the component damage continues and risk increases as well as the risk of the PRD over time.

a) DF Calculation Procedure for PRD with Fixed Equipment.

The damage adjusted POF that is calculated at the normal operating pressure of the component is adjusted when evaluating PRDs. When a PRD fails to open on demand, the protected component pressure exceeds the normal operating pressure and may significantly exceed the MAWP. Equation (5.99) is used to calculate the protected component damage POF based on the expected pressure for each overpressure demand case. The damage adjusted component POF, $P_{f,j}$, is the probability of a loss of containment of the protected component resulting from the overpressure event.

$$P_{f,j} = \min\left(\left(a \cdot D_f \cdot F_{MS}\right) \cdot e^{\left(b \cdot \frac{P_{o,j}}{MAWP}\right)}, 1.0 \right) \tag{5.99}$$

where a and b are the constants from Table 6.11 for $P_{f,j}$ are based on the design margin, DM, from Table 6.10 for the protected component material of construction determined in Step 1.2.

During PRD overpressure events, the probability of loss of containment in the protected component increases. An undamaged component $\left(D_f = 1\right)$ has an upper limit probability of loss of containment of 1.0 when the overpressure is equal to the burst pressure (the expected failure pressure of the component). The burst pressure of the component is estimated using the design margin times the MAWP (with design margins for components constructed in accordance with various codes shown in Table 6.10). Alternatively, the burst pressure can be more accurately calculated using a more advanced analysis such as Svensson's method [11]. For damaged components $\left(D_f >> 1\right)$, the probability of loss of containment of 1.0 may occur at pressures much lower than the damaged component burst pressure (see Figure 6.6).

b) Selection of DF Class when PRD RBI Is Performed Without Fixed Equipment.

The D_f for the protected component may be specified using a DF class defined in Table 6.12 if a fixed equipment RBI study is not available. This D_f assignment is more qualitative than when an RBI analysis conducted to determine component D_f.

6.3.6 Calculation Procedure

The following calculation procedure may be used to determine the probability of a PRD failing to open.

a) Step 2.1—Grade the PRD inspection and test histories for each inspection using Part 2, Annex 2.C, Table 2.C.3.1 for guidance. Grade each inspection as pass/fail and no-leak/leak, assign the confidence factors, CF_i, and calculate the time duration, $t_{\text{dur},i}$.

   1) Step 2.1.1—Grade each inspection and test using Part 2, Annex 2.C, Table 2.C.3.1.

   2) Step 2.1.2—Record the inspection and test result as pass/fail and assign the appropriate CF_i.

   3) Step 2.1.3—Calculate the service duration, $t_{\text{dur},i}$, for each inspection.

   4) Step 2.1.4—Determine if the PRD was overhauled. If the PRD was overhauled, the date of the most recent overhaul is the date to be used in Step 2.7 (Figure 6.7). The owner–operator may consider using the return to service date instead of the overhaul date to calculate the next inspection date. The owner–operator should define the timeframe (delay between overhaul and in-service date) for when the return to service date should be used. Refer to Section 5.1.4 and Section 5.1.5 for more information on acceptable time delays before a retest should be considered.

b) Step 2.2—Select the most recent inspection and test history and service duration, $t_{\text{dur},i}$.

c) Step 2.3—Determine the default values for the Weibull parameters, β and η_{def}, based on category of service severity [Section 6.3.4 a)], selection of the default POFOD curve [Section 6.3.4) c)], type of PRD [Sections 6.3.4 c) through 6.3.4 e)], and using Table 6.5 and Table 6.6.

d) Step 2.4—Determine the adjustment factor, F_c, for conventional PRDs discharging to a closed system or flare [Section 6.3.4) f)].

e) Step 2.5—Determine the environmental adjustment factor for conventional PRDs, F_{env}, using Table 6.6.

f) Step 2.6—Calculate the modified characteristic life, η_{mod}, using Equation (5.100), η_{def} from Step 2.3, and F_c Step 2.4.

$$\eta_{\text{mod}} = F_c \cdot F_{\text{env}} \cdot \eta_{\text{def}} \tag{5.100}$$

g) Step 2.7—Calculate the updated characteristic life, η_{upd}, using η_{mod} from Step 2.6 and PRD inspection and test history from Step 2.1.

   1) Step 2.7.1—Calculate the prior POF, $P_{\text{f,prior}}^{\text{prd}}$, using Equation (5.94) and the time period, $t_{\text{dur},i}$, from Step 2.6.

   NOTE For the first inspection record, η_{mod} from Step 2.1 is used with subsequent inspection records using η_{upd} from Step 2.7.6.

   2) Step 2.7.2—Calculate the prior probability of passing, $P_{\text{p,prior}}^{\text{prd}}$, using Equation (5.95).

   3) Step 2.7.3—Determine the conditional probability of pass test result, $P_{\text{p,cond}}^{\text{prd}}$, using Equation (5.96).

   4) Step 2.7.4—Determine the conditional probability of failed test result, $P_{\text{f,cond}}^{\text{prd}}$, using Equation (5.97).

   5) Step 2.7.5—Calculate the weighted POF, $P_{\text{f,wgt}}^{\text{prd}}$, using the equations in Table 5.9.

6) Step 2.7.6—Calculate the η_{upd} using Equation (5.101) using Weibull parameters β from Step 2.3 and the weighted POF, $P_{f,wgt}^{prd}$, established in Step 2.7.5.

$$\eta_{upd} = \left(\frac{t_{insp}}{\left(-\ln\left(1 - P_{f,wgt}^{prd}\right)\right)^{\frac{1}{\beta}}} \right) \tag{5.101}$$

7) Step 2.7.7—Repeat these steps for each of the inspection records available for the PRD to calculate the final η_{upd}.

8) Step 2.7.8—Calculate the POFOD as a service duration, $t_{dur,i}$, for the PRD using Equation (5.102) and η_{upd} from Step 2.7.7.

$$P_{fod} = 1 - \exp\left[-\left(\frac{t_{dur,i}}{\eta_{upd}} \right)^{\beta} \right] \tag{5.102}$$

h) Step 2.8—For each overpressure scenario, determine the overpressure adjustment factor, $F_{op,j}$, using Equation (5.98).

i) Step 2.9—Calculate the adjusted POFOD using Equation (5.103) and $F_{op,j}$ from Step 2.8.

$$P_{fod,j} = P_{fod} \cdot F_{op,j} \tag{5.103}$$

j) Step 2.10—For each overpressure demand case, determine the initiating event frequency, EF_j, using Table 6.3 or based on owner–operator experience for the overpressure demand case.

k) Step 2.11—Determine the demand rate reduction factor, $DRRF_j$, accounting for layers of protection that may reduce the probability of an overpressure of the protected component; see Section 6.3.3 b) and Table 6.3 for guidance.

l) Step 2.12—For each overpressure demand case, determine the demand rate, DR_j, placed on the PRD, using Equation (5.92).

m) Step 2.13—Determine the MAWP of the protected equipment.

n) Step 2.14—Calculate the protected component damage adjusted DF, D_f. The DF should be determined at the PRD service duration, $t_{dur,i}$, from Step 2.2 for a DF as a function of time. If a fixed equipment RBI analysis has not been completed, the DF may be estimated using Table 6.12.

o) Step 2.15—Calculate the protected component POF at the overpressure, $P_{f,j}$, using Equation (5.99) and the overpressure is determined in Step 1.3 of Section 6.2.2.

p) Step 2.16—Calculate the PRD POF, $P_{f,j}^{prd}$, using Equation (5.91) using $P_{fod,j}$ from Step 2.9, DR_j from Step 2.12, and $P_{f,j}$ from Step 2.15.

q) Step 2.17—Repeat Step 2.1 through Step 2.16 for each component protected by the PRD.

6.4 POL

6.4.1 Overview

The POL case is a function of failure during continuous operation. Industry data associated with POL, P_l, is presented in failures/yr with not impacted by demand rate.

a) Categories of Service Severity.

Guidance on selecting the proper service severity for the POL case is provided in Table 6.13. The owner–operator's experience with a PRD in a particular service provides guidance for selecting the severity.

b) Default POL Rates vs Time in Service.

A set of Weibull curves provided for the POL case are from data of PRDs in continuous service (i.e. a continuous demand). The data were collected in units of failures/yr and were not modified by demand rate. Table 6.14 provides the default PRD POL vs time information using a Weibull function to describe three types of service (mild, moderate, and severe). These data were based on a limited amount of industry data and should be supplemented by owner–operator data, where available.

The default cumulative POL distribution curves for spring-loaded conventional PRVs using the Weibull function to describe the three categories of service severity are provided in Figure 6.3 as an example.

c) Default Weibull Parameters for Balanced Bellows PRVs.

The Weibull parameters for the POL curve for balanced bellows PRVs provided in Table 6.14 match the industry failure rate data. These data reflect a minor increase in the POL compared to conventional PRVs.

d) Default Weibull Parameters for Pilot-operated PRVs.

The design of pilot-operated PRVs provide a better seal as the operating pressure approaches the set pressure. Owner–operator Weibull parameters for conventional or pilot-operated PRVs should be used, if available, until improved failure rate data are developed for η characteristic life for leakage provided in Table 6.14.

e) Default Weibull Parameters for Rupture Disks.

Since no industry data were available for rupture disk leakage, Weibull parameters are based on the mild severity curve for conventional PRVs [see Section 6.3.4 e) for additional information].

f) Adjusted Default POL Curve for PRVs Containing Soft Seats.

Soft seats (O-rings) are often added to spring-loaded PRVs to reduce the potential for leakage across the seat. When a conventional or balanced bellows PRV contains a soft seat design, the η parameter for the default POL Weibull curve is increased by a factor of 1.25 in accordance with the following factors:

$F_s = 1.25$ for soft-seated designs

$F_s = 1.0$ for all other cases

g) Environmental Modifiers to the Default POFOD and POL Data.

Table 6.6 provides environmental adjustment factors, F_{env}, for the POL Weibull curves [Section 6.3.4 g)]

h) Set Pressure Adjustment.

The POL decreases as the ratio of operating pressure to set pressure, $\frac{P_s}{P_{set}}$, decreases, as shown in Table 6.8.

i) Presence of an Upstream Rupture Disk.

The POL is negligible (i.e. $P_l^{prd} = 0.0$) and the COF = 0 with a rupture disk installed upstream of the PRV.

j) Modification of Leakage Rates Based on PRD-specific Inspection and Test Data.

The characteristic life updating based on inspection and test history is the same as the approach described in Section 6.3.4 h) for the POFOD case.

6.4.2 POL Calculation Procedure

The PRD POL is calculated using the following steps.

a) Step 3.1—Determine default Weibull parameters, β and η_{def}, based on category of service severity and PRD type [Section 6.3.4 a) through Section 6.3.4 i)].

b) Step 3.2—Apply an adjustment factor, F_s, for the presence of soft seats [Section 6.3.4 j)].

c) Step 3.3—Apply an adjustment factor, F_{env}, for environmental factors [Section 6.3.4 j)].

d) Step 3.4—Calculate the modified characteristic life, η_{mod}, using Equation (6.104).

$$\eta_{mod} = F_s \cdot F_{env} \cdot \eta_{def} \tag{5.104}$$

e) Step 3.5—Calculate the updated characteristic life, η_{upd}, using η_{mod} from Step 3.4 and PRD inspection and test history from Step 2.6.

1) Step 3.5.1—Calculate the prior probability of leak, $P_{f,prior}^{prd}$, using Equation (5.94) and the time period, $t_{dur,i}$, from Step 2.6.

NOTE For the first inspection record, η_{mod} from Step 2.1 is used with subsequent inspection records using η_{upd} from Step 3.5.6.

2) Step 3.5.2—Calculate the prior probability of no leak, $P_{p,prior}^{prd}$, using Equation (5.95).

3) Step 3.5.3—Determine the conditional probability of no-leak test result, $P_{p,cond}^{prd}$, using Equation (5.96).

4) Step 3.5.4—Determine the conditional probability of leak test result, $P_{f,cond}^{prd}$, using Equation (5.97).

5) Step 3.5.5—Calculate the weighted POF, $P_{f,wgt}^{prd}$, using the equations in Table 6.9.

6) Step 3.5.6—Calculate η_{upd} using Equation (5.101) using Weibull parameters β from Step 2.3 and the weighted POF, $P_{f,wgt}^{prd}$, established in Step 3.5.5.

7) Step 3.5.7—Repeat these steps for each of the inspection records available for the PRD to calculate the final η_{upd}.

f) Step 3.6—Calculate the set pressure factor, F_{set}, based on the PRD type, operating pressure, P_s, and set pressure, P_{set} (see Table 6.8).

g) Step 3.7—Calculate the updated characteristic life, η_{upd}, from Step 3.5.7 using Equation (5.105).

$$P_l^{prd} = 1 - \exp\left[-\left(\frac{t_{dur,i}}{\eta_{upd}}\right)^{\beta}\right] \cdot F_{set} \tag{5.105}$$

6.5 PRD Consequence of Failure to Open on Demand (COFOD)

6.5.1 General

The COFOD calculations for event outcomes such as fires, explosions, and toxic exposure are described in Part 3. A PRD failure to open on demand will result in the protected component being exposed to significantly higher pressures than during normal operation. The PRD COFOD calculates the impact of each demand case scenario failure at the overpressure.

Table 6.15 shows the expected potential consequences of a pressure vessel as a percentage of an overpressure above the MAWP. Table 6.15 is provided as a qualitative discussion of the potential risks to pressure vessels due to an overpressure event and is not intended to indicate any specific event outcome. The methodology accounts for the effects of overpressure on protected equipment by increasing the probability of loss of containment. At an overpressure equal to the burst pressure (estimated to be the design margin times the MAWP), the probability of loss of containment is conservatively assumed to be equal to 1.0 [Section 6.3.4 i)].

The COFOD, $C_{f,j}^{prd}$, is calculated for each overpressure demand case scenario as follows.

a) Step 4.1—For each overpressure demand case, calculate the financial COFOD, $C_{f,j}^{prd}$, for the protected component using the overpressure from Step 1.6 and methodology in Part 3.

6.6 Consequence of Leakage (COL)

6.6.1 General

The PRD consequence of leak is typically less significant than a component loss of containment resulting from a PRD COFOD. While the frequency of leakage is less significant, a leak may result in a high risk ranking of the PRD.

The COL, C_l^{prd}, from PRDs is calculated by summing the following costs and using Equation (5.106):

$$C_l^{prd} = Cost_{inv} + Cost_{env} + Cost_{sd} + Cost_{prod} \tag{5.106}$$

— Lost inventory cost based on the product of the cost of fluid, the leakage rate (Section 5.4), and the estimated number of days to discover the leak (Table 6.15).

— Regulatory and environmental costs associated with leakage.

— Downtime cost to repair or replace the PRD if a leaking or stuck open PRD cannot be tolerated.

— Production cost while conducting the repair or replacement of the leaking PRD.

For a multiple PRD installation, the POL for any one specific PRD does not increase. However, since the number of PRDs increases, the POL and the associated consequences increase in proportion to the number of PRDs protecting the system.

6.6.2 Estimation of PRD Leakage Rate

Analysis of industry bench test data indicates approximately 8.4 % of PRVs tested leaked during a bench test between 70 % and 90 % of the set pressure, 6.6 % of PRVs leaked at pressures below 70 % of the set pressure, and an additional 2.4 % of PRVs leaked significantly below 70 % of their set pressure. A summary of the leakage rates used for the consequence calculation is provided in Table 6.17.

A leakage rate of 1 % of the PRD rated capacity, W_c^{prd} (calculated at normal operating conditions), was used for minor or moderate leaks and calculated using Equation (5.107). A minor or moderate leakage, C_l^{mild}, represents 90 % of the potential leakage cases, as shown in Table 6.17.

$$lrate_{mild} = 0.01 \cdot W_c^{prd} \tag{5.107}$$

The leakage rate for a stuck open or spurious leaks is assumed to be 25 % of the PRD rated capacity, W_c^{prd}, and calculated using Equation (5.108). A leak from a stuck open PRD, C_l^{so}, represents 10 % of all potential leakage cases.

$$lrate_{so} = 0.25 \cdot W_c^{prd} \tag{5.108}$$

The rated capacity of the PRD, W_c^{prd}, can usually be found on the PRD datasheet. It can also be calculated using the methods presented in API 520, Part 1 [8].

6.6.3 Estimated Leakage Duration

The leakage duration, D_{mild}, is calculated mild or moderate leakage, as shown in Table 6.14, assuming that mild leakage from larger PRDs will be discovered sooner than leakage from smaller PRDs. The leakage duration for the stuck open case is calculated using Equation (5.109), assuming that an immediate PRD repair is required with an isolation time of 30 minutes.

$$D_{so} = \frac{30 \text{ min}}{60 \text{ min/hr} \cdot 24 \text{ hr/day}} = 0.021 \text{ days} \tag{5.109}$$

6.6.4 Credit for Recovery of Leaking Fluid

The cost of lost inventory is not considered to be as severe when the unit has a flare recovery system installed or the discharge from the PRD is to a closed system. A recovery factor, F_r, is based on the discharge location of the PRD as follows:

$F_r = 0.5$ if the PRD discharges to flare and a flare recovery system is installed

$F_r = 0.0$ if the PRD discharges to a closed system

$F_r = 1.0$ for all other cases

6.6.5 Lost Inventory Cost

The cost of lost fluid inventory, $Cost_{\text{inv}}$, is calculated using Equation (5.110) or Equation (5.111) from mild or stuck open leaks. When calculating the COL, the fluid cost, $Cost_{\text{flu}}$, is based on the process fluid at the PRD physical location.

$$Cost_{\text{inv}}^{\text{mild}} = 24 \cdot F_{\text{r}} \cdot Cost_{\text{flu}} \cdot D_{\text{mild}} \cdot lrate_{\text{mild}} \tag{5.110}$$

$$Cost_{\text{inv}}^{\text{so}} = 24 \cdot F_{\text{r}} \cdot Cost_{\text{flu}} \cdot D_{\text{so}} \cdot lrate_{\text{so}} \tag{5.111}$$

6.6.6 Environmental Cost

The environmental cost, $Cost_{\text{env}}$, is calculated when PRD leakage is released to the atmosphere or a flare system and may require cleanup costs or results in regulatory fines.

6.6.7 Shutdown for Repair PRD Cost

The cost associated with repair and maintenance, $Cost_{\text{sd}}$, is calculated if a leaking PRD cannot be tolerated, by using the following costs:

$Cost_{\text{sd}} = \$1000$ for PRDs < NPS 6 inlet size

$Cost_{\text{sd}} = \$2000$ for PRDs $\geq$ NPS 6 inlet size

It is recommended that actual owner–operator work order costs be used that are associated with maintenance, inspection and test, and repair of the PRD.

6.6.8 Lost Production Cost

The cost of lost production, $Cost_{\text{prod}}$, to repair a leaking PRD is calculated using Equation (5.112) or Equation (5.113). Production losses are not considered when spare PRDs are installed in parallel or in cases where isolation valves underneath the PRD offer flexibility to repair without shutting down. For the stuck open case, it is assumed that prolonged operation cannot be tolerated and the production cost is calculated using Equation (5.114).

$$Cost_{\text{prod}}^{\text{mild}} = 0.0 \quad \text{if a leaking PRD can be tolerated or if the PRD can be isolated and repaired without requiring a shutdown} \tag{5.112}$$

$$Cost_{\text{prod}}^{\text{mild}} = Unit_{\text{prod}} \cdot D_{\text{sd}} \quad \text{if a leaking PRD cannot be tolerated} \tag{5.113}$$

$$Cost_{\text{prod}}^{\text{so}} = Unit_{\text{prod}} \cdot D_{\text{sd}} \quad \text{for a stuck open PRD} \tag{5.114}$$

6.6.9 Calculation of Final Leakage Consequence

The final leakage consequence is calculated for the two leaks cases discussed above.

a) Minor or Moderate Leakage.

The final consequence of the minor or moderate leakage, $Cost_{\text{l}}^{\text{mild}}$, is calculated using Equation (5.115).

$$Cost_{\text{l}}^{\text{mild}} = Cost_{\text{inv}}^{\text{mild}} + Cost_{\text{env}} + Cost_{\text{sd}} + Cost_{\text{prod}}^{\text{mild}} \tag{5.115}$$

b) Stuck Open Leakage.

The final consequence of the stuck open leak case, $Cost_{\text{l}}^{\text{so}}$, is calculated using Equation (5.116).

$$Cost_{\text{l}}^{\text{so}} = Cost_{\text{inv}}^{\text{so}} + Cost_{\text{env}} + Cost_{\text{sd}} + Cost_{\text{prod}}^{\text{so}} \tag{5.116}$$

c) Final Leakage Consequence.

The final total leakage weighted consequence is calculated using Equation (5.117).

$$C_{\text{l}}^{\text{prd}} = 0.9 \cdot Cost_{\text{l}}^{\text{mild}} + 0.1 \cdot Cost_{\text{l}}^{\text{so}} \tag{5.117}$$

6.6.10 COL Calculation Procedure

The following procedure may be used to determine the PRD COL.

a) Step 5.1—Determine the flow capacity of the PRD, $W_{\text{c}}^{\text{prd}}$, from the PRD datasheet or calculated using the methods presented in API 520, Part 1 [8].

b) Step 5.2—Calculate the minor or moderate leakage rate, $Irate_{\text{mild}}$, using Equation (5.107) and the rated capacity of the PRD obtained in Step 6.1.

c) Step 5.3—Calculate the stuck open leakage rate, $Irate_{\text{so}}$, using Equation (5.108) and the rated capacity of the PRD obtained in Step 6.1.

d) Step 5.4—Determine the leakage duration, D_{mild}, using Table 6.16.

e) Step 5.5—Determine the stuck open duration, D_{so}, using Equation (5.109).

f) Step 5.6—Calculate the cost of lost inventory for leakage, $Cost_{\text{inv}}^{\text{mild}}$, using Equation (5.110), recovery factor, F_{r}, from Section 5.6.4, and based on the PRD discharge location and discharge location.

g) Step 5.7—Calculate the cost of lost inventory for stuck open, $Cost_{\text{inv}}^{\text{so}}$, using Equation (5.111), recovery factor, F_{r}, from Section 5.6.4, and based on the PRD discharge location.

h) Step 5.8—Determine the environmental consequence associated with PRD leakage, $Cost_{\text{env}}$.

i) Step 5.9—Determine the consequence associated with repair and maintenance of the PRD, $Cost_{\text{sd}}$. Default values based on PRD size are given in Section 6.6.7 or actual owner–operator costs may be used.

j) Step 5.10—Calculate the cost of lost production for mild leaks, $Cost_{\text{prod}}^{\text{mild}}$, using Equation (5.112) or Equation (5.113) based on whether or not PRD leakage can be tolerated and the ability to isolate and repair a leaking PRD without a unit shutdown.

k) Step 5.11—Calculate the costs of lost production for the stuck open case, $Cost_{\text{prod}}^{\text{so}}$, using Equation (5.114).

l) Step 5.12—Calculate the final consequence associated with mild leakage, $Cost_{\text{l}}^{\text{mild}}$, using Equation (5.115).

m) Step 5.13—Calculate the final consequence associated with a stuck open PRDs, $Cost_{\text{l}}^{\text{so}}$, using Equation (5.116).

n) Step 5.14—Calculate the total final leakage consequence, $Cost_{\text{l}}^{\text{prd}}$, using Equation (5.117).

6.7 Risk Analysis

6.7.1 Failure to Open on Demand Risk

The calculation of risk for a PRD failing to open at a specified service duration, $t_{\text{dur},i}$, is calculated for each applicable overpressure demand case scenario using Equation (5.118).

$$Risk_{\text{f},j}^{\text{prd}} = P_{\text{f},j}^{\text{prd}} \cdot C_{\text{f},j}^{\text{prd}} \tag{5.118}$$

The overall risk for the fail to open case is calculated by the sum of the risks for each overpressure demand case scenario using Equation (5.119).

$$Risk_{\text{f}}^{\text{prd}} = \sum_{j=1}^{ndc} P_{\text{f},j}^{\text{prd}} \cdot C_{\text{f},j}^{\text{prd}} \tag{5.119}$$

where j represents each of the number of overpressure demand case scenarios, ndc.

If the PRD protects multiple components, the risk calculations are repeated for each protected component. The final risk is the maximum risk calculated for each protected component.

6.7.2 Leakage Risk

Risk associated with PRD leakage is calculated using Equation (5.120):

$$Risk_{\text{l}}^{\text{prd}} = P_{\text{l}}^{\text{prd}} \cdot C_{\text{l}}^{\text{prd}} \tag{5.120}$$

6.7.3 Total Risk

The total PRD risk is calculated using Equation (5.121).

$$Risk^{\text{prd}} = Risk_{\text{f}}^{\text{prd}} + Risk_{\text{l}}^{\text{prd}} \tag{5.121}$$

6.7.4 Risk Calculation Procedure

The following summarizes the calculation procedure for the failure to open case.

a) Step 6.1—Calculate the failure to open on demand risk associated with each applicable overpressure demand case scenario, $Risk_{\text{f},j}^{\text{prd}}$, using Equation (5.118).

b) Step 6.2—Calculate the total risk for the failure to open case, $Risk_{\text{f}}^{\text{prd}}$, with the sum risk associated with each applicable overpressure demand case scenarios using Equation (5.119).

c) Step 6.3—Calculate the risk for the PRD leakage case, $Risk_{\text{l}}^{\text{prd}}$ using Equation (5.120).

d) Step 6.4—Calculate the total risk using Equation (5.121).

6.8 Inspection Planning Based on Risk Analysis

6.8.1 RBI Intervals

Risk increases as a function of time as both PRD POF and the probability of PRD leakage increases with time. The recommended PRD interval is calculated based on the date at which the PRD risk reaches the risk target (Part 1, Section 4.4.2).

6.8.2 Effect of PRD Inspection, Testing, and Overhaul on Risk Curve

Figure 6.7 shows the effect of inspection/test and repair of the PRDs and illustrates the effect of setting a risk target. The example presented in Figure 6.7 uses a risk target of $25,000/yr and resulted in inspection intervals of 5 years. Alternatively, if the risk target were $10,000/yr, the resulting inspection interval would have been every 3 years.

Since PRDs are normally overhauled or replaced at the time of testing, the risk of failure goes to zero after inspection and test since the PRD is returned to an as-new condition after overhaul.

6.8.3 Effect of PRD Testing Without Overhaul on Risk Curve

A PRD is typically overhauled after inspection and test to return the PRD to the as-new condition. Occasionally a PRD is not overhauled after inspection and test. For example, a pop test performed in the shop in the as-received condition may be returned to service without overhaul. Or, for example, an in-situ pop test may be performed without a shop inspection and test. In the case where an overhaul has not been performed, confidence is increased that the PRD was in working condition is gained, but the PRD was not restored to an as-new condition. The POF and leakage curves are adjusted (characteristic life, η). If the test passed, the test interval will be increased, but the risk does not go to zero as if the PRD was overhauled.

6.9 Nomenclature

A^{prd}	is the orifice area of the PRD, in.^{2} (mm^2)
$A^{\text{prd}}_{\text{total}}$	is the total installed orifice area of a multiple PRD installation, in.^{2} (mm^2)
$C^{\text{prd}}_{\text{f},j}$	is the PRD COF to open associated with the j^{th} overpressure demand case, $
$C^{\text{mild}}_{\text{l}}$	is the consequence of a mild or moderate leak through a PRD, $
$C^{\text{prd}}_{\text{l}}$	is the PRD COL, $
C^{so}_{l}	is the consequence of a stuck open PRD, $
C_{sd}	is the consequence associated with the repair and maintenance of the PRD, $
CF	is the confidence factor placed on the inspection effectiveness
CF_{fail}	is the confidence factor that a failed test represents the true condition of the PRD at the time of the test
CF_i	is the confidence factor placed on the inspection effectiveness associated with the i^{th} historical inspection record

CF_{pass}	is the confidence factor that a passed test represents the true condition of the PRD at the time of the test
$Cost_{env}$	is the environmental costs due to a PRD leak, $
$Cost_{flu}$	is the cost of the lost fluid, $/lb ($/kg)
$Cost_{inv}$	is the lost inventory or fluid costs due to a PRD leak, $
$Cost_{inv}^{mild}$	is the cost of lost inventory due to a minor or moderate PRD leak, $
$Cost_{inv}^{so}$	is the cost of lost inventory due to a stuck open PRD, $
$Cost_{prod}$	is the production losses as a result of shutting down to repair a PRD, $
$Cost_{prod}^{mild}$	is the production losses as a result of shutting down to repair a mild or moderate leaking PRD, $
$Cost_{prod}^{so}$	is the production losses as a result of shutting down to repair a stuck open PRD, $
$Cost_{sd}$	is the maintenance and repair costs associated with a PRD, $
D_f	is the DF as a function of time for equipment components protected by the PRD
D_{mild}	is the duration that a minor or moderate PRD leak will go undiscovered, days
D_{sd}	is the number of days required to shut a unit down to repair a leaking or stuck open PRD, days
D_{so}	is the duration of a stuck open PRD, days
DR_j	is the demand rate associated with the j^{th} overpressure demand case, demands/yr
DR_{total}	is the total demand rate on a PRD, demands/yr
$DRRF_j$	is the demand rate reduction factor associated with the j^{th} overpressure demand case
EF_j	is the initiating event frequency associated with the j^{th} overpressure demand case, demands/yr
F_a	is the multiple PRD installation adjustment factor
F_c	is the adjustment factor for conventional PRVs
F_{env}	is the adjustment factor for environmental factors
F_{MS}	is the management systems factor

F_{op}	is the adjustment factor for overpressure
$F_{\text{op},j}$	is the adjustment factor for the overpressure for the j^{th} overpressure demand case
F_{r}	is the recovery factor applied to lost inventory
F_{s}	is the adjustment factor for the presence of soft seats
F_{set}	is the adjustment factor for the ratio of operating pressure to set pressure
$F(t)$	is the cumulative failure density function or unreliability
gff_n	is the GFF for the protected equipment associated with the n^{th} hole size, failures/yr
gff_{total}	is the total GFF for the protected equipment, years
$lrate_{\text{mild}}$	is the leakage rate of a mild or moderate leaking PRD, lb/hr (kg/hr)
$lrate_{\text{so}}$	is the leakage rate for a stuck open PRD, lb/hr (kg/hr)
$MAWP$	is the maximum allowable working pressure of the protected equipment, psig (kPa)
$MTTF$	is the mean time to failure
ndc	is the number of demand cases
$P_{\text{f},j}$	is the POF (loss of containment) of the protected equipment associated with the j^{th} overpressure demand case, failures/yr
$P_{\text{f}}(t)$	is the POF (loss of containment) of the protected equipment, failures/yr
$P_{\text{f,cond}}^{\text{prd}}$	is the conditional POFOD, failures/demand
$P_{\text{p,cond}}^{\text{prd}}$	
$P_{\text{f},j}^{n}$	is the POF (loss of containment) of the protected equipment for the n^{th} hole size associated with the j^{th} overpressure demand case, failures/yr
$P_{\text{f},j}^{\text{prd}}$	is the POF of a PRD associated with the j^{th} overpressure demand case, failures/yr
$P_{\text{f,prior}}^{\text{prd}}$	is the prior POFOD, failures/demand
$P_{\text{f,wgt}}^{\text{prd}}$	is the weighted POFOD, failures/demand
P_{fod}	is the PRD POFOD, failures/demand
$P_{\text{fod},j}$	is the PRD POFOD associated with the j^{th} overpressure demand case, failures/demand
$P_{\text{l}}^{\text{prd}}$	is the PRD POF, failures/yr

P_o is the overpressure likely to occur as a result of a PRD failing to open upon demand, psig (kPa)

$P_{o,j}$ is the overpressure likely to occur as a result of a PRD failing to open upon demand, associated with the j^{th} overpressure demand case, psig (kPa)

$P_{p,cond}^{prd}$ is the conditional probability of a no-leak or passing test result, failures/year

$P_{p,prior}^{prd}$ is the prior probability of passing on demand, failures/demand

P_s is the storage or operating pressure of the protected equipment, psig (kPa)

P_{set} is the set pressure of the PRD, psig (kPa)

$Risk_f^{prd}$ is the total risk for a PRD, \$/yr

$Risk_f^{prd}$ is the risk of a PRD failure to open, \$/yr

$Risk_{f,j}^{prd}$ is the risk of a PRD failure to open associated with the j^{th} overpressure demand case, \$/yr

$Risk_l^{prd}$ is the risk of PRD leakage, \$/yr

$R(t)$ is the risk as a function of time, ft^2/yr (m^2/yr) or \$/yr

t is time, years

$t_{dur,i}$ is the actual duration between inspections associated with the i^{th} historical inspection record, years

t_{insp} is the service duration, years

$Unit_{prod}$ is the daily production margin on the unit, \$/day

W_c^{prd} is the rated capacity of a PRD, lb/hr (kg/hr)

β is the Weibull shape parameter

η is the Weibull characteristic life parameter, years

η_{def} is the Weibull characteristic life parameter based on the default service severity chosen for a specific PRD, years

η_{mod} is the Weibull characteristic life parameter modified to account for installation factors, design features, overpressure, and environmental factors, years

η_{upd} is the Weibull characteristic life parameter updated to account for inspection history, years

6.10 Tables

Table 6.1—Basic Data Needed for the PRD Module

<table>
<tr><th>Data</th><th>Description</th><th>Data Source</th></tr>
<tr><td>PRD type</td><td>Type of PRD
— Conventional spring-loaded PRV (default)
— Balanced bellows PRV
— Pilot-operated PRV
— PRV with rupture disk
— Rupture disk only</td><td>User specified</td></tr>
<tr><td>Fluid composition</td><td>Process fluid mixture components, either mass or mole fraction. Limit of 10 components in mixture definition.</td><td>Fixed equipment</td></tr>
<tr><td rowspan="3">Service severity</td><td>Severity of process fluid. Choices are Mild, Moderate, and Severe. The service severity provides the basis for the selection of the default POFOD and POL curves.</td><td rowspan="3">User specified</td></tr>
<tr><td>Fail to Open
— Mild
— Moderate (default)
— Severe</td></tr>
<tr><td>Leakage
— Mild
— Moderate (default)
— Severe</td></tr>
<tr><td>Overpressure scenarios</td><td>Provide a listing of the applicable overpressure scenarios for each PRD. For each overpressure scenario, default values for the initiating event frequency and the PRD demand rate reduction factor (DRRF) are provided in Table 5.2. These two parameters when multiplied together provide an estimate of the demand rate on the PRD installation.</td><td>User specified</td></tr>
<tr><td>PRD discharge location</td><td>— Atmosphere
— Flare (default)
— Closed process</td><td>User specified</td></tr>
<tr><td>PRD inspection history</td><td>— Date of testing
— Install date
— Type of test (effectiveness)
— Results of test/inspection
— Overhauled? Yes/No (see Section 5.1.6)
— Inlet and outlet piping condition [see Section 5.2.4 i) 1)]</td><td>User specified</td></tr>
<tr><td>Protected equipment details</td><td>Operating conditions, design conditions, dimensions, damage mechanisms, GFF, and DFs</td><td>Fixed equipment</td></tr>
<tr><td>Fluid inventory</td><td>Fluid inventory associated with the protected equipment (lbm). May be less than the RBI calculated inventory due to shut-in conditions, e.g. reactor discharge valve fails closed.</td><td>Fixed equipment</td></tr>
<tr><td>Injury costs</td><td>Cost of serious injury, $</td><td>Fixed equipment</td></tr>
<tr><td>Environmental costs</td><td>Environmental fines and costs associated with PRD leakage or loss of equipment containment, $/event.</td><td>Fixed equipment</td></tr>
<tr><td>Production costs</td><td>Cost of lost production, $</td><td>Fixed equipment</td></tr>
<tr><td>Unit costs</td><td>Cost to replace unit, $/ft^2</td><td>Fixed equipment</td></tr>
</table>

Table 6.2—Overpressure Scenario Logic

Initiating Event Frequency	Equipment Type	PRD DRRF	Qualifier	Overpressure Potential	Background and Comments
Overpressure Scenario—Fire					
1 per 250 years See Lees [12], Table A7.4, states major fire at plant 1 every 10 years	All equipment types	0.1 Industry experience justifies this value	N/A	Calculated burst pressure or estimated as design margin × MAWP	— Modified by industry data that indicate demand rates on the order of 1 per 400 years — The DRRF factor of 0.1 recognizes the industry experience that relatively few vessels exposed to a fire will experience a PRD opening — Assumption is made that in those rare cases where a PRD would open during a fire, rupture will occur if the PRD failed to open upon demand
Overpressure Scenario—Loss of Cooling					
1 per 10 years	Process tower with fired heater heat source	1.0 Consider LOPA or risk reduction analysis associated with loss of flow controls on the fired heater	Heat source to tower is a fired heater	Calculated burst pressure or estimated as design margin × MAWP	Assumption is made that rupture occurs
	All other equipment with internal or external heat sources	1.0		Bubble point pressure of the feed stream at heat source temperature	
Overpressure Scenario—Electrical Power Failure					
0.08 per year (1 per 12.5 years) power supply failure per Table 9.7 on page 316 of Lees [12]	Process tower with fired heater heat source	1.0 Consider LOPA or risk reduction analysis associated with loss of flow controls on the fired heater	Heat source to tower is a fired heater	Calculated burst pressure or estimated as design margin × MAWP	Assumption is made that rupture occurs
	Process tower and other equipment with internal or external (non-fired) heat sources	1.0		Bubble point pressure of the feed stream at heat source temperature	

Initiating Event Frequency	Equipment Type	PRD DRRF	Qualifier	Overpressure Potential	Background and Comments
Overpressure Scenario—Blocked Discharge (Manual Valve)					
1 per 100 years (admin controls) 1 per 10 years (w/o admin controls Multiply event frequency times the # of applicable block valves located in process flow path Lees [13] suggests an estimated rate of 0.5 to 0.1 events per year for shutting manual valve in error	Exchangers, fin fans, reactors, piping, drums, or rotating equipment	1.0	Downstream of rotating equipment other than positive displacement type	Deadhead pressure or 1.3 times the normal discharge pressure or bubble point pressure of the feed stream at heat source temperature (for cases where the equipment has internal or external heat sources), whichever is greatest	Most centrifugal rotating equipment will deadhead at 30 % above the normal operating point. Initiating event frequency should be adjusted if the protected equipment is removed from service for maintenance or operational needs (filter replacement or cyclic process operation) at a frequency greater than the unit turnaround frequency. Equipment with internal or external heat sources may have a significant potential for overpressure as a result of vaporization of the contained fluid stream.
		1.0	Downstream of positive displacement type rotating equipment	Calculated burst pressure or estimated as design margin × MAWP	Discharge pressure from positive displacement pumps will continue to increase pressure. Assumption is made that rupture will occur.
		1.0	Downstream of steam turbines	Steam supply pressure or bubble point pressure of the feed stream at steam supply temperature (for cases where the equipment has internal or external heat sources), whichever is greatest	
		1.0	Downstream of process units or vessels	1.1 × MAWP of upstream vessel source pressure	
	Process tower with fired heater heat source	1.0 Consider LOPA or risk reduction analysis associated with loss of flow controls on the fired heater	Heat source to tower is a fired heater	Calculated burst pressure or estimated as design margin × MAWP	Assumption is made that rupture occurs. This applies to the blocked vapor outlet line only; see liquid overfilling case for blocked liquid/bottoms outlet.
	Process tower, all other heat sources	1.0	No upstream fired heater	Bubble point pressure of the feed stream at heat source temperature	This applies to the blocked vapor outlet line only; see liquid overfilling case for blocked liquid/bottoms outlet
	Heaters	1.0		Calculated burst pressure or estimated as design margin × MAWP	Added increase in potential overpressure with fired/radiant heat transfer. Assumption is made that rupture occurs.

<table>
<tr><th>Initiating Event Frequency</th><th>Equipment Type</th><th>PRD DRRF</th><th>Qualifier</th><th>Overpressure Potential</th><th>Background and Comments</th></tr>
<tr><td colspan="6">Overpressure Scenario—Control Valve Fail Close at Outlet</td></tr>
<tr><td rowspan="7">1 per 10 years [14] for fail-closed control valves

1 per 50 years for fail-open control valves

Multiply event frequency times the # of applicable control valves located in process flow path</td><td rowspan="3">Exchangers, fin fans, reactors, piping or drums, or rotating equipment</td><td>1.0</td><td>Downstream of rotating equipment other than positive displacement type</td><td>Deadhead pressure or 1.3 times the normal discharge pressure or bubble point pressure of the feed stream at heat source temperature (for cases where the equipment has internal or external heat sources), whichever is greatest</td><td>Most centrifugal rotating equipment will deadhead at 30 % above the normal operating point. Initiating event frequency should be adjusted if the protected equipment is removed from service for maintenance or operational needs (filter replacement or cyclic process operation) at a frequency greater than the unit turnaround frequency. Equipment with internal or external heat sources may have a significant potential for overpressure as a result of vaporization of the contained fluid stream.</td></tr>
<tr><td>1.0</td><td>Downstream of positive displacement type rotating equipment</td><td>Calculated burst pressure or estimated as design margin × MAWP</td><td>Discharge pressure from positive displacement pumps will continue to increase pressure. Assumption is made that rupture will occur.</td></tr>
<tr><td>1.0</td><td>Downstream of steam turbines</td><td>Steam supply pressure or bubble point pressure of the feed stream at steam supply temperature (for cases where the equipment has internal or external heat sources), whichever is greatest</td><td></td></tr>
<tr><td rowspan="2">Process tower with fired heater heat source</td><td>1.0</td><td>Downstream of process units or vessels</td><td>1.1 × MAWP of upstream vessel source pressure</td><td></td></tr>
<tr><td>1.0
Consider LOPA or risk reduction analysis associated with loss of flow controls on the fired heater</td><td>Heat source to tower is a fired heater</td><td>Calculated burst pressure or estimated as design margin × MAWP</td><td>Assumption is made that rupture occurs. This applies to the blocked vapor outlet line only; see liquid overfilling case for blocked liquid/bottoms outlet.</td></tr>
<tr><td>Process tower, all other heat sources</td><td>1.0</td><td></td><td>Bubble point pressure of the feed stream at heat source temperature</td><td>This applies to the blocked vapor outlet line only; see liquid overfilling case for blocked liquid/bottoms outlet</td></tr>
<tr><td>Heaters</td><td>1.0</td><td></td><td>Calculated burst pressure or estimated as design margin × MAWP</td><td>Added increase in potential overpressure with fired/radiant heat transfer. Assumption is made that rupture occurs.</td></tr>
</table>

Initiating Event Frequency	Equipment Type	PRD DRRF	Qualifier	Overpressure Potential	Background and Comments
Overpressure Scenario—Control Valve Fail Open at Inlet, Including the HP/LP Gas Breakthrough Case					
1 per 10 years [14] for fail-closed control valves 1 per 50 years for fail-open control valves Multiply event frequency times the # of applicable control valves located in process flow path	All equipment types	1.0	N/A	Use the upstream source pressure	Overpressure potential is a function of the pressure ratio across the control valve
Overpressure Scenario—Runaway Chemical Reaction					
1 per year	All equipment	1.0		Calculated burst pressure or estimated as design margin × MAWP	This overpressure scenario should be based on a thorough review of the wide variety of potential initiating events and mitigation measures associated with the reactor system installation. The DRRF and the potential overpressure associated with failure of PRD to open upon demand should be chosen based on a risk assessment. Per shell study, 50 % of all vessel ruptures are attributed to reactive overpressure case.
Overpressure Scenario—Tube Rupture					
1 per 1000 years (9×10^{-4} per exchanger per [15])	Exchangers—HP gas in tubes, LP liquid in shell	1.0		Normal maximum operating pressure of the high-pressure side of the exchanger	Likelihood of shell rupture is increased when high-pressure tubeside gas enters low-pressure shellside liquid

Initiating Event Frequency	Equipment Type	PRD DRRF	Qualifier	Overpressure Potential	Background and Comments
Overpressure Scenario—Tower P/A or Reflux Pump Failure					
1 per 5 years	Process tower with fired heater heat source	1.0 Consider LOPA or risk reduction analysis associated with loss of flow controls on the fired heater	Heat source to tower is a fired heater	4.0 × MAWP (rupture)	Assumption is made that rupture occurs
	All other process towers	1.0		Bubble point pressure of the feed stream at heat source temperature	
Overpressure Scenario—Thermal/Hydraulic Expansion Relief					
1 per 100 years (manual valve w/admin controls) 1 per 10 years (manual valve w/o admin controls or control valve Multiply initiating event frequency times the number of applicable block valves located in process flow path	Piping or other liquid filled equipment	1.0	N/A	Operating pressure or bubble point pressure of contained fluid at 140 °F, whichever is larger	Assumption is made that the probability of a leak is 1.0 (flange leaks), modeled as a $^1/_4$ in. hole. The probability of rupture is assumed to be 0.0. For fluids that will not boil, since the pressure is relieved immediately upon leakage, the pressure for the consequence calculation will be the normal operating pressure of the piping. Not likely to result in rupture, likely to cause flange leaks/small leaks, heated only. If the fluid can boil due to solar energy, the consequence pressure could be maintained at the bubble point pressure of the contained fluid. Leak and rupture probabilities will be calculated as a function of the bubble point pressure.
	Cold side of heat exchangers	1.0	N/A	Operating pressure or bubble point pressure of contained fluid at the hot side fluid inlet temperature, whichever is larger	Added increase in potential overpressure with additional heat transfer from hot side. For liquids that do not boil, the assumption is made that the POF is 1.0 (flange leaks), modeled as a $^1/_4$ in. hole, and the probability of rupture is 0.0. If the cold side fluid can boil, the consequence pressure could reach the bubble point pressure of the stored fluid at the hot side fluid inlet temperature. Leak and rupture probabilities will be calculated as a function of the bubble point pressure.

Initiating Event Frequency	Equipment Type	PRD DRRF	Qualifier	Overpressure Potential	Background and Comments
Overpressure Scenario—Liquid Overfilling					
1 per 100 years (admin controls) 1 per 10 years (w/o admin controls Multiply event frequency times the number of applicable block valves located in process flow path	All equipment including process tower (blocked outlet of liquid bottoms)	1.0	Downstream of rotating equipment other than positive displacement type	Deadhead pressure or 1.3 times the normal discharge pressure or bubble point pressure of the feed stream at heat source temperature (for cases where the equipment has internal or external heat sources), whichever is greatest	Most centrifugal rotating equipment will deadhead at 30 % above the normal operating point. Initiating event frequency should be adjusted if the protected equipment is removed from service for maintenance or operational needs (filter replacement or cyclic process operation) at a frequency greater than the unit turnaround frequency. Equipment with internal or external heat sources may have a significant potential for overpressure as a result of vaporization of the contained fluid stream.
		1.0	Downstream of positive displacement type rotating equipment	Calculated burst pressure or estimated as design margin × MAWP	Discharge pressure from positive displacement pumps will continue to increase pressure. Assumption is made that rupture will occur.
		1.0	Downstream of steam turbines	Steam supply pressure or bubble point pressure of the feed stream at steam supply temperature (for cases where the equipment has internal or external heat sources), whichever is greatest	
		1.0	Downstream of process units or vessels	1.1 × MAWP of upstream pressure source vessel	

Table 6.3—Default Initiating Event Frequencies

Overpressure Demand Case	Event Frequency	EF_j (events/yr)	$DRRF_j$ (see Notes 2 and 3)	Reference
1. Fire	1 per 250 years	0.0040	0.10	[12]
2. Loss of cooling water utility	1 per 10 years	0.10	1.0	[12]
3. Electrical power supply failure	1 per 12.5 years	0.080	1.0	[12]
4a. Blocked discharge with administrative controls in place (see Note 1)	1 per 100 years	0.010	1.0	
4b. Blocked discharge without administrative controls (see Note 1)	1 per 10 years	0.10	1.0	
5. Control valve failure, initiating event is same direction as control valve normal fail position (i.e. fail safe)	1 per 10 years	0.10	1.0	[14]
6. Control valve failure, initiating event is opposite direction as control valve normal fail position (i.e. fail opposite)	1 per 50 years	0.020	1.0	[14]
7. Runaway chemical reaction	1 per year	1.0	1.0	
8. Heat exchanger tube rupture	1 per 1000 years	0.0010	1.0	[15]
9. Tower P/A or reflux pump failures	1 per 5 years	0.2	1.0	
10a. Thermal relief with administrative controls in place (see Note 1)	1 per 100 years	0.010	1.0	Assumed same as blocked discharge
10b. Thermal relief without administrative controls (see Note 1)	1 per 10 years	0.10	1.0	Assumed same as blocked discharge
11a. Liquid overfilling with administrative controls in place (see Note 1)	1 per 100 years	0.010	1.0	[12]
11b. Liquid overfilling without administrative controls (see Note 1)	1 per 10 years	0. 10	1.0	[12]

NOTE 1 Administrative controls for isolation valves are procedures intended to ensure that personnel actions do not compromise the overpressure protection of the equipment.

NOTE 2 The DRRF recognizes the fact that demand rate on the PRD is often less than the initiating event frequency. As an example, PRDs rarely lift during a fire since the time to overpressure may be quite long and firefighting efforts are usually taken to minimize overpressure.

NOTE 3 The DRRF can also be used to take credit for other layers of overpressure protection such as control and trip systems that reduce the likelihood of reaching PRD set pressure.

NOTE 4 Where the Item Number has a subpart (such as “a” or “b”), this clarifies that the overpressure demand case will be on same subpart of Table 5.3.

Table 6.4—Categories of PRD Service Severity (Fail Case Only)

PRD Service Severity	Characteristic MTTF	Characteristic of Failure	Expected Stream Characterization	Typical Temperature	Examples of Service
Mild	Failure is characterized by a long (25 years) MTTF	Failure is strongly characterized as a “wear out” type of failure, in which the failure occurs due to an accumulation of damage over a long period of time	— Clean hydrocarbon products at moderate temperature — No aqueous phase present — Low in sulfur and chlorides	Low temperature, always << 500 °F	Examples include: product hydrocarbon streams (including lubricating oils), liquefied petroleum gas (LPG), BFW, low-pressure steam, and clean gases such as nitrogen and air
Moderate	Failure occurs at an average (15 years) MTTF	Failure is weakly characterized as a “wear out” type of failure, in which the failure occurs due to an accumulation of damage over a long period of time	— Hydrocarbons that may contain some particulate matter — A separate aqueous phase may be present but is a minor component — Clean, filtered, and treated water may be included in this category — Some sulfur or chlorides may be present	Up to 500 °F (may exist)	Examples include: intermediate hydrocarbon streams, in-service lube and seal oils, process water (NOT cooling water or BWF), and medium- to high-pressure steam
Severe	Failure is characterized as a relatively short (7 years) MTTF	Failure is characterized as a “random” type of failure, in which the failure can occur due to a variety of mechanisms (such as corrosion or plugging)	— High-temperature hydrocarbon streams with significant tendency to foul — Sulfur and chloride concentrations may be high — Monomers processed at any temperature that can polymerize are in this group as well — Sometimes included are aqueous solutions of process water, including cooling water	> 500 °F	Examples include: heavy hydrocarbon streams such as crude, amine services, cooling water, corrosive liquids and vapors, and streams containing H_2S

NOTE 1 MTTF does not reflect replacement history, where the history indicates a renewal of the asset without a failure noted.

NOTE 2 Refer to Table 5.13 for the categories for the LEAK case.

Table 6.5—Default Weibull Parameters for POFOD

Fluid Severity	Conventional and Balanced Bellows PRVs [1]		Pilot-operated PRVs [2]		Rupture Disks [3]	
	β	η_{def}	β	η_{def}	β	η_{def}
Mild	1.8	50.5	1.8	33.7	1.8	50.5
Moderate	1.8	23.9	1.8	8.0	1.8	50.5
Severe	1.8	17.6	1.8	3.5	1.8	50.5

NOTE 1 The η_{def} parameter values for conventional PRVs are reduced by 25 % if the discharge is to a closed system or to flare; see Section 5.2.4 g).

NOTE 2 The η_{def} parameter values for pilot-operated PRVs are currently based on the conventional PRV data; however, reduced by a factor of 1.5, 3, and 5 for Mild, Moderate, and Severe services, respectively; see Section 5.2.4 e).

NOTE 3 Without any failure rate data for rupture disks, the conventional PRV values for Mild services were used. This assumes that the rupture disk material has been selected appropriately for the fluid service; see Section 5.2.4 f).

Table 6.6—Environmental Adjustment Factors to Weibull η Parameter

Environment Modifier	Adjustment to POFOD η Parameter	Adjustment to POL η Parameter
Operating temperature 200 °F < T < 500 °F	1.0	0.8
Operating temperature > 500 °F	1.0	0.6
Operating ratio > 90 % for spring-loaded PRVs or > 95 % for pilot-operated PRVs	1.0	0.5 [1]
Installed piping vibration	1.0	0.8
Pulsating or cyclical service, such as downstream of positive displacement rotating equipment	1.0	0.8
History of excessive actuation in service (greater than 5 times per year)	0.5	0.5 [2]
History of chatter	0.5	0.5

NOTE 1 Some pilot-operated PRVs operate extremely well with operating ratios approaching 98 %. In these cases, the environmental factor should not be applied (reference API 520, Part 1).

NOTE 2 This factor should not be applied if the environmental factor for operating ratio is already applied.

Table 6.7—Level of Inspection Confidence Factors

Inspection Result	Confidence Factor That Inspection Result Determines the True Damage State, CF			
	Ineffective	Fairly Effective	Usually Effective	Highly Effective
Pass, CF_{pass}	0.4	0.5	0.70	0.9
Fail, CF_{fail}	0.4	0.70	0.95	0.95
No Leak, CF_{noleak}	0.4	0.5	0.70	0.9
Leak, CF_{leak}	0.4	0.70	0.95	0.95

Table 6.8—Set Pressure Factor

PRV Type	Set Pressure Factor
Pilot-operated PRVs	$F_{set} = 1 - \left[\dfrac{0.95 - \min\left[0.95, \dfrac{P_S}{P_{set}}\right]}{0.95}\right]$
Rupture disks	$F_{set} = 1$
Conventional PRVs and balanced bellows PRVs	$F_{set} = 1 - \left[\dfrac{0.90 - \min\left[0.90, \dfrac{P_S}{P_{set}}\right]}{0.90}\right]$
NOTE P_S denotes the operating pressure, and P_{set} denotes the set pressure.	

Table 6.9—Inspection Updating Equations

Inspection Effectiveness and Result	Equation for Weighted POFOD
Highly Effective Pass	$P_{f,wgt}^{prd} = P_{f,prior}^{prd} - 0.2 \cdot P_{f,prior}^{prd}\left(\dfrac{t}{\eta}\right) + 0.2 \cdot P_{f,cond}^{prd}\left(\dfrac{t}{\eta}\right)$
Usually Effective Pass	
Fairly Effective Pass	
Highly Effective Fail	$P_{f,wgt}^{prd} = P_{f,cond}^{prd}$
Usually Effective Fail	$P_{f,wgt}^{prd} = 0.5 \cdot P_{f,prior}^{prd} + 0.5 \cdot P_{f,cond}^{prd}$
Fairly Effective Fail	
Ineffective/No Inspection	$P_{l,cond}^{prd} = CF_{l} \cdot P_{l,prior}^{prd} + \left(1 - CF_{nl}\right) \cdot P_{nl,prior}^{prd}$

Table 6.10—Design Margins for Various Codes of Construction

Construction Code	Design Margin
ASME Section VIII, Division 1, pre-1950	5.0
ASME Section VIII, Division 1, 1950–1998	4.0
ASME Section VIII, Division 1, 1999 and later	3.5
ASME Section VIII, Division 2, pre-2007	3.0
ASME Section VIII, Division 2, 2007 and later	2.4
ASME B31.3	3.0
AS 1210	3.5

NOTE For any construction code not listed in this table or when design by analysis was utilized to design the equipment, it is the responsibility of the owner–operator to determine the design margin.

Table 6.11—Constants for Design Margin

Design Margin	Constant a	Constant b
5	2.28E-06	2.598628
4	9.57E-07	3.464837
3.5	4.79E-07	4.157804
3	1.69E-07	5.197255
2.4	1.82E-08	7.42465

NOTE 1 Constants a and b are used in Equation (5.99).

NOTE 2 A gff of 3.06E-05 is used to calculate constant a.

Table 6.12—DF Classes for Protected Equipment

DF Class	DF	Description
None	1	New vessel or inspection shows little if any damage.
Minimal	20	Equipment has been in service for a reasonable amount of time and inspection shows evidence of minor damage. Damage mechanisms have been identified and inspection data are available.
Minor	200	One or more damage mechanisms have been identified, limited inspection data available, and fairly minor evidence of damage. Single damage mechanism identified, recent inspection indicates minor evidence of damage.
Moderate	750	Moderate damage found during recent inspection. Low susceptibility to one or more damage mechanisms, and limited inspection exists.
Severe	2000	One or more active damage mechanisms present without any recent inspection history. Limited inspection indicating high damage susceptibility.

Table 6.13—Categories of PRD Service Severity (LEAK Case Only)

PRD Service Severity	Typical Temperature	Expected Stream Characterization	Examples of Service
Mild	Low temperature, always << 500 °F	Many heavy liquid streams such as crude oil tend not to leak through a PRD and are considered mild service severity	— Cooling water and amine services are examples of corrosive/fouling fluids that do not leak — Clean fluids such as LPG, air, and nitrogen are Mild leakage services
Moderate	Up to 500 °F (may exist)	Most of the intermediate and product hydrocarbon streams and most hydrocarbon vapors	— Lube, seal and cycle oils, and process water (**NOT** cooling water, condensate, or BFW)
Severe	> 500 °F	High-temperature services	BFW/condensate, steam, and corrosive liquids such as caustic and acids

NOTE Refer to Table 5.4 for the categories for the FAIL case.

Table 6.14—Default Weibull Parameters for POL

Fluid Severity	Conventional PRVs [1]		Balanced Bellows PRVs [1]		Pilot-operated PRVs [2]		Rupture Disks [3]	
	β	η_{def}	β	η_{def}	β	η_{def}	β	η_{def}
Mild	1.6	17.5	1.6	16.0	1.6	17.5	1.6	17.5
Moderate	1.6	15.5	1.6	14.0	1.6	15.5	1.6	17.5
Severe	1.6	13.1	1.6	11.5	1.6	13.1	1.6	17.5

NOTE 1 The η_{def} parameter values are increased by 25 % for conventional and balanced PRVs that have soft seats.

NOTE 2 The η_{def} parameter values for pilot-operated PRVs are currently based on the conventional PRV data, since there are currently no failure rate data to support otherwise.

NOTE 3 Without any failure rate data for rupture disks, the conventional PRV values for Mild service were used.

Table 6.15—Potential Consequences of Pressure Vessel Overpressure

Accumulation (% over MAWP)	Significance [11]	Potential Consequence
10 %	ASME Code allowable accumulation for process upset cases (non-fire) protected by a single PRD	No expected consequence at this accumulation level
16 %	ASME Code allowable accumulation for process upset cases protected by multiple PRDs	No expected consequence at this accumulation level
21 %	ASME Code allowable accumulation for external fire relief cases regardless of the number of PRDs	No expected consequence at this accumulation level
50 %	ASME standard hydrostatic test pressure (may be 30 % on new designs)	Possible leaks in associated instrumentation, etc. Medium consequence.
90 %	Minimum yield strength (dependent on materials of construction)	Catastrophic vessel rupture, remote possibility. Significant leaks probable. Failure of damaged vessel areas (corrosion, cracks, blisters, etc.) likely. High consequence.
300 %	Ultimate tensile strength (dependent on materials of construction)	Catastrophic vessel rupture predicted. Highest consequence.

Table 6.16—Estimated Leakage Duration from PRDs

PRD Inlet Size (in.)	Leak Duration Discharge to Flare or Closed System, D_{mild} (days)	Leak Duration Discharge to Atmosphere, D_{mild} (days)
$\leq 3/4$ in.	60	8
$3/4 <$ inlet size $\leq 1\,1/2$	30	4
$1\,1/2 <$ inlet size ≤ 3	15	2
$3 <$ inlet size ≤ 6	7	1
Greater than 6	2	0.33

Table 6.17—Estimated Leakage Rate from PRVs

Bench Test Leak Description	Leak Categorization	Percent of PRVs Leaking on Bench	Percent of All Leaks	Assumed Leakage (Percent of Capacity)
Leaked between 70 % and 90 % of set pressure, PRV opened at set pressure	Minor	8.4	50	1
Leakage below 70 % of set pressure, PRV opened at set pressure	Moderate	6.6	40	10
Immediate leakage or PRV leaked too much to open	Severe	2.4	10	25

6.11 Figures

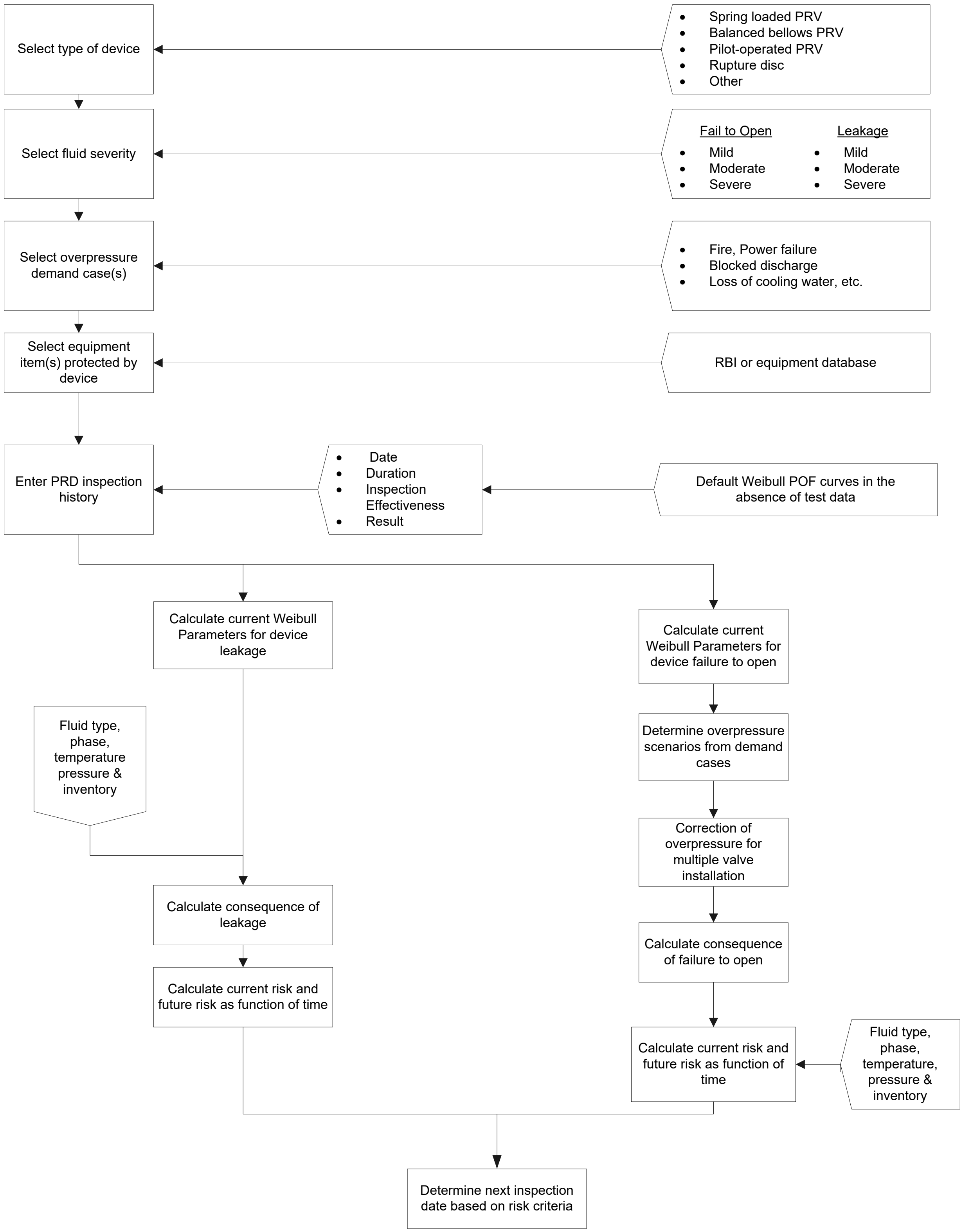


Figure 6.1—PRD RBI Methodology

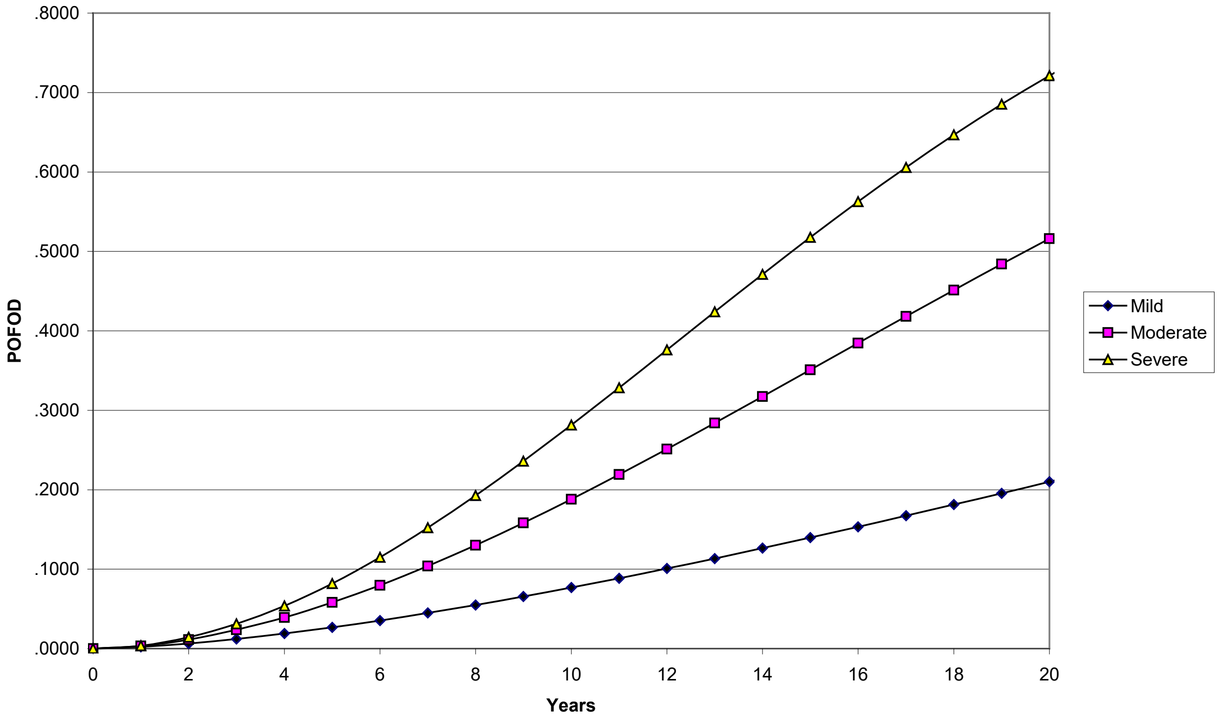


Figure 6.2—Default Conventional PRV Fail to Open on Demand Weibull Curves

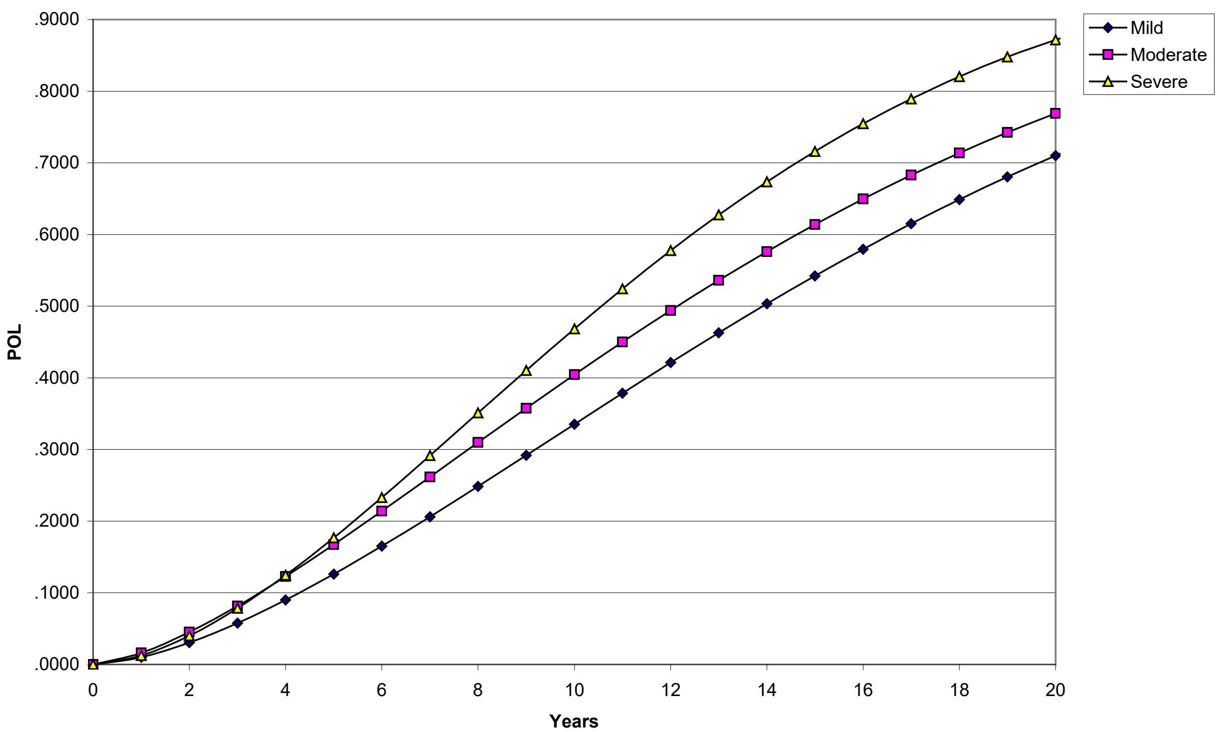


Figure 6.3—Default Leakage Failure Rate for Conventional PRVs

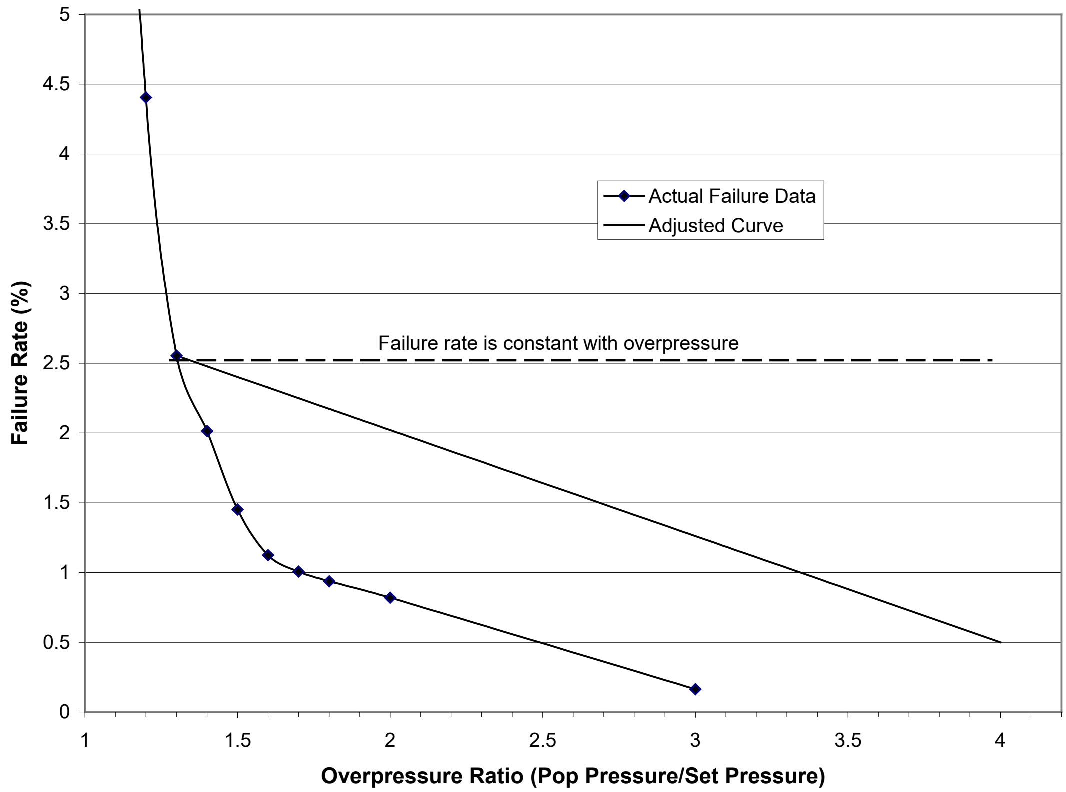


Figure 6.4—PRD Failure Rate as a Function of Overpressure

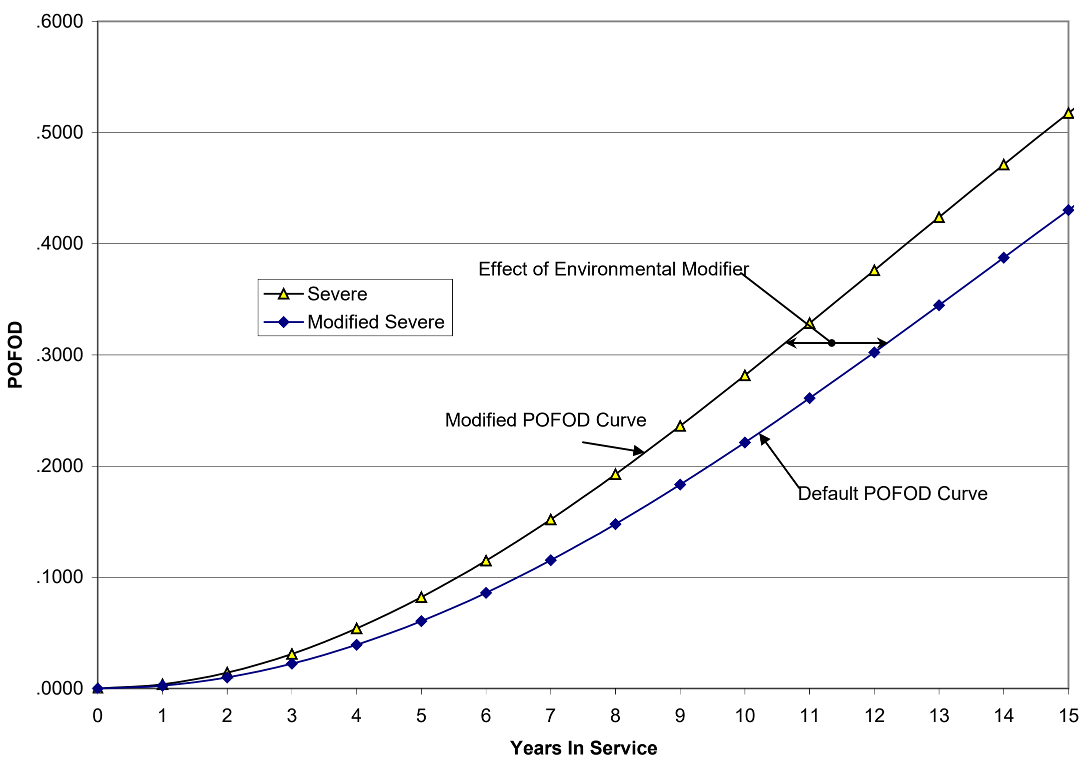
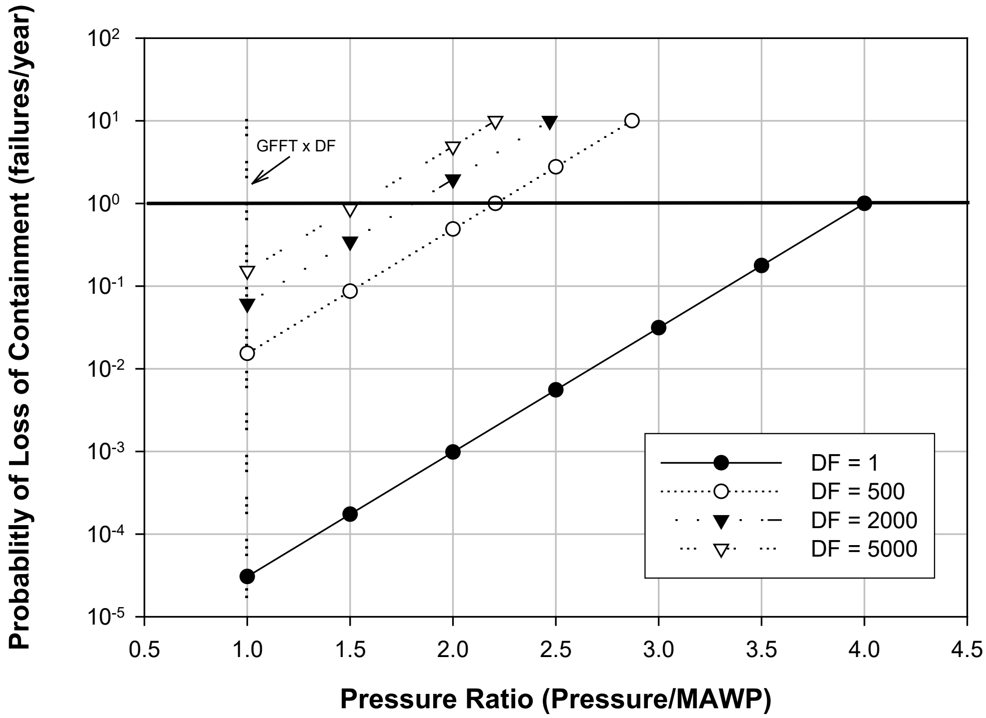


Figure 6.5—Effect of Environmental Factors on PRD Weibull Curves



For an example pressure vessel with:

$gff_{total} = 3.06 \times 10^{-5}$

Design margin = 4

Estimated burst pressure of 4 × MAWP

Figure 6.6—Probability of Loss of Containment as a Function of Overpressure

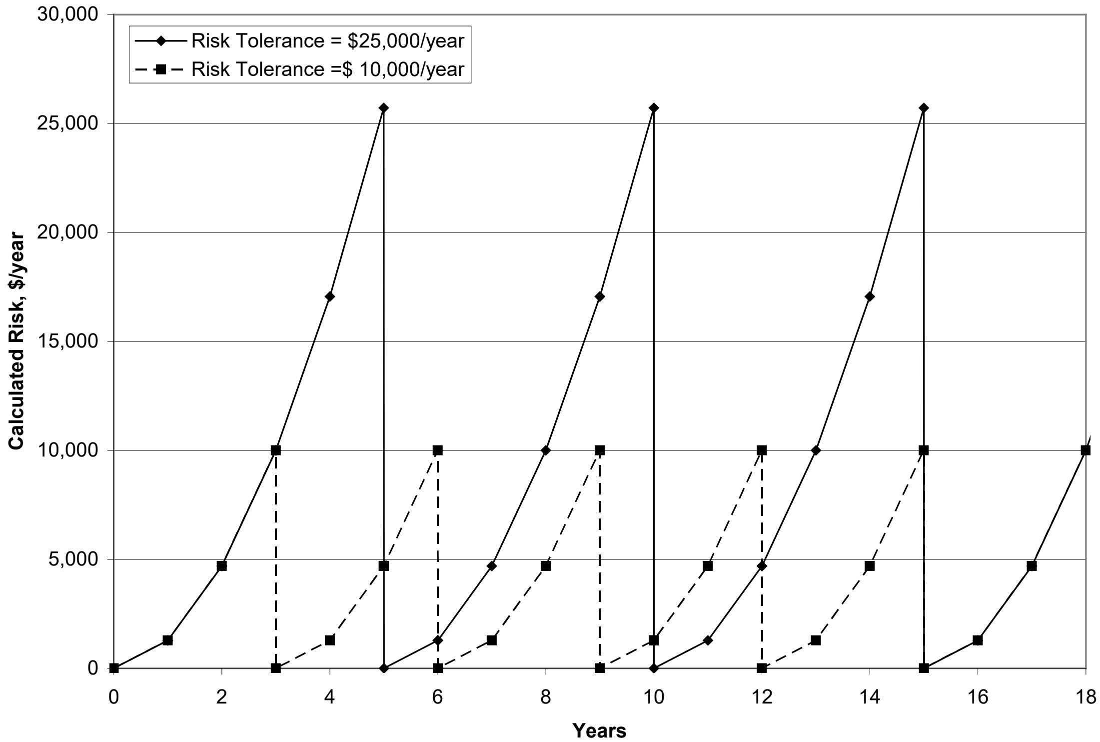


Figure 6.7—Inspection Test Updating of PRDs

7 Steam System

7.1 Overview

7.1.1 General Background

Steam systems account for approximately 30 % of the total energy used in a typical petroleum refinery [17] based on U.S. Department of Energy figures. Steam systems are utilized throughout the plant for motive, heating, and process purposes, such as in the steam turbine driver for the recycle gas compressor, the reboiler for the depropanizer column, and for stripping steam for crude distillation.

Steam system specialists work with plants to identify opportunities to reduce the amount of energy consumed by steam systems to stay competitive. Steam system maintenance costs should also be optimized and to protect health and safety issues as well as avoid unplanned downtime. The integrity and efficiency of steam-using equipment is critical to the operation and productivity of petrochemical industry as well as steam distribution systems and steam tracing systems that provide the heat necessary to maintain flow rates in product distribution piping, vessels, and reactors [18].

Routine inspection and testing of steam systems consisting of steam traps, associated piping, and steam equipment is required to avoid failures of the traps, associated piping, or equipment, leading to failure of the system. Such failures have resulted in a significant loss of steam and have led to personal injury.

A risk-based approach to evaluate the criticality of equipment in steam systems is covered here to set inspection and testing interval or possible mitigation actions. The scope of this section includes steam traps, associated steam distribution piping, and equipment using steam. The methodology involves the use of reliability data for steam trap types in the form of Weibull parameters.

It is assumed that devices have been designed in accordance with specific design standards and sized, selected, and installed appropriately. It is also assumed that the devices are included in inspection plans. The fundamental approach is to determine the POF from plant-specific data if available or to be determined from industry default data. These inputs are used to generate a POF as a function of time via a Weibull statistical approach. The consequence of device failure is calculated using methods outlined in Part 3, modified to include different failure scenarios. The combination of consequence and time-based POF provides a risk value that increases with time between inspections/tests. This allows inspection and test intervals to be determined based on risk targets. Figure 7.1 illustrates the basic methodology required for the determination of POF and is the basis for setting up inspection and test intervals or any mitigation actions.

7.1.2 Steam Application Types

Steam is essential for heating, mechanical drives, and several other applications in process plants, and steam traps are commonly used to ensure that steam is not wasted. A steam trap is a type of automatic valve that filters out condensate (e.g. condensed steam) and non-condensable gases such as air without letting steam escape. As described in ANSI/FCI 69-1 (1989), a steam trap is a self-contained valve which automatically drains the condensate from a steam-containing enclosure while remaining tight to live steam, or if necessary, allows steam to flow at a controlled or adjusted rate [19]. Most steam traps will also pass non-condensable gases while remaining tight to live steam. Various types of steam trap mechanisms (operating principles) have been developed to automatically discharge condensate and non-condensable gases. The most widely used mechanisms are those reliant on differences in temperature, specific gravities, and pressure. Each of these types of steam traps has its own advantages and applications.

Steam traps are usually required to drain condensate from steam piping, steam-using process and comfort heating equipment, tracer piping, and drive-power equipment such as turbines. Each of these applications may require the steam trap to perform a slightly different role.

In general, there are five major steam application groups that use steam traps: steam distribution piping; steam-heated equipment; steam-driven equipment; steam tracing; and direct steam applications. These systems can be indispensable in delivering the energy needed for operating an industrial plant, including process heating (e.g. heat exchangers) and steam tracing systems, as well as mechanical drives (e.g. steam turbines) [20].

Examples of equipment used in steam systems, illustrating the importance of their application to the refining process, are listed in Table 7.1 [20].

7.2 The Definition of Steam System

7.2.1 Overview

The role of the steam system is to reliably supply steam of the highest quality to the steam-using equipment. In order for this to be achieved, condensate is quickly and efficiently removed through steam traps to the correct condensate discharge location (CDL). Therefore, steam systems are an integral part of the process plant. A steam system is defined as one piece of steam-using equipment and its associated piping and traps. Figure 7.2 shows multiple steam systems with the following components:

a) steam traps,

b) associated steam piping (distributing and condensate),

c) equipment (steam-using equipment).

Depending on the system design, mechanical pumps or control valves may be installed in place of steam traps (as shown in Figure 7.2).

COF is a key driver for an RBI approach in steam-using/distribution systems, for assessment of steam traps, associated steam piping, and steam-using equipment (as described in Section 7.4).

7.2.2 Steam Trap

Steam traps are a type of automatic valve that filters out condensate (i.e. condensed steam) and non-condensable gases, such as air, without letting steam escape. In industry, steam is used regularly for heating or as a driving force for mechanical power. Steam traps are used in such applications to ensure steam is not wasted. Based on the operating principles of steam traps, they can be classified as mechanical, thermostatic, or thermodynamic. Table 7.2 describes different types of steam traps for each of the above categories.

7.2.3 Steam Piping

Steam piping supply steam to the steam-using equipment. As described, condensate is removed through steam traps installed at CDLs. The steam flow rates are typically higher in steam distribution piping than in other equipment, reaching velocities of > 100 ft/s (30 m/s). At these speeds, when the cross-sectional area of a pipe section is liquid full, slugs of condensate can be carried through the piping at high velocities, causing water hammer. Potentially, this may cause failures of piping, valves, and equipment as well as personal injuries. The higher velocities in steam piping should be considered during design when the location of trap installations is being decided.

7.2.4 Steam-using Equipment

As described in Section 7.1.2, there are many applications for steam, and depending on the application, various types of steam-using equipment are used. Table 7.1 provides examples of five steam application groups.

7.2.5 Steam System Damage Mechanism Equipment and Failure Modes

7.2.5.1 Background

The role of steam distribution piping is to reliably supply high-quality steam to steam-using equipment. Condensate is quickly and efficiently removed through steam traps installed in proper CDL installations. CDLs are susceptible to failures due to blockage (cold) or leakage (described in Section 7.2.5.3.1 and Section 7.2.5.3.2). This methodology currently does not cover freeze protection of CDLs.

The failures described in this section will also result in equipment failure consequences such as industrial steam turbine erosion failures, flooding of heat exchangers, and failures in steam tracing systems, flare systems (loss of steam will prevent atomizing of gases prior to burning), distillation towers, and strippers.

7.2.5.2 Damage Mechanism

7.2.5.2.1 Water Hammer

A sudden release of steam or scalding water can occur due to the consequences of water hammer, a common damage mechanism affecting steam systems. Water hammer has been cited by Paffel [20] as the primary problem in steam systems and is sometimes referred to as condensate induced water hammer. Water hammer occurs when steam is introduced into cold pipework that has not been drained sufficiently. As the steam cools, it turns into condensate, taking up a smaller volume in the pipework than steam. This produces a vacuum or pocket into which the water flows rapidly, creating an impact against the pipework.

Water hammer generated in steam and condensate recovery systems is ordinarily classified via two main causes:

a) high-speed condensate slamming into, for example, piping;

b) sudden condensation of steam, which produces walls of condensate that crash into each other.

When water hammer occurs, a momentary abrupt pressure change of over 1450 psi (10 MPa) may occur inside the piping. The change in pressure may result in an impact and can cause pipe rupture, severely jarring piping, equipment, or machinery housings, possibly resulting in damage to gaskets and valve flanges or the valves themselves. Water hammer in steam distribution piping interrupts service and can cause failures leading to personal injury and property damage. According to historical failures, 82 % of steam systems experience some type of water hammer. In a typical steam-using system, water hammer causes 67 % of premature steam system component failures [17].

Water hammer events are commonly caused by the following systemic failures.

a) Failure to ensure water (condensate) has been removed using steam traps and drains prior to admitting steam into the piping system.

b) Failure to correctly maintain steam traps, drain, and blowdown valves (in order to preserve operable condition).

c) Failure to ensure an adequate number of steam traps and drains have been installed at locations conducive to condensate removal.

d) Failure to operate system valves correctly as well as failure to use bypass valves to safely warm system piping downstream of isolation valves.

7.2.5.3 Failure Modes

7.2.5.3.1 Steam Trap Blockage Leading to Water Hammer

Condensate cannot be discharged when the steam trap is blocked, often resulting in water hammer contributing to potential equipment damage.

7.2.5.3.2 Steam Trap Leakage

Leakage is another mode of steam trap failure resulting in energy waste and poor environmental compliance. The failure COL is described in Section 7.4.2.

7.3 POF Methodology

7.3.1 Use of Weibull Curves

The POF for steam systems is calculated using a two-parameter Weibull distribution as expressed in Equation (5.122) and as shown in Part 1, Section 4.1.3. Use of Weibull curves for establishing POF is further described in Part 1, Section 4.1.3.

$$P_f = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{5.122}$$

where β is the Weibull shape parameter, η is the Weibull characteristic life parameter, in years, and t is the independent variable time in years.

The POF of the specific trap is related to identifiable process and installation conditions. Such conditions may be related to design, operational, and maintenance/inspection history conditions. Also associated with failure are conditions such as poor manufacturing and installation and excessive piping vibration. Improper installations or poor operational and maintenance condition may also increase the POF.

7.3.2 Required Data

The basic data required for the evaluation of POF for steam systems are listed in Table 7.3.

7.3.3 Overview

This section presents a procedure to calculate the POF for a steam system. Figure 7.2 provides an overview of the POF calculation framework for steam systems. POF is a function of time for a range of steam trap types and properties, using Weibull fitting of steam trap failure data. The POF of the associated piping is then derived and combined with the steam-using equipment GFFs to calculate a system POF. Final POF values are obtained by tailoring the POF for steam traps and equipment to local conditions by customized probability factors.

As described in Section 7.2, a steam system is defined as one piece of steam-using equipment and its associated piping and traps. The POF of each system will be considered as the combined effect of individual equipment with its associated traps for both leakage and blockage, i.e.:

$$P(t)_{\text{f,final,leak(steam system)}} = P(t)_{\text{f(equ)}} \cdot P(t)_{\text{f,final,leak}_{\text{(ST,MP or CV)}}} \tag{5.123}$$

$$P(t)_{\text{f,final,cold(steam system)}} = P(t)_{\text{f(equ)}} \cdot P(t)_{\text{f,final,cold}_{\text{(ST,MP or CV)}}} \tag{5.124}$$

The procedure for calculation of $P(t)_{\text{f,final,leak}_{\text{(ST,MP or CV)}}}$ and $P(t)_{\text{f,final,cold}_{\text{(ST,MP or CV)}}}$ is provided in Section 7.3.4 and Section 7.3.5. $P(t)_{\text{f(equ)}}$ is the POF calculated for the steam-using equipment as explained in Section 7.3.6.

7.3.4 POF (Steam Piping)

7.3.4.1 POF for Steam Traps, Mechanical Pumps, and Control Valves

Analysis has been carried out on the historical time to failure data (for various failure types), and a Weibull distribution has been fitted. As described in Section 7.3.1, Weibull functions are suitable for such analysis with the added advantage of having the ability to evaluate large populations of data to seek trends. In the absence of large sets of failure data, the functions are still useful as a starting point.

Equation (5.122) is the cumulative failure density function of a two-parameter Weibull distribution, also referred to as the probability of failure (POF) for a steam trap. In this equation, t is the in-service life of the steam trap (in years), η is the characteristic life (also in years), and β is the shape parameter.

Once the characteristic life parameter $\eta_{\text{def,ST}}$ (for leak and blockage) and shape β_{ST} parameters are obtained from Table 7.4 (from historical data analysis), the POF of the steam trap is calculated using Equation (5.125) for leakage and (5.126) for blockage.

$$P(t)_{\text{f,def,leak}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{def,leak,ST}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.125}$$

$$P(t)_{\text{f,def,cold}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{def,cold,ST}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.126}$$

The data presented in Table 7.4 are based on the best available sources and experience to date from owner–operators. Table 7.4 introduces default Weibull parameters for the different steam trap types in both failure modes. However, it is recommended that both Weibull parameters be used by the owner–operator where more accurate data for default shape/characteristic life parameters are available. The default parameters in Table 7.4 are suggested for use when data is unavailable.

7.3.4.2 Adjusted POF for Steam Traps, Mechanical Pumps, and Control Valves

Adjustments are made to the η parameter to increase or decrease POF as a result of condition of design/installation, operation, or maintenance history factors. POF is adjusted based on the adjustment multiplier for each design/installation, F_{D}, operational, F_{O}, or maintenance history, F_{M}, conditions. The default POF [$P(t)_{\text{f,def,leak}}$ and $P(t)_{\text{f,def,cold}}$] needs to be adjusted by the adjustment multipliers given in Table 7.5 to Table 7.13.

$$\eta_{\text{adj,leak}_{\text{ST,MP or CV}}} = \eta_{\text{def,leak,ST}} \cdot F_{\text{D}\,(\text{ST,MP or CV})} \cdot F_{\text{O}\,(\text{ST,MP or CV})} \cdot F_{\text{M}\,(\text{ST,MP or CV})} \tag{5.127}$$

$$\eta_{\text{adj,cold}_{\text{ST,MP or CV}}} = \eta_{\text{def,cold,ST}} \cdot F_{\text{D}\,(\text{ST,MP or CV})} \cdot F_{\text{O}\,(\text{ST,MP or CV})} \cdot F_{\text{M}\,(\text{ST,MP or CV})} \tag{5.128}$$

$$P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{adj,leak}_{(\text{ST,MP or CV})}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.129}$$

$$P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{adj,cold}_{(\text{ST,MP or CV})}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.130}$$

The adjusted η parameter [$\eta_{\text{adj,leak}_{(\text{ST,MP or CV})}}$ and $\eta_{\text{adj,cold}_{(\text{ST,MP or CV})}}$] is used to calculate the final (tailored) POF using Equation (5.129) for leakage and Equation (5.130) for blockage for each steam trap, mechanical pump, or control valve operating within a steam system. The shape factor β_{ST} used in Equation (5.129) and (5.130) is the same shape factor generated from Table 7.4. Equation (5.129) and Equation (5.130) provide the final POF for each steam trap, mechanical pump, or control valve in a steam system.

Suggested adjustment multiplier categories that need to be considered for steam traps, mechanical pumps, and control valves are given in Table 7.5 to Table 7.13. It should be noted that the value of each adjustment multiplier depends on engineering judgement.

7.3.5 Multiple Steam Trap or Mechanical Pumps or Control Valves Installations

For any steam-using equipment, there are several associated piping with steam traps (or mechanical pumps or control valves) installed. The piping usually have steam traps installed in parallel or series. When there are multiple steam traps (or mechanical pumps or control valves) installed, the calculated POF for any one specific steam trap in the multiple installation will remain the same. However, the overall combined POF for leakage and blockage of multiple traps (in parallel or series) should be considered for each piping using Equations (5.131) and (5.132) for traps in series and Equations (5.133) and (5.134) for traps in parallel.

$$P(t)_{\text{f,final series,leak}_{(\text{ST,MP or CV})}} = 1 - \left(1 - P(t)_{\text{f1,leak}}\right) \cdot \left(1 - P(t)_{\text{f2,leak}}\right) \cdot \ldots \cdot \left(1 - P(t)_{\text{f}n\text{,leak}}\right) \tag{5.131}$$

$$P(t)_{\text{f,final series,cold}_{(\text{ST,MP or CV})}} = 1 - \left(1 - P(t)_{\text{f1,cold}}\right) \cdot \left(1 - P(t)_{\text{f2,cold}}\right) \cdot \ldots \cdot \left(1 - P(t)_{\text{f}n\text{,cold}}\right) \tag{5.132}$$

$$P(t)_{\text{f,final parallel,leak}_{(\text{ST,MP or CV})}} = P(t)_{\text{f1,leak}} \cdot P(t)_{\text{f2,leak}} \cdot \ldots \cdot P(t)_{\text{f}n\text{,leak}} \tag{5.133}$$

$$P(t)_{\text{f,final parallel,cold}_{(\text{ST,MP or CV})}} = P(t)_{\text{f1,cold}} \cdot P(t)_{\text{f2,cold}} \cdot \ldots \cdot P(t)_{\text{f}n\text{,cold}} \tag{5.134}$$

For example, Figure 7.3 is the sample arrangement of the traps showing their different capacity. Calculation of the POF for each piping is given by Equation (5.133) and Equation (5.134), which allow calculation of the total POF for the piping in parallel configuration [Figure 7.3 a)]. In addition, if the capacity of Trap 1 and Trap 2 are not sufficient for the equipment requirement individually, these two traps (or mechanical pumps or control valves) are treated as series configurations [Figure 7.3 b)] using Equation (5.131) and Equation (5.132).

7.3.6 POF for Equipment

As discussed in Section 7.1.2, there are different types of equipment used in steam systems. Examples of some of these types were given in Table 7.1. In this section, the POF calculation due to steam related failure will be covered. Equipment consists of the following:

a) heat exchanger,

b) distillation tower/column,

c) stripper,

d) flare,

e) steam turbine

f) piping (steam main or condensate piping),

g) tracing (instrumentation/relief valve).

The calculation of the POF of equipment takes into account the effect of both equipment and its associated piping. It is also important to note that the calculation assumes that each individual item of equipment is independent.

For example, Figure 7.4 a) shows an arrangement of a steam turbine with traps. Block diagrams for combining the POF calculation for the same system Steam Trap 1 and Steam Trap 2 in parallel and series are provided in Figure 7.4 b) and Figure 7.4 c), respectively.

The equations below are used in estimating the POF for the equipment listed above, and each equipment is considered independent and assessed separately.

$$\eta_{\text{adj,equ}} = \eta_{\text{def,equ}} \cdot \left(F_{\text{D}_{\text{equ}}} \cdot F_{\text{O}_{\text{equ}}} \cdot F_{\text{M}_{\text{equ}}} \right) \tag{5.135}$$

$$P(t)_{\text{f,final(equ)}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{adj,equ}}} \right)^{\beta_{\text{equ}}} \right] \tag{5.136}$$

The default characteristic life parameter, $\eta_{\text{def,equ}}$, and shape parameter, β_{equ}, are obtained from historical data analysis. Table 7.14 shows default Weibull parameters for the different types of steam-using equipment. The data presented in Table 7.14 are based on the best available sources and experience to date from owner–operators. However, it is recommended that other Weibull parameters be used by the owner–operator where plant-specific data for default shape/characteristic life parameters are available. The default parameters in Table 7.14 are suggested when plant-specific data is unavailable and are based on failure of steam systems.

Similar to the approach for steam traps discussed in Section 7.3.4.2, $\eta_{\text{adj,equ}}$ is used to calculate the final (tailored) POF [Equation (5.136)] for steam-using equipment. The shape factor β_{equ} used in Equation (5.136) is the shape factor from Table 7.14. $P(t)_{\text{f,final(equ)}}$ is the final POF of the steam-using equipment. The adjustment multiplier categories for each design/installation, $F_{\text{D}_{\text{equ}}}$, operational, $F_{\text{O}_{\text{equ}}}$, or maintenance history, $F_{\text{M}_{\text{equ}}}$, factors are given in Table 7.15 to Table 7.17 and are used to modify the default characteristic life parameter, $\eta_{\text{def,equ}}$. It should be noted that the value of each adjustment multiplier depends on engineering judgement.

7.3.7 POF for Steam Systems

The total POF for one piece of steam system is calculated using Equation (5.123) and Equation (5.124) where $P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}}$ and $P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}}$ is calculated from Equation (5.129) and Equation (5.130) for individual steam traps, and for multiple steam traps the procedure in Section 7.3.5 is used.

7.3.8 POF After Inspection

7.3.8.1 General

Weibull parameters for the failure on demand curves are determined based on the analysis of a sample set of data (Section 7.3.1). However, as inspection data is collected, these parameters may be adjusted for each device based on the actual inspection results. This approach assumes that the Weibull shape parameter, β, remains constant based on the historical data and adjusts the characteristic life, η, as inspection data are collected.

The effectiveness of inspection and testing is provided in Annex 2.F, Section 2.F.11.2, Table 2.F.11.1. The probability of succeeding the inspection prior to inspection is given by Equation (5.137) and Equation (5.138).

$$P(t)_{\text{f,prior,leak}} = 1 - P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} \tag{5.137}$$

$$P(t)_{\text{f,prior,cold}} = 1 - P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}} \tag{5.138}$$

After inspection, the POF is updated based on the results. Use Equations (5.139) and (5.140) if the inspection results do not show the expected failure.

$$P(t)_{\text{f,after,leak}} = \left(1 - CF_{\text{pass}}\right) P(t)_{\text{f,prior,leak}} \tag{5.139}$$

$$P(t)_{\text{f,after,cold}} = \left(1 - CF_{\text{pass}}\right) P(t)_{\text{f,prior,cold}} \tag{5.140}$$

Use Equations (5.141) and (5.142) if the inspection confirms the expected failure.

$$P(t)_{\text{f,after,leak}} = \left(1 - CF_{\text{pass}}\right) \cdot P(t)_{\text{f,prior,leak}} + \left(P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} \cdot CF_{\text{fail}}\right) \tag{5.141}$$

$$P(t)_{\text{f,after,cold}} = \left(1 - CF_{\text{pass}}\right) \cdot P(t)_{\text{f,prior,cold}} + \left(P(t)_{\text{f,final,cold}(\text{ST,MP or CV})} \cdot CF_{\text{fail}}\right) \tag{5.142}$$

Based on the outcome of the inspection and its effectiveness, the updated POF after inspection is calculated using equations in Table 7.19. The characteristic life $\left[\eta_{\text{adj,leak}(\text{ST,MP or CV})} \text{ and } \eta_{\text{adj,cold}(\text{ST,MP or CV})}\right]$ is updated based on the outcome of the inspection using Equation (5.143) and Equation (5.144).

$$\eta_{\text{upd,leak}} = \frac{t}{\left(-\ln\left(1 - P(t)_{\text{f,wgt,leak}}\right)\right)^{\frac{1}{\beta_{\text{ST}}}}} \tag{5.143}$$

$$\eta_{\text{upd,cold}} = \frac{t}{\left(-\ln\left(1 - P(t)_{\text{f,wgt,cold}}\right)\right)^{\frac{1}{\beta_{\text{ST}}}}} \tag{5.144}$$

where β_{ST} is shape factor established earlier and t is the inspection interval. The updated characteristic life is then used in the calculation of the POF using Equation (5.145) and (5.146).

$$P(t)_{\text{f,upd,leak}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{upd,leak}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.145}$$

$$P(t)_{\text{f,upd,cold}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{upd,cold}}}\right)^{\beta_{\text{ST}}}\right] \tag{5.146}$$

7.3.8.2 POF After Cleaning

The steam trap POF will be reduced after each cleaning. For example, if the periodic cleaning is done every 0.5 years, the POF at 0.6 years will be reduced to the same POF value as at 0.1 year, and at 1.1 years the POF will also be equal to the POF at 0.1 years.

7.3.9 POF Calculation Procedure

The following calculation procedure is used to determine the POF due to leak and blockage for steam traps and steam-using equipment. The POF of each steam system is calculated as the combined effect of individual equipment with its associated traps for both leak and blockage.

a) Step 1—Identify the steam traps, mechanical pumps, control valves, and associated steam-using equipment item in the steam system. Provide required data defined in Table 7.3.

b) Step 2—Calculate the POF for each steam trap, mechanical pump, and control valve for both failure modes.

   1) Step 2.1—Determine the default values of the Weibull parameters for both failure modes from Table 7.4.

   2) Step 2.2—Using Table 7.5 to Table 7.13, determine the design, operating, and maintenance condition adjustment for each item (steam trap, mechanical pump, and control valve).

3) Step 2.3—Using Equation (5.127) and Equation (5.128), adjust the Weibull parameters $\eta_{\text{def,leak,ST}}$ and $\eta_{\text{def,cold,ST}}$ based on the values in Step 2.2 for both failure modes.

4) Step 2.4—Calculate $P(t)_{\text{f,final,leak}(\text{ST,MP or CV})}$ and $P(t)_{\text{f,final,cold}(\text{ST,MP or CV})}$ using Equation (5.129) and Equation (5.130) based on the adjusted Weibull parameters $\eta_{\text{adj,leak}(\text{ST,MP or CV})}$ and $\eta_{\text{adj,cold}(\text{ST,MP or CV})}$ using Equation (5.127) and Equation (5.128). Repeat for each steam trap, mechanical pump, and control valve.

5) Step 2.5—For steam traps, mechanical pumps, and control valves installed in parallel or series, use Equations (5.131) to (5.134) for both failure modes to calculate POF.

c) Step 3—Inspection POF updating for each steam trap, mechanical pump, and control valve for both failure modes. Repeat the following steps in case of multiple steam traps, mechanical pumps, and control valves.

1) Step 3.1—Identify the effectiveness of the inspection and testing method using Annex 2.F, Section 2.F.11.2, Table 2.F.11.1.

2) Step 3.2—Using Equations (5.137) and (5.138), calculate the probability of not failing the inspection prior to inspection for both failure modes.

3) Step 3.3—Identify the confidence factor associated with the inspection effectiveness and inspection result using Table 7.18.

4) Step 3.4—Calculate $P(t)_{\text{f,after}}$ for blockage and leakage failures using Equations (5.139) and (5.140) if the inspection results do not show the expected failure and Equations (5.141) and (5.142) if the inspection confirms the expected failure.

5) Step 3.5—Calculate $P(t)_{\text{f,wgt}}$ using the appropriate equation for inspection using Table 7.19 and based on the inspection effectiveness and inspection results.

6) Step 3.6—Calculate the updated characteristic life, using Equations (5.143) and (5.144).

7) Step 3.7—Calculate the POF at year in service using Equations (5.145) and (5.146).

8) Step 3.8—Calculate the POF for both failure modes, at $t_{\text{service(ST)}}$ based on the steam trap arrangement using Equations (5.131) and (5.132) for series or Equations (5.133) and (5.134) for parallel configuration.

d) Step 4—Calculate the POF for one piece of steam-using equipment in the steam system. Repeat the following steps for each piece of steam-using equipment in the steam system.

1) Step 4.1—Use the default Weibull parameters for the steam-using equipment from Table 7.14.

2) Step 4.2—Using Table 7.15, determine the design condition adjustment, $F_{\text{D}_{\text{equ}}}$, for the steam-using equipment.

3) Step 4.3—Using Table 7.16, determine the operation condition adjustment, $F_{\text{O}_{\text{equ}}}$,for the steam-using equipment.

4) Step 4.4—Using Table 7.17, determine the maintenance history/inspection condition adjustment, $F_{\text{M}_{\text{equ}}}$, for the steam-using equipment.

5) Step 4.5—Using Equation (5.135), adjust the Weibull parameter, $\eta_{\text{def,equ}}$, based on the values in Steps 4.2, 4.3, and 4.4.

6) Step 4.6—Using Equation (5.136), calculate the, $P(t)_{\text{f,final(equ)}}$, for the steam-using equipment based on the adjusted Weibull parameter, $\eta_{\text{adj,equ}}$.

e) Step 5—Calculate the final POF for the steam system using Equations (5.123) and (5.124) for both failure modes.

Steps 1 to 5 are repeated for multiple steam systems—a steam system is one piece of steam-using equipment and its associated piping and traps.

7.4 COF Methodology

7.4.1 Background

This section presents a procedure to calculate COF for a steam system. Equipment can be connected to either an open system or a closed system and have COF due to leakage and blockage. An open system will allow the steam/condensate to escape into the environment, while a closed system circulates the steam/condensate to be reused.

7.4.2 Models for Assessing COF

7.4.2.1 Overview

The calculation of the COF is performed by evaluating costs involved in different failure consequences, such as the cost of the loss of inventory, regulatory cost, cost of downtime, and cost of repairs. Failure will result in a consequence, i.e. potential impact on people, as well as product loss and component damage in some cases.

COF varies with different equipment and failure modes. The following sections provide the potential costs due to failures and outlines the COF calculation steps.

7.4.2.2 Cost of Steam Loss Due to Leakage

$$FC_{\text{loss}} = \left(\frac{lrate \cdot 8760 \cdot FC_{\text{steam}}}{1000} \right) \tag{5.147}$$

The leakage rate ($lrate$) is based on historical inspection data.

7.4.2.3 Cost of Condensate Loss Due to Downstream Equipment Rupture

$$FC_{\text{loss,D/S}} = mass_{\text{condensate}} \cdot FC_{\text{condensate}} \tag{5.148}$$

The condensate mass, $mass_{\text{condensate}}$, is calculated following the procedure recommended in Part 3, Section 4.7.2, Equation (3.14). The cost of condensate, $FC_{\text{condensate}}$, is user specified.

7.4.2.4 Cost of Component Damage Due to Rupture Caused by Water Hammer

The temporary default component damage cost uses the recommended values from Part 3, Section 4.12.2 for heat exchangers and steam tracing process pipes and the North American Electric Reliability Corporation (NERC) Generating Availability Data System (GADS) for steam turbines. The default values are able to be customized by the user.

7.4.2.5 Cost of Production Loss Due to Shutdown or Reduced Service Efficiency

The production loss value can be manually assigned or calculated using Equation (5.149).

$$FC_{\text{prod}} = Unit_{\text{prod}} \cdot \left(\frac{Rate_{\text{red}}}{100} \right) \cdot D_{\text{sd}} \tag{5.149}$$

where $Unit_{\text{prod}}$ is the daily profit margin on the unit ($/day). This will be input by the user. $Rate_{\text{red}}$ is the production rate reduction on a unit as a result of the equipment being out of service (%), which will also be user input. D_{sd} is the number of days required to shut down a unit in order to repair the equipment during an unplanned shutdown.

7.4.2.6 Cost of Safety Impact to Personnel Due to Rupture and Leakage

The steam released through leakage or rupture may result in a safety impact on personnel. The total personnel injury cost, FC_{inj}, within a certain area is calculated using Equation (5.150).

$$FC_{\text{inj}} = CA_{\text{f,inj}} \cdot popdens \cdot injcost \tag{5.150}$$

where $CA_{\text{f,inj}}$ is calculated by using the procedure in Part 3, Section 4.10.2.

The hole size used to calculate the $CA_{\text{f,inj}}$ due to rupture from blockage is the inlet/connection size using Part 3, Equation (3.70). A medium hole size of 1 in. (25 mm) is used to calculate $CA_{\text{f,inj}}$ due to leakage using Part 3, Equation (3.69). The $popdens$ and $injcost$ used in Equation (5.150) is defined in Part 3, Section 4.12.5. The required input parameters are listed in Table 7.20.

The cost of safety impact to personnel due to rupture and leakage of downstream equipment $\left(FC_{\text{inj,D/S}}\right)$ is calculated by using water as model fluid.

Financial consequence as a result of serious injury to personnel due to process $\left(FC_{\text{inj,process}}\right)$ is calculated using Equation (5.151) based on the hole size in Part 3, using the product in the process pipe.

$$FC_{\text{inj,process}} = \max\left(FC_{\text{inj,nfnt}} + FC_{\text{inj,flam}} + FC_{\text{inj,toxic}}\right) \tag{5.151}$$

For multiple traps, use Equations (5.152) and Equation (5.153) to calculate COF.

Blockage:

$$FC_{\text{inj,cold}} = \max\left(FC_{\text{inj,cold}_1}, FC_{\text{inj,cold}_2}, \ldots, FC_{\text{inj,cold}\_n}\right) \tag{5.152}$$

Leak:

$$FC_{\text{inj,leak}} = \left(FC_{\text{inj,leak}_1} + FC_{\text{inj,leak}_2} + \ldots + FC_{\text{inj,leak}\_n}\right) \tag{5.153}$$

7.4.3 Cost Models for Steam System with Different Equipment

7.4.3.1 Overview

The financial COF varies for steam systems with different equipment and failure modes. A list of potential costs due to failure and calculation methods was introduced in Section 7.4.2. The financial COF is calculated differently for steam system depending on the type of equipment connected. Currently, "type of connected equipment" is one of the data requirements for steam distribution COF calculation. Section 7.4.3.2 through Section 7.4.3.10 outline the calculation methodology for estimating financial COF for different types of steam systems, which includes steam traps and steam-using equipment. Only one of these sections will apply for a steam system.

7.4.3.2 COF Model for Steam System with Heat Exchanger or Steam Turbine

The failure modes for heat exchanger and steam turbines can be either blockage or leakage and are calculated separately. The presence of an opening bypass for the steam system should be determined in the case of a blockage. If no opening bypass exists, a blockage could cause the steam system to shut down and may result in water hammer inside the equipment, causing a production loss and/or rupture. A rupture may cause a financial loss due to component damage and safety impact (personnel injury). The financial COF due to blockage without an opened bypass for heat exchanger and turbine is calculated using Equation (5.154).

$$FC_{\text{cold}}^{\text{HEX,Turbine}} = FC_{\text{prod}} + FC_{\text{comp}} + FC_{\text{inj}} \tag{5.154}$$

The blockage consequence is calculated the same as a leakage consequence [Equation (5.155)] in an open system if the bypass is opened.

The total steam loss is calculated for both leakage and blockage with an open bypass. If the bypass is open, the safety impact is considered in addition to the loss of steam.

If the outlet is closed while the traps are leaking, there will be a subsequent consequence of water hammer occurring to the downstream equipment/pipe in addition to steam loss from leaking traps. In the worst case, the downstream pipe will be ruptured. This will result in production loss due to downstream equipment shutdown, downstream pipe component damage, loss of condensate, and associated safety impacts. The financial COF due to both leakage and blockage with an open bypass for a heat exchanger and turbine is calculated using Equation (5.155) and Equation (5.156) If the bypass is closed or if there is no bypass, then $FC_{\text{inj}} = 0$ in Equation (5.155).

$$FC_{\text{leak,open}}^{\text{HEX,Turbine}} = FC_{\text{loss}} + FC_{\text{inj}} \tag{5.155}$$

$$FC_{\text{leak,closed}}^{\text{HEX,Turbine}} = FC_{\text{loss}} + FC_{\text{loss,D/S}} + \left(FC_{\text{prod,D/S}} + FC_{\text{comp,D/S}} + FC_{\text{inj,D/S}}\right) \tag{5.156}$$

7.4.3.3 COF Model for Steam System with General Steam Tracing

The failure modes for general steam tracing equipment (tracing with steam temperatures above 356 °F [180 °C)] can be either blockage or leakage, which are calculated separately. Unlike a heat exchanger or turbine (as described in Section 7.4.3.2), the COF for tracing is considered for the process pipe and tracing piping. When "blockage" happens, it shall be established whether there is an opened bypass for the system or the trap is disconnected. If the bypass is closed or the trap is not disconnected, the blockage will cause the steam system to shut down or the content to cool down and possibly water hammer inside the tracing piping. In one case, the steam system shut down and content sub-cooling will result in production loss in addition to the cost of process pipe cut-off (component damage). In another case, the water hammer inside the tracing piping will cause the tracing piping to rupture (worst case scenario), which will result in costs of the tracing piping component damage in addition to associated safety impacts.

The COF due to blockage in an open and closed system without opened bypass or trap disconnection for general steam tracing is calculated using Equation (5.157).

$$FC_{\text{cold}}^{\text{Tracing,HT}} = FC_{\text{prod}} + FC_{\text{comp,process}} + FC_{\text{comp,line}} + FC_{\text{inj}} + FC_{\text{inj,process}} \tag{5.157}$$

For leakage, in an open system the COF is calculated using Equation (5.155). For a closed system, the leakage COF is calculated using Equation (5.156).

7.4.3.4 COF Model for Steam System with Low-temperature Steam Tracing

Low-temperature steam tracing is used in applications that require low flow or needs to be kept warm due to low ambient conditions. The temperature of steam used in low-temperature steam tracing is between 302 °F and 356 °F (150 °C and 180 °C). The failure modes can be either blockage or leakage, which will be calculated separately. The COF for tracing is considered for process pipe and tracing piping separately.

Similar to the general steam tracing (Section 7.4.3.3), when blockage occurs, the COF is calculated using Equation (5.157) for both open and closed system without bypass.

For both leakage and blockage with open bypass or trap disconnection, the common failure consequence for both an open and closed system is as follows.

a) The steam leaking will result in costs from steam loss; if multiple traps are leaking, the sum of steam loss costs should be reported.

b) Leakage causes equipment shutdown or overheating, which gives rise to costs from production loss.

Water hammer may occur inside the process piping due to leakage may results in a rupture of the process piping and costs from process piping component damage and safety impact. The fluid within the process piping is assigned as flammable or toxic or flammable and toxic. The semiquantitative model to estimate safety COF is developed based on Part 3. If the fluid is both flammable and toxic, the worst case will be used.

In addition to costs listed above, for an open system (i.e. the outlet is opened), there are further safety impacts caused by leaking steam. If it is a closed system, there is a subsequent consequence of water hammer occurring to the downstream equipment/pipe; use Equation (5.158) with $FC_{\text{inj}} = 0$.

The COF due to both leakage and blockage with open bypass or trap disconnection for low-temperature steam tracing is calculated using Equation (5.158) for open system and Equation (5.159) for closed system.

$$FC_{\text{leak,open}}^{\text{Tracing,LT}} = FC_{\text{inj}} + \left(FC_{\text{loss}} + FC_{\text{comp,process}} + FC_{\text{prod,process}} + FC_{\text{inj,process}}\right) \tag{5.158}$$

$$\begin{aligned} FC_{\text{leak,closed}}^{\text{Tracing,LT}} = &\left(FC_{\text{loss}} + FC_{\text{loss,D/S}} + FC_{\text{comp,process}} + FC_{\text{prod,process}} + FC_{\text{inj,process}}\right) \\ &+ \left(FC_{\text{prod,D/S}} + FC_{\text{comp,D/S}} + FC_{\text{inj,D/S}}\right) \end{aligned} \tag{5.159}$$

where $FC_{\text{inj,process}}$ is calculated using Equation (5.151).

7.4.3.5 COF Model for Steam System with Steam Tracing with Relief Valve

The relief valve is a type of valve used to control or limit the pressure in the steam tracing system. Pressure can build up as a result of a process, instrument, or equipment failure. However, if the relief valve fails, there is the possibility the high pressure of the fluid within the pipe is raised further and causes leakage through the joints. In this case, the failure consequence is the sum of the cost of fluid loss and injury costs due to the leakage where the relief valve is installed (see Section 6.1.7). The financial COF calculation follows the COF equations for low-temperature steam tracing.

7.4.3.6 COF Model for Steam System with Steam Tracing with Flow Meter

A flow meter is an instrument used to measure linear, nonlinear, volumetric or the mass flow rate of fluids, which can be found on both general tracing and low-temperature applications. If the flow meter fails, the fluid is transported without measurement. This will not cause any safety consequence or financial loss in terms of product loss or component damage. However, without measurement, there may be a certain amount of business loss, which will be assessed by the user. In summary, the total financial COF is the same as for general tracing on a low-temperature tracing system, with modified business loss that will be assessed by the user directly.

7.4.3.7 COF Model for Steam System with Distillation Columns with Stripping Steam

The steam trap failure modes considered for distillation columns are leakage and blockage. For the failure mode of leakage in an open system when the bypass is open, financial COF is the sum of steam loss and cost of the safety impact due to condensate/steam discharge into the open air [Equation (5.155)]. If the outlet is closed, steam loss is the leakage financial COF [Equation (5.156)]. In terms of failure due to blockage when the bypass is not open, there is the possibility of condensate carryover and/or water hammer, and the financial COF is calculated as the sum of component damage, production loss, and the cost of safety impact using Equation (5.154). If the bypass is open, the financial COF of due to blockage is the same as the COF of leakage.

7.4.3.8 COF Model for Steam System with Flare

The steam trap failure modes considered for flare are leakage and blockage. Similar to distillation columns (Section 7.4.3.7), if the steam trap of the flare leaks and its outlet is open, financial COF is the sum of steam loss and the cost of the safety impact due to condensate/steam discharge to the open air [Equation (5.155)]. Otherwise, if the outlet is closed, steam loss is the only leakage financial COF [Equation (5.156)]. In terms of failure due to blockage when the bypass is not open, there is the possibility of condensate carryover and/or water hammer, and the financial COF is calculated using Equation (5.160) as the sum of component damage, production loss, the cost of safety impact due to pipe rupture, and environmental costs due to reduced burning efficiency. If the bypass is open, the financial COF of due to blockage is the same as the COF of leakage.

$$FC_{\text{cold}}^{\text{Flare}} = FC_{\text{loss}} + FC_{\text{comp}} + FC_{\text{inj}} + FC_{\text{comp,process}} + FC_{\text{prod,process}} + FC_{\text{inj,process}} + FC_{\text{env}} \tag{5.160}$$

where $FC_{\text{inj,process}}$ is calculated from Equation (5.151).

7.4.3.9 COF Model for Steam System with Steam Distribution Piping

The failure modes considered for steam distribution piping are leakage and blockage. Similar to distillation columns (Section 7.4.3.7), if the steam trap of the main steam distribution piping leaks and its outlet is open, financial COF is the sum of steam loss and cost of the safety impact due to condensate/steam discharge to open air using Equation (5.155). If the outlet is closed, the leakage financial COF due to steam loss is calculated by using Equation (5.155) with $FC_{\text{inj}} = 0$. In terms of failure due to blockage when the bypass is not open, there will be the possibility of water hammer; the financial COF is calculated as the sum of component damage (steam distribution piping), production loss, and the cost of any safety impact [Equation (5.154)]. If the bypass is open, the financial COF due to blockage is the same as the financial COF of leakage.

7.4.3.10 COF Model for Steam System with Condensate Recovery Piping

The failure mode considered for the steam recovery piping is leakage only. This is because blocked steam traps are not discharging into the condensate recovery piping, so they do not have any effect. When the recovery piping fails due to a steam trap leakage, the condensate pipe may rupture due to water hammer. The financial COF is calculated as the sum of any component damage (pipe), cost of safety impact, condensate loss, and downstream equipment production loss using Equation (5.161).

$$FC_{\text{leak}}^{\text{Recovery}} = FC_{\text{loss,D/S}} + FC_{\text{prod,D/S}} + FC_{\text{comp,D/S}} + FC_{\text{inj,D/S}} \tag{5.161}$$

7.4.4 COF Calculation Procedure

The following calculation procedure may be used to determine the financial COF for a steam system. The financial COF needs to be calculated for both failure modes.

a) Step 1—Calculate the cost of steam loss due to leakage using Equation (5.147).

b) Step 2—Calculate the cost of condensate loss due to downstream equipment rupture using Equation (5.148). Go to Step 3 if no downstream equipment is connected or if the system is open, i.e. the condensate is discharged to open.

c) Step 3—Calculate the cost of production loss due to shutdown or reduced service efficiency using Equation (5.149).

d) Step 4—Calculate the cost of safety impact to personnel due to steam and process release using Equation (5.150) and Equation (5.151), respectively. If there are multiple steam traps, use Equation (5.152) and Equation (5.153).

e) Step 5—Determine if the steam system is open or closed and calculate the financial COF (FC_{leak} and FC_{cold}) for steam system based on the type of steam-using equipment, using Table 7.21 and Table 7.22.

7.5 Risk-based Analysis

The risks due to leakage and blockage are calculated using Equations (5.162) and (5.163), where the POF of steam system is calculated from Equations (5.123) and (5.124) for both leakage and blockage. The FC_{leak} and FC_{cold} are calculated in Step 5 in Section 7.4.4.

$$R(t)_{\text{leak}} = P(t)_{\text{f,final,leak(steam system)}} + FC_{\text{leak}} \tag{5.162}$$

$$R(t)_{\text{cold}} = P(t)_{\text{f,final,cold(steam system)}} + FC_{\text{cold}} \tag{5.163}$$

The total risk $R(t)$ is the sum of the risk due to blockage and leakage and is calculated from Equation (5.164).

$$R(t) = R(t)_{\text{leak}} + R(t)_{\text{cold}} \tag{5.164}$$

For the output, the risk is calculated as a function of time on a risk matrix. All of the post-assessment analysis are conducted based on this; this will be discussed in the following sections.

7.6 Inspection and Risk Mitigation Planning

7.6.1 Risk Mitigation Plan

7.6.1.1 Overview

The mitigation plan comprises risk mitigation suggestions/actions to assist asset owner–operator managing their steam system through the identification of the influence of each mitigation action on the system. The method for illustration of the risk target is the “iso-risk target.” the iso-risk target is defined as a line of constant risk and a method of graphically showing POF and COF values in a log-log, two-dimensional plot where risk increases toward the upper right-hand corner. The value of the target risk will be determined by the user.

The possible mitigation actions listed in Section 7.6.2.1 to Section 7.6.2.3 are suggestions only and may not be applicable in all situations.

7.6.1.2 Configuration of Steam System

The risk can be modified by changing the configurations of the steam system, either by adding spare equipment or extra steam traps to the piping or changing the type of the existing steam traps. The influence will depend on the number and location of the extra steam traps. Specifically, if extra steam traps are added, the arrangement of the steam system will be changed. The value of POF will be amended accordingly. Meanwhile, different steam traps will have a different $P(t)_{\text{adjusted}}$, which will affect the POF of the steam system [Equations (5.123) and (5.124)].

7.6.1.3 Inspection

If an inspection is performed, or a condition monitoring device installed, the risk categories will also be shifted as the tailored characteristic life η_{adjusted} will be updated accordingly. The procedure proposed in Section 7.3.9 will be followed. For sensors, the confidence factor, CF, value will be defaulted to "usually effective."

Cleaning of the steam trap has a significant impact on the POF; the more frequent the cleaning, the lower the POF over time.

7.6.1.4 Spare Equipment

If any spare equipment is included in one steam system, this may help to reduce the consequential cost of production loss. The POF can also be mitigated by intentionally releasing steam, e.g. via "bypass open." However, this action is not recommended due to environmental and safety viewpoints. In addition, it not only causes an increment of COF due to loss of steam but could also lead to local corrosion damage, i.e. FC_{loss} and FC_{comp}.

7.7 Nomenclature

$CA_{\text{f,inj}}$	is the final personnel injury consequence area, ft^2 (m^2)
CF_{fail}	is the confidence factor for the inspection results in failure
CF_{pass}	is the confidence factor for the inspection not to result in failure
D_{sd}	is the time required to shut down a unit to perform a repair, days
$F_{\text{D}_{\text{CV}}}$	is the design adjustment multiplier for control valve
$F_{\text{D}_{\text{equ}}}$	is the design adjustment multiplier for steam-using equipment
$F_{\text{D}_{\text{MP}}}$	is the design adjustment multiplier for mechanical pump
$F_{\text{D}_{\text{ST}}}$	is the design adjustment multiplier for steam traps
$F_{\text{M}_{\text{CV}}}$	is the maintenance/inspection history adjustment multiplier for control valve
$F_{\text{M}_{\text{equ}}}$	is the maintenance/inspection history adjustment multiplier for steam-using equipment

$F_{M_{MP}}$ is the maintenance/inspection history adjustment multiplier for mechanical pump

$F_{M_{ST}}$ is the maintenance/inspection history adjustment multiplier for steam traps

$F_{O_{CV}}$ is the operational adjustment multiplier for control valve

$F_{O_{equ}}$ is the operational adjustment multiplier for steam-using equipment

$F_{O_{MP}}$ is the operational adjustment multiplier for mechanical pump

$F_{O_{ST}}$ is the operational adjustment multiplier for steam traps

FC_{cold} is the financial COF of steam system due to blockage, $

FC_{cold}^{Flare} is the financial COF of flare due to blockage, $

$FC_{cold}^{HEX,Turbine}$ is the financial COF of heat exchanger and turbine due to blockage, $

FC_{comp} is the cost of component damage, $

$FC_{comp,D/S}$ is the cost of component damage (downstream), $

$FC_{comp,line}$ is the cost of component damage (tracing piping), $

$FC_{comp,main}$ is the cost of component damage (main pipe), $

$FC_{comp,process}$ is the cost of component damage (process piping), $

$FC_{condensate}$ is the cost of condensate, $/lb ($/kg)

FC_{env} is the cost of environmental damage, $

FC_{inj} is the financial consequence as a result of serious injury to personnel, $

$FC_{inj,cold}$ is the financial consequence due to blockage as a result of serious injury to personnel, $

$FC_{inj,D/S}$ is the financial consequence as a result of serious injury to personnel (downstream), $

$FC_{inj,flam}$ is the financial consequence of as a result of serious injury to personnel due to flammable release, $

$FC_{inj,leak}$ is the financial consequence due to leakage as a result of serious injury to personnel, $

$FC_{inj,nfnt}$ is the financial consequence as a result of serious injury to personnel due to nonflammable, nontoxic, $

$FC_{inj,process}$ is the financial consequence as a result of serious injury to personnel (process piping), $

$FC_{inj,toxic}$ is the financial consequence of as a result of serious injury to personnel due to toxic release, $

FC_{leak}	is the financial COF of steam system due to leakage, \$
$FC_{\text{leak}}^{\text{Recover}}$	is the financial COF of condensate recover piping due to leakage, \$
$FC_{\text{leak,closed}}^{\text{HEX,Turbine}}$	is the financial COF of heat exchanger and turbine due to leakage (closed system), \$
$FC_{\text{cold}}^{\text{Tracing,HT}}$	is the financial COF of general steam tracing due to blockage, \$
$FC_{\text{leak,closed}}^{\text{Tracing,LT}}$	is the financial COF of low-temperature tracing due to leakage (closed system), \$
$FC_{\text{leak,open}}^{\text{HEX,Turbine}}$	is the financial COF of heat exchanger and turbine due to leakage (open system), \$
$FC_{\text{leak,open}}^{\text{Tracing,LT}}$	is the financial COF of low-temperature tracing due to leakage (open system), \$
FC_{loss}	is the cost of steam loss, \$
$FC_{\text{loss,D/S}}$	is the cost of condensate loss (downstream), \$
FC_{prod}	is the cost of production loss, \$
$FC_{\text{prod,D/S}}$	is the cost of production loss (downstream), \$
$FC_{\text{prod,process}}$	is the cost of production loss (process piping), \$
FC_{steam}	is the cost of steam production, \$/lb (\$/kg)
$F_{\text{D (ST, MP, or CV)}}$	is the design adjustment multiplier for steam traps, mechanical pump, or control valves
$F_{\text{O (ST, MP, or CV)}}$	is the operational adjustment multiplier for steam traps, mechanical pump, or control valves
$F_{\text{M (ST, MP, or CV)}}$	is the maintenance/inspection history adjustment multiplier for steam traps, mechanical pump, or control valves
$injcost$	is cost of personnel injury per individual, \$
$lrate$	leakage rate is based on historical inspection data, lb/hr (kg/hr)
$mass_{\text{condensate}}$	is the condensate mass used in the consequence calculation associated with the n^{th} release hole size, lb (kg)
$P(t)_{\text{adjusted}}$	is the tailored probability of failure calculation based on the condition of design/installation, operation, or maintenance history factors for steam trap, failure/year
$P(t)_{\text{f,after,cold}}$	is the POF due to blockage after inspection depending on the results, failure/year
$P(t)_{\text{f,after,leak}}$	is the POF due to leakage after inspection depending on the results, failures/year

$P(t)_{\text{f,def,cold}}$ is the POF due to leakage of steam traps, mechanical pumps, and control valves based on default values for Weibull parameters, failures/year

$P(t)_{\text{f,def,leak}}$ is the POF due to leakage of steam traps, mechanical pumps, and control valves based on default values for Weibull parameters, failures/year

$P(t)_{\text{f(equ)}}$ is the POF calculated for the steam-using equipment, failtures/year

$P(t)_{\text{f,final,cold}(\text{ST,MP or CV})}$ is the tailored POF due to blockage calculated for the associated piping (combined POF), consisting of multiple steam traps, mechanical pumps, and control valves, failures/year

$P(t)_{\text{f,final,cold}(\text{steam system})}$ is the POF for steam system due to blockage, failures/year

$P(t)_{\text{f,final(equ)}}$ is the tailored POF calculated for the steam-using equipment, failures/year

$P(t)_{\text{f,final,leak}(\text{ST,MP or CV})}$ is the tailored POF due to leakage calculated for the associated piping (combined POF), consisting of multiple steam traps, mechanical pumps, and control valves, failures/year

$P(t)_{\text{f,final,leak}(\text{steam system})}$ is the POF for steam system due to leakage, failures/year

$P(t)_{\text{f,final parallel,cold}(\text{ST,MP or CV})}$ is the POF due to blockage for multiple steam traps, mechanical pumps, and control valves in parallel, failures/year

$P(t)_{\text{f,final parallel,leak}(\text{ST,MP or CV})}$ is the POF due to leakage for multiple steam traps, mechanical pumps, and control valves in parallel, failures/year

$P(t)_{\text{f,final series,cold}(\text{ST,MP or CV})}$ is the POF due to blockage for multiple steam traps, mechanical pumps, and control valves in series, failures/year

$P(t)_{\text{f,final series,leak}(\text{ST,MP or CV})}$ is the POF due to leakage for multiple steam traps, mechanical pumps, and control valves in series, failures/year

$P(t)_{\text{f,prior,cold}}$ is the probability of not failing due to blockage the inspection prior to inspection, failures/year

$P(t)_{\text{f,prior,leak}}$ is the probability of not failing due to leakage the inspection prior to inspection, failures/year

$P(t)_{\text{f,upd,cold}}$ is the probability of failure due to blockage used for inspection updating, failures/year

$P(t)_{\text{f,upd,leak}}$ is the probability of failure due to leakage used for inspection updating, failures/year

$P(t)_{\text{f,wgt,cold}}$ is the updated POF due to blockage after inspection, failures/year

$P(t)_{\text{f,wgt,leak}}$ is the updated POF due to leakage after inspection, failures/year

$P(t)_{\text{f}n\text{,cold}}$ is the POF due to blockage of steam traps, mechanical pumps, and control valves, n in series or parallel configurations, failures/year

$P(t)_{\text{f}n\text{,leak}}$ is the POF due to leakage of steam traps, mechanical pumps, and control valves, n in series or parallel configurations, failures/year

$popdens$ is the population density of personnel or employees in the unit, personnel/ft^2 (personnel/m^2)

$Rate_{\text{red}}$ is the production rate reduction on a unit as a result of the equipment being out of service (%)

$R(t)$ is the risk as a function of time, \$/year

$R(t)_{\text{cold}}$ is the risk due to blockage as a function of time, \$/year

$R(t)_{\text{leak}}$ is the risk due to leakage as a function of time, \$/year

t is the time at which the risk is to be calculated, years

$Unit_{\text{prod}}$ is the unit production margin (\$/day)

B is the Weibull shape parameter estimated using AFT model

β_{equ} is the shape factor for equipment from Table 7.14

β_{ST} is the shape factor for steam traps, mechanical pumps, and control valves from Table 7.4

η is the Weibull characteristic life parameter, years

η_{adjusted} is the tailored characteristic life for the probability of failure calculation based on the condition of design/installation, operation, or maintenance history factor for steam trap, years

$\eta_{\text{adj,cold}(\text{ST,MP or CV})}$ is the tailored characteristic life for blockage based on condition of design/installation, operation, or maintenance history factors for equipment, years

$\eta_{\text{adj,equ}}$ is the tailored characteristic life based on condition of design/installation, operation, or maintenance history factors for equipment, years

$\eta_{\text{adj,leak}(\text{ST,MP or CV})}$ is the tailored characteristic life for leakage based on condition of design/installation, operation, or maintenance history factors for equipment, years

$\eta_{\text{def,cold,ST}}$ is the characteristic life parameter for blockage estimated using Weibull AFT model from Table 7.4, years

$\eta_{def,equ}$ is the characteristic life parameter for equipment estimated using Weibull AFT model from Table 7.14, years

$\eta_{def,leak,ST}$ is the scaled parameter for leakage estimated using Weibull AFT model from Table 7.4, years

$\eta_{upd,cold}$ is the updated characteristic life for blockage after inspection results, years

$\eta_{upd,leak}$ is the updated characteristic life for leakage after inspection results, years

7.8 Tables

Table 7.1—Steam-using Application Groups and Equipment Examples

Application Group	Equipment Example	Process Application Examples
Steam-heated equipment	Process heat exchanger	Alkylation, distillation, gas recovery, isomerization, visbreaking, coking, storage tank heating
Direct steam application	Distillation tower	Distillation, fractionation
	Stripper	Crude and vacuum distillation, catalytic cracking, catalytic reforming, asphalt processing, lube oil processing, hydrogen treatment
	Flare	Air-assisted flares, pressure-assisted flares, enclosed ground flares
Steam-driven equipment	Steam turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive
Steam distribution piping	Piping	Piping to distribute steam and condensate recovery
Steam tracing	Tracing	Utility stations, steam and condensate piping

Table 7.2—Steam Trap Types for Each of Three Categories of Steam Trap

Steam Trap Category	Common Applications	Steam Trap Type
Mechanical steam traps	The mainstream of traps used today on equipment that requires large discharge capacities. Temperature/pressure-controlled applications with fluctuating loads.	Free float
		Lever float
		Inverted bucket
Thermostatic steam traps	Where condensate backup can be tolerated or is required in order to remove excess enthalpy, e.g. noncritical tracing	Bimetal
		Balanced pressure trap
Thermodynamic steam traps	Tracing, drip, and certain light process steam applications	Thermodynamic disc
		Thermodynamic piston

Table 7.3—Basic Data Needed for POF Calculation of Steam System

Data	Description	Data Source

Steam trap type	Type of steam trap:
	— mechanical steam traps
	    — free float
	    — lever float
	    — inverted bucket
	— thermostatic steam traps
	    — bimetal
	    — balanced pressure trap
	— thermodynamic steam traps
	    — thermodynamic disc
	    — thermodynamic piston
		User specified

Steam trap/mechanical pump or control valve design, operational and maintenance/inspection history conditions	Data required on whether the following conditions apply: — design conditions exceed maximum allowable pressure or maximum allowable temperature (PMA/TMA) — steam trap configuration and capacity of individual steam traps — possibility of steam locking — any pipe bundling (i.e. inlet tracing pipe is heated by other bundled pipes) — no protection from weather — poor installation environment (i.e. higher than average failure rate at this location or area) — no strainer exists — trap is made of stainless steel (any grade) — internal and/or external strainer upstream of steam trap is installed — operation conditions do not exceed maximum operating pressure or PMO/TMO — operational stability is high, i.e. pressure/temperature/flow rate does not vary during normal operation — water hammer near the trap is recorded — disassembly preventive maintenance exists — built-in integral/self-cleaning exists	User specified
Steam system inspection history	— Date of testing — Type of test (effectiveness) — Results of test/inspection — Overhauled?	User specified
Steam-using Equipment	Steam-using equipment: — steam turbine — heat exchanger — tracing—general — tracing—low temperature [lower than 176 °F (80 °C)] — tracing—instrumentation — tracing—relief valve — steam main piping — condensate piping (recovery) — flare — distillation column	Fixed equipment
Equipment details	— Operating conditions — Design conditions — Dimensions	User specified

Table 7.4—Default Weibull Parameters for Different Steam Traps, Control Valve, and Mechanical Pump

Steam Trap Category	Steam Trap Type	Default β_{ST}	Default Value for Leakage Failure Mode $\eta_{def,leak,ST}$	Default Value for Blockage Failure Mode $\eta_{def,cold,ST}$
Mechanical steam traps	Free float	1.8	16.1	13.8
	Inverted bucket	1.6	16.1	13.8
	Lever float	1.7	11.7	8.5
Thermostatic steam traps	Bimetal	1.8	8	7.5
	Balanced pressure	2	5.3	5.2
Thermodynamic steam traps	Disc	2	9.4	5
	Impulse	2	9.4	5
Control valve		1.8	61.5	61.5
Mechanical pump		1.2	3.1	3.1

Table 7.5—Design Condition Adjustment for Steam Trap

Design Condition	Description	Adjustment Multiplier for Design Conditions, $F_{D_{ST}}$
Poor	If all of the below criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. if any pipe bundling d. no protection from weather e. poor installation environment f. no strainer exists	0.5
Average	If any of the following criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. if any pipe bundling d. no protection from weather e. poor installation environment f. no strainer exists	0.85
Good	If none of the following criteria are true AND the trap is not made of stainless steel (any grade) AND internal or external strainer is installed: a. design conditions exceed PMA/TMA b. possibility of steam locking c. if any pipe bundling d. no protection from weather e. poor installation environment f. no strainer exists	1.0
Very Good	If none of the following criteria are true AND the trap is made of stainless steel (any grade) AND both internal and external strainer is installed: a. design conditions exceed PMA/TMA b. possibility of steam locking c. if any pipe bundling d. no protection from weather e. poor installation environment f. no strainer exists	1.15

NOTE 1 Steam locking: equipment configuration causing steam-condensate mixture entering the trap or piping configuration causing steam to move ahead of condensate into the trap.

NOTE 2 Pipe bundling: inlet tracing pipe is heated by other bundled pipes.

NOTE 3 Poor installation environment: higher than average failure rate at this location or area.

Table 7.6—Operation Condition Adjustment for Steam Trap

Operation Condition	Description	Adjustment Multiplier for Design Conditions, $F_{O_{ST}}$
Poor	If operation conditions exceed PMO/TMO AND operational stability is low (i.e. $>$ 50 % operation load variations expected)	0.77
Average	If operation conditions do not exceed PMO/TMO AND operational stability is medium (i.e. $\leq$ 50 % operation load variations expected)	0.85
Good	If operation conditions do not exceed PMO/TMO AND operational stability is high (i.e. no operation load variations expected)	1

Table 7.7—Maintenance History/Inspection Condition Adjustment for Steam Trap

Maintenance Condition	Description	Adjustment Multiplier for Design Conditions, $F_{M_{ST}}$
Poor	If water hammer near the trap (i.e. within 10 m) is recorded in the past AND no disassembly preventive maintenance exists	0.65
Average	If water hammer near the trap (i.e. within 10 m) is recorded in the past AND disassembly preventive maintenance exists	0.72
Good	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance does not exist AND built-in manual cleaning exists	1.0
Very Good	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance exists AND built-in integral/self-cleaning exists	1.1

Table 7.8—Design Condition Adjustment for Mechanical Pump

Design Condition	Description	Adjustment Multiplier for Design Conditions, $F_{D_{MP}}$
Poor	If all of the below criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment d. system installation is nonideal	0.5
Average	If any of the following criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment d. system installation is nonideal	0.8
Good	If none of the following criteria are true AND the trap is not made of stainless steel (any grade) AND system installation is average: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment	1.0
Very Good	If none of the following criteria are true AND the trap is made of stainless steel (any grade) AND system installation is ideal AND strainer installed: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment	1.25
NOTE System installation is nonideal: functionality is affected by sizing or configuration.		

Table 7.9—Operation Condition Adjustment for Mechanical Pump

Operation Condition	Description	Adjustment Multiplier for Design Conditions, $F_{O_{MP}}$
Poor	If operation conditions exceed PMO/TMO AND operational stability is low (i.e. $>$ 50 % operation load variations expected) AND pump load is high (i.e. $>$ 75 % of pump capacity)	0.76
Average	If operation conditions do not exceed PMO/TMO AND operational stability is medium (i.e. $\leq$ 50 % operation load variations expected) OR pump load is medium (i.e. 50 % to 75 % of pump capacity)	1.2
Good	If operation conditions do not exceed PMO/TMO AND operational stability is high (i.e. no operation load variations expected) AND pump load is low (i.e. $<$ 50 % of pump capacity)	1.6

Table 7.10—Maintenance History/Inspection Condition Adjustment for Mechanical Pump

Maintenance Condition	Description	Adjustment Multiplier for Design Conditions, $F_{M_{MP}}$
Poor	If water hammer near the pump (i.e. within 10 m) is recorded in the past	0.65
Average	If water hammer near the pump (i.e. within 10 m) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the pump (i.e. within 10 m) is not recorded AND disassembly preventive maintenance exists	2

Table 7.11—Design Condition Adjustment for Control Valve

Design Condition	Description	Adjustment Multiplier for Design Conditions, $F_{D_{CV}}$
Poor	If all of the below criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment (i.e. higher than average failure rate at this location or area)	0.6
Average	If any of the following criteria are true: a. design conditions exceed PMA/TMA b. possibility of steam locking c. poor installation environment (i.e. higher than average failure rate at this location or area)	0.75
Good	If none of the following criteria are true: d. design conditions exceed PMA/TMA e. possibility of steam locking f. poor installation environment (i.e. higher than average failure rate at this location or area)	1.0
Very Good	If none of the following criteria are true AND the trap is made of stainless steel (any grade) AND strainer installed: g. design conditions exceed PMA/TMA h. possibility of steam locking i. poor installation environment (i.e. higher than average failure rate at this location or area)	1.3

Table 7.12—Operation Condition Adjustment for Control Valve

Operation Condition	Description	Adjustment Multiplier for Design Conditions, $F_{O_{CV}}$
Poor	If operation conditions exceed PMO/TMO AND operational stability is low (i.e. > 50 % operation load variations expected) AND load is high (i.e. > 75 % of valve capacity)	0.77
Average	If operation conditions do not exceed PMO/TMO AND operational stability (i.e. ≤ 50 % operation load variations expected) is medium OR load is medium (i.e. 50 % to 75 % of valve capacity)	0.9
Good	If operation conditions do not exceed PMO/TMO AND operational stability is high (i.e. no operation load variations expected) AND load is low (i.e. < 50 % of valve capacity)	1.0

Table 7.13—Maintenance History/Inspection Condition Adjustment for Control Valve

Maintenance Condition	Description	Adjustment Multiplier for Design Conditions, $F_{M_{CV}}$
Poor	If water hammer near the trap (i.e. within 10 m) is recorded in the past	0.65
Average	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance exists	1.1

Table 7.14—Default Weibull Parameters for Steam-using Equipment

Equipment	Default $\eta_{def,equ}$	Default β_{equ}
Steam turbine	34.48	3
Heat exchanger	22.73	3
Tracing—instrumentation	52.63	3
Tracing—relief valve	55.56	3
Steam header	25.1	3
Condensate recovery piping	21.5	3
Distillation column	37	3
Flare	13.3	3

Table 7.15—Design Condition Adjustment for Steam-using Equipment

Design Condition	Description	Adjustment Multiplier for Design Conditions, $F_{D_{equ}}$
Poor	If all of the below criteria are true: a. no inlet steam separator b. no appropriate steam trap (type and capacity) is installed c. major reduction in number of steam traps (as per design) d. no automatic/manual start function e. one or more locations on steam supply that require condensate drainage cannot discharge continuously	0.5
Average	If any of the following criteria are true: a. no inlet steam separator b. no appropriate steam trap (type and capacity) is installed c. major reduction in number of steam traps (as per design) d. no automatic/manual start function e. one or more locations on steam supply that require condensate drainage cannot discharge continuously	0.7
Good	If none of the below criteria are true AND steam traps are not equipped with bypass: a. no inlet steam separator b. no appropriate steam trap (type and capacity) is installed c. major reduction in number of steam traps (as per design) d. no automatic/manual start function e. one or more locations on steam supply that require condensate drainage cannot discharge continuously	1.0
Very Good	If none of the below criteria are true AND all steam traps equipped with bypass a. no inlet steam separator b. no appropriate steam trap (type and capacity) is installed c. major reduction in number of steam traps (as per design) d. no automatic/manual start function e. one or more locations on steam supply that require condensate drainage cannot discharge continuously	1.1

Table 7.16—Operation Condition Adjustment for Steam-using Equipment

Operation Condition	Description	Adjustment Multiplier for Design Conditions, $F_{O_{equ}}$
Poor	If all of the below criteria are true: a. superheat rate < 18 °F (10 °C) b. cyclic operation c. exceed PMO/TMO/steam mass d. in the case of turbine: superheat rate < 27 °F (15 °C) AND (for condensing turbine only) operating vacuum > 25 % weaker than design e. in the case of heat exchanger: superheat rate is ≥ 18 °F (10 °C) AND steam passing through outlet control valve (if existing) AND > 50 % operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.45
Average	If minimum of four criteria from the below are true: a. superheat rate < 10 °C (18 °F) b. cyclic operation c. exceed PMO/TMO/steam mass d. in the case of turbine: superheat rate < 27 °F (15 °C) AND (for condensing turbine only) operating vacuum > 25 % weaker than design e. in the case of heat exchanger: superheat rate is ≥ 18 °F (10 °C) AND steam passing through outlet control valve (if existing) AND > 50 % operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.7
Good	If minimum of two criteria from the below are true: a. superheat rate < 18 °F (10 °C) b. cyclic operation c. exceed PMO/TMO/steam mass d. in the case of turbine: superheat rate < 27 °F (15 °C) AND (for condensing turbine only) operating vacuum > 25 % weaker than design e. in the case of heat exchanger: superheat rate is ≥ 18 °F (10 °C) AND steam passing through outlet control valve (if existing) AND > 50 % operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.85
Very Good	If none of the below criteria is true: a. superheat rate < 18 °F (10 °C) b. cyclic operation c. exceed PMO/TMO/steam mass d. in the case of turbine: superheat rate < 27 °F (15 °C) AND (for condensing turbine only) operating vacuum > 25 % weaker than design e. in the case of heat exchanger: superheat rate is ≥ 18 °F (10 °C) AND steam passing through outlet control valve (if existing) AND > 50 % operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	1.0

Table 7.17—Maintenance History/Inspection Condition Adjustment for Steam-using Equipment

Maintenance Condition	Description	Adjustment Multiplier for Design Conditions, $F_{M_{equ}}$
Poor	Ongoing likelihood of water hammer AND damage/repair AND trips reported previously AND no maintenance conducted as recommended	0.4
Average	Low likelihood of water hammer AND damage/repair AND trips reported previously AND no maintenance conducted as recommended	0.6
Good	No likelihood of water hammer AND damage/repair AND trips not reported previously in previous AND maintenance recommendations are all conducted	1.0

Table 7.18—Level of Inspection Confidence Factor for Steam Traps, Mechanical Pumps, and Control Valves

Inspection Results	Confidence Factor that Inspection Result Determines the True Damage State, CF				
	Ineffective	Poorly Effective	Fairly Effective	Usually Effective	Highly Effective
Leak detected, CF_{fail}	No credit	0.3	0.6	0.85	0.95
Leak not detected, CF_{pass}	No credit	0.3	0.6	0.75	0.9
Blocked, CF_{fail}	No credit	0.3	0.6	0.85	0.95
Not blocked, CF_{pass}	No credit	0.3	0.6	0.85	0.95

Table 7.19—Equations for Updating POF After Inspection

<table>
<tr><th>Inspection Effectiveness</th><th>Inspection Results</th><th>Equation for Updating the POF After Inspection</th></tr>
<tr><td>Highly Effective</td><td rowspan="4">No leakage or blockage detected</td><td rowspan="4">$$P(t)_{\text{f,wgt,leak}} = P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} - 0.2 \cdot P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} \left(\frac{t}{\eta_{\text{adj,leak}_{(\text{ST,MP or CV})}}} \right) + 0.2 \cdot P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}} \left(\frac{t}{\eta_{\text{adj,leak}_{(\text{ST,MP or CV})}}} \right)$$
$$P(t)_{\text{f,wgt,cold}} = P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}} - 0.2 \cdot P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}} \left(\frac{t}{\eta_{\text{adj,cold}_{(\text{ST,MP or CV})}}} \right) + 0.2 \cdot P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}} \left(\frac{t}{\eta_{\text{adj,cold}_{(\text{ST,MP or CV})}}} \right)$$</td></tr>
<tr><td>Usually Effective</td></tr>
<tr><td>Fairly Effective</td></tr>
<tr><td>Poorly Effective</td></tr>
<tr><td>Highly Effective</td><td rowspan="4">Leakage or blockage detected</td><td rowspan="2">$$P(t)_{\text{f,wgt,leak}} = P(t)_{\text{f,after,leak}}$$
$$P(t)_{\text{f,wgt,cold}} = P(t)_{\text{f,after,cold}}$$</td></tr>
<tr><td>Usually Effective</td></tr>
<tr><td>Fairly Effective</td><td rowspan="2">$$P(t)_{\text{f,wgt,leak}} = \left(0.5 \cdot P(t)_{\text{f,final,leak}_{(\text{ST,MP or CV})}}\right) + \left(0.5 \cdot P(t)_{\text{f,after,leak}}\right)$$
$$P(t)_{\text{f,wgt,cold}} = \left(0.5 \cdot P(t)_{\text{f,final,cold}_{(\text{ST,MP or CV})}}\right) + \left(0.5 \cdot P(t)_{\text{f,after,cold}}\right)$$</td></tr>
<tr><td>Poorly Effective</td></tr>
</table>

Table 7.20—Required Data for COF Assessment

Cost Description	Data Source
Cost of steam, \$/lb $\left(FC_{\text{steam}}\right)$	User specified
Cost of condensate, \$/lb $\left(FC_{\text{condensate}}\right)$	User specified
Leakage rate is based on historical inspection data, lb/hr (kg/hr) $(lrate)$	User specified
Cost of personnel injury per individual as per Part 3, Section 4.12.5, \$ $(injcost)$	User specified
Population density of personnel or employees in the unit as per Part 3, Section 4.12.5, personnel/ft^2 $(popdens)$	User specified
Inspection interval, 8760 hours IF not defined by user	User specified
Daily production margin, $Unit_{\text{prod}}$, on the unit (\$/day)	User specified
Production rate reduction, $Rate_{\text{red}}$, on a unit as a result of the equipment being out of service (%)	User specified
The number of days, D_{sd}, required to shut a unit down to repair the equipment during an unplanned shutdown, days	User specified
The cost of production loss from downstream equipment, \$ $\left(FC_{\text{prod,D/S}}\right)$	User specified
The cost of production loss in process piping, \$ $\left(FC_{\text{prod,process}}\right)$	User specified
Component damage costs, applies to the cost of all downstream equipment as in Table 7.14, \$ $\left(FC_{\text{comp}}, FC_{\text{comp,line}}, FC_{\text{comp,main}}, FC_{\text{comp,process}}, FC_{\text{comp,D/S}}\right)$	User specified

Table 7.21—COF Equations for Blockage $\left(FC_{\text{cold}}\right)$ in Steam System

<table>
<tr><th>Equipment</th><th>Open/Closed System</th><th>Bypass (Open)</th><th>Bypass (Close)</th></tr>
<tr><td rowspan="2">Steam turbine</td><td>Open</td><td>5.155</td><td rowspan="4">5.154</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
<tr><td rowspan="2">Heat exchanger</td><td>Open</td><td>5.155</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
<tr><td rowspan="2">Tracing—general</td><td>Open</td><td>5.155</td><td rowspan="12">5.157</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
<tr><td rowspan="2">Tracing—low temperature</td><td>Open</td><td>5.158</td></tr>
<tr><td>Closed</td><td>5.159</td></tr>
<tr><td rowspan="4">Tracing—instrumentation</td><td>Open (general)</td><td>5.155</td></tr>
<tr><td>Open (low-temp)</td><td>5.158</td></tr>
<tr><td>Closed (general)</td><td>5.156</td></tr>
<tr><td>Closed (low-temp)</td><td>5.159</td></tr>
<tr><td rowspan="4">Tracing—relief valve</td><td>Open (general)</td><td>5.155</td></tr>
<tr><td>Open (low-temp)</td><td>5.158</td></tr>
<tr><td>Closed (general)</td><td>5.156</td></tr>
<tr><td>Closed (low-temp)</td><td>5.159</td></tr>
<tr><td rowspan="2">Steam header</td><td>Open</td><td>5.155</td><td rowspan="2">5.154</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
<tr><td rowspan="2">Condensate recovery</td><td>Open</td><td rowspan="2" colspan="2">N/A</td></tr>
<tr><td>Closed</td></tr>
<tr><td rowspan="2">Distillation column</td><td>Open</td><td>5.155</td><td rowspan="2">5.154</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
<tr><td rowspan="2">Flare</td><td>Open</td><td>5.155</td><td rowspan="2">5.16</td></tr>
<tr><td>Closed</td><td>5.156</td></tr>
</table>

Table 7.22—COF Equations for Leakage (FC_{leak}) in Steam System

Equipment	Open/Closed System	Bypass (Open)	Bypass (Close)
Steam turbine	Open	5.155	5.155 (see Note)
	Closed	5.156	
Heat exchanger	Open	5.155	
	Closed	5.156	
Tracing—general	Open	5.155	
	Closed	5.156	
Tracing—low temperature	Open	5.158	5.158 (see Note)
	Closed	5.159	
Tracing—instrumentation	Open (general)	5.155	5.155 (see Note)
	Open (low-temp)	5.158	5.158 (see Note)
	Closed (general)	5.155	5.155 (see Note)
	Closed (low-temp)	5.159	5.158 (see Note)
Tracing—relief valve	Open (general)	5.155	5.155 (see Note)
	Open (low-temp)	5.158	5.158 (see Note)
	Closed (general)	5.155	5.155 (see Note)
	Closed (low-temp)	5.159	5.158 (see Note)
Steam header	Open	5.155	5.155 (see Note)
	Closed	5.156	
Condensate recovery	Open	N/A	
	Closed	5.161	N/A
Distillation column	Open	5.155	5.155 (see Note)
	Closed	5.156	
Flare	Open	5.155	
	Closed	5.156	

NOTE For leakage with a closed bypass in an open or closed system, use $FC_{\text{inj}} = 0$ in appropriate equations.

7.9 Figures

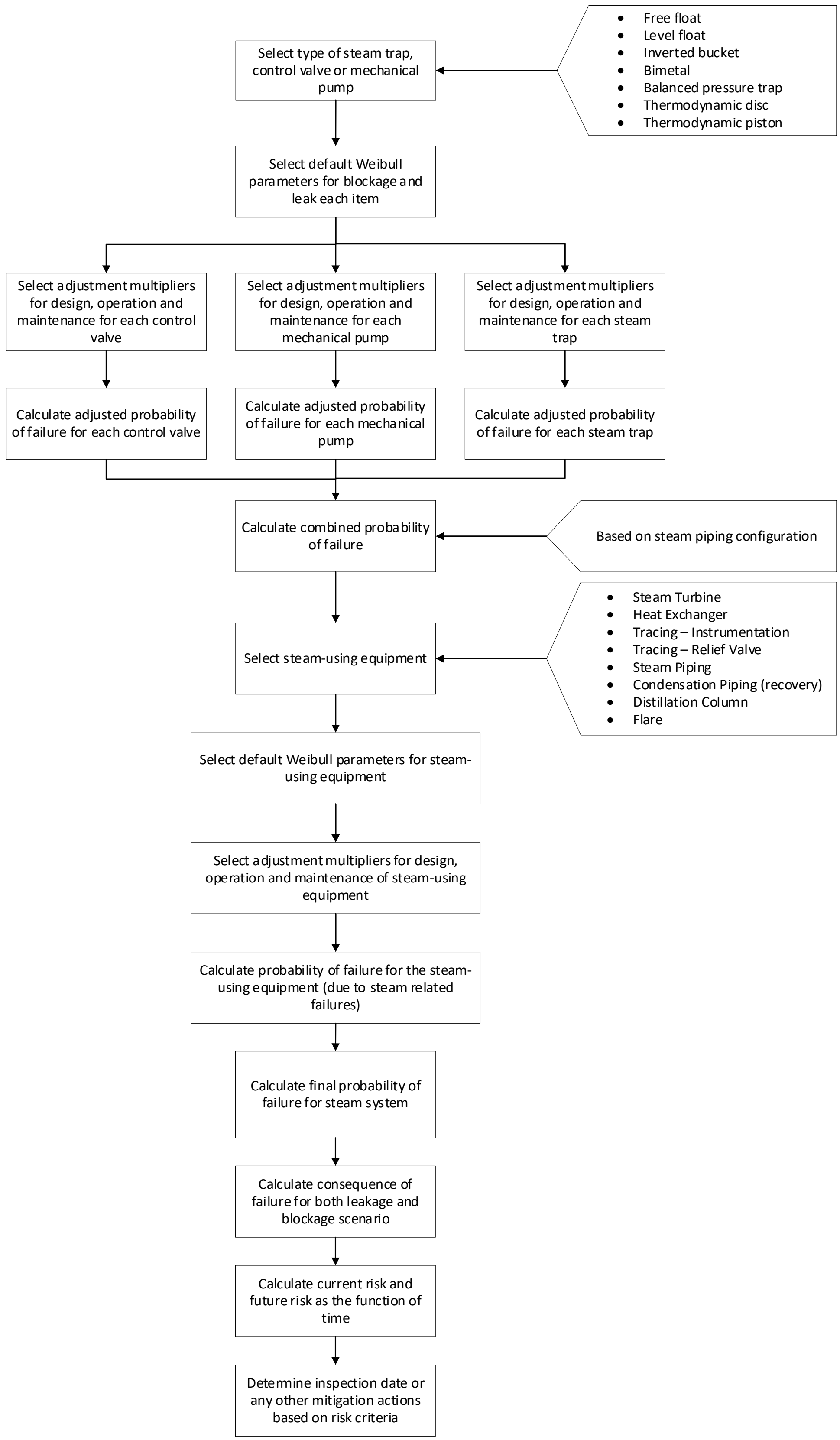


Figure 7.1—Overview of POF Calculation Framework for Steam Systems

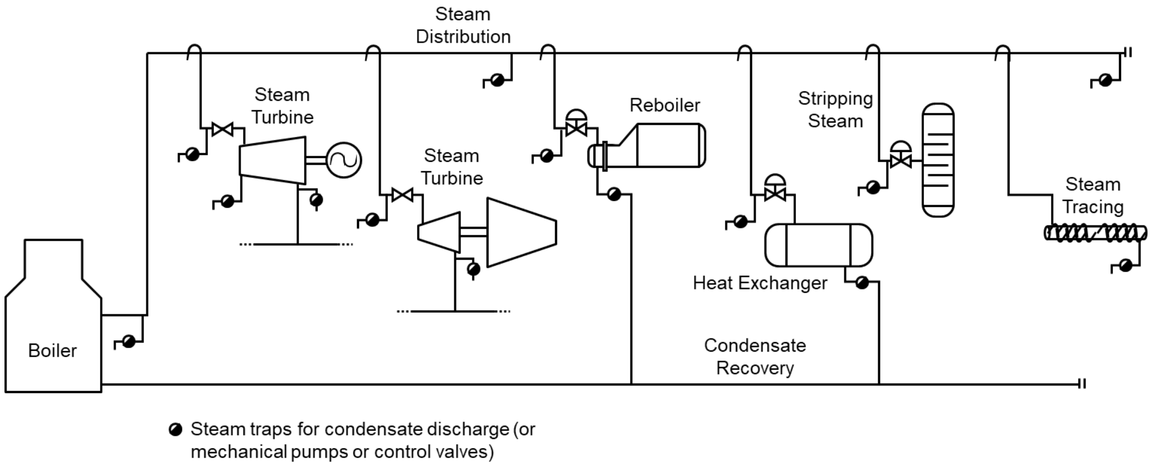


Figure 7.2—A Typical Layout of Multiple Steam Systems Containing Steam Traps (or Mechanical Pumps or Control Valves), Steam Piping, and Associated Equipment

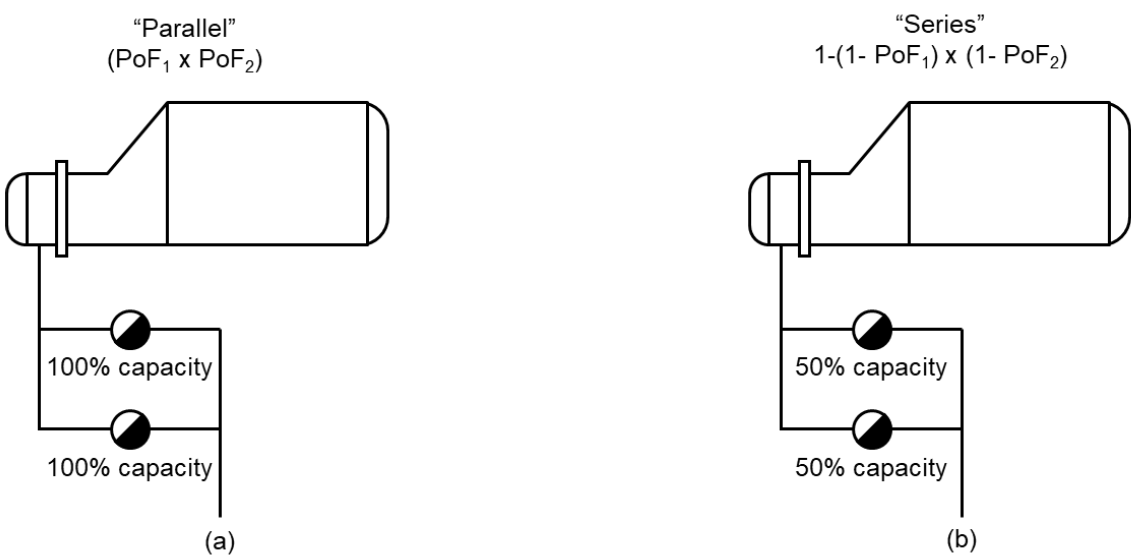
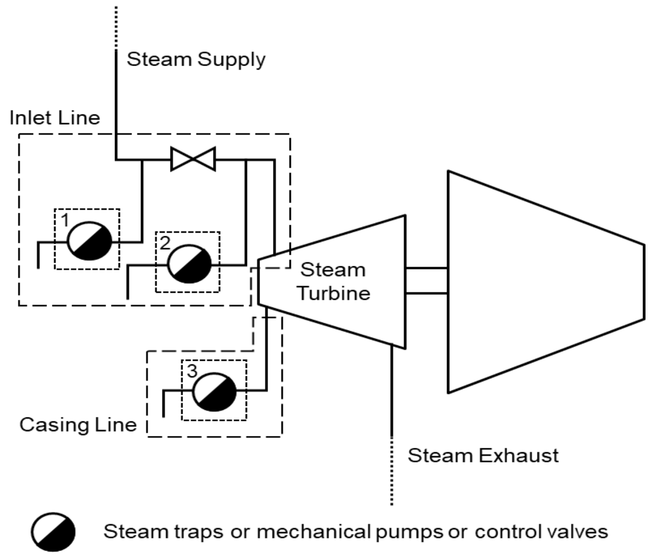
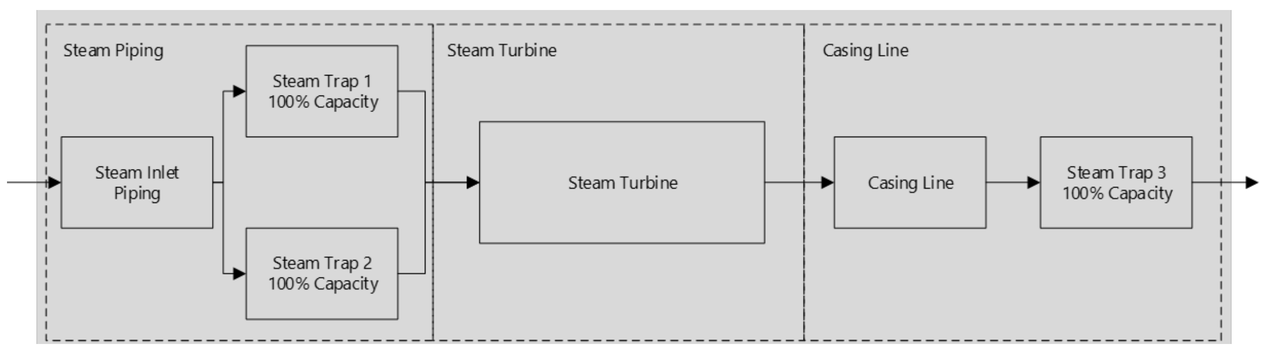


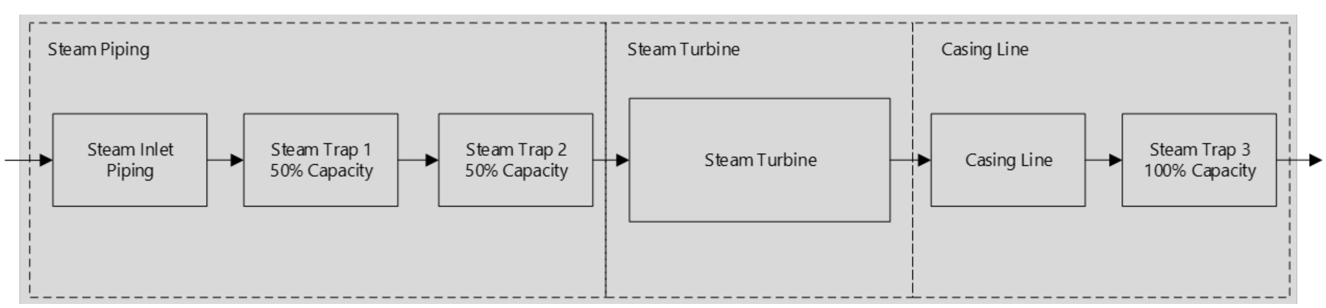
Figure 7.3—Sample Configuration of Multiple Steam Traps (or Mechanical Pumps or Control Valves)



a) Configuration of a Steam Turbine with Steam Traps or Mechanical Pumps or Control Valves



b) Reliability Block Diagram when Steam Trap 1 and 2 Are in Parallel and Operating at 100 % Capacity for the Calculation of POF



c) Reliability Block Diagram when Steam Trap 1 and 2 Are in Series and Operating at 50 % Capacity for the Calculation of POF

Figure 7.4—Sample Configuration of a Steam Turbine with Steam Traps or Mechanical Pumps or Control Valves

Part 5, Annex 5.A—Bundle Weibull Approach

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Risk-based Inspection Methodology
Part 5—Special Equipment
Annex 5.A—Bundle Weibull Approach

5.A.1 General

One method of an exchanger bundle Weibull analysis is performed using an exchanger reliability library to calculate β and η parameters. This annex provides an example and additional information for conducting a Weibull analysis using the reliability library described in Part 5.

5.A.2 References

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 1—Introduction to Risk-Based Inspection Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 3—Consequence of Failure Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 4—Inspection Planning Methodology*

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 5—Special Equipment*

5.A.3 Determining Weibull Parameters

Weibull parameters (eta, η, and beta, β) are required to determine the POF of a heat exchanger bundle unless an MTTF is specified. Part 5 references the process of statistically determining Weibull parameters of a set of previous bundles of a given heat exchanger or a set of similar bundles from an exchanger bundle reliability library. The Weibull parameters are used to calculate POF as a function of time for a bundle. This annex provides an example of calculating the Weibull parameters from a bundle failure library.

The advantage of using Weibull analysis to calculate POF is engineering decisions can be made with fewer failure data points than needed with other statistical distributions [11]. Weibull analysis is performed with less data, which is an advantage when little or no specific bundle failure data is available to provide a POF determination.

Two Weibull analyses to consider are provided in Part 5, as follows.

1) An exchanger has experienced multiple tube bundle failures. A Weibull analysis is performed using the failure data from that specific exchanger. For example, if there is an exchanger with a sixth bundle in service, a Weibull analysis is performed using the five previous bundles failure data for that exchanger. This is a two-parameter (η and β) Weibull analysis.

2) An exchanger has no prior tube bundle failure data. In this case a slightly different Weibull analysis (Weibayes) is used. The Weibayes approach combines the methods of Weibull with the principles of Bayes theorem to develop statistical inferences using a combination of prior knowledge and current observations. The principle assumption of the Weibayes approach is that the shape parameter, β, which represents the slope of the Weibull plot for the group of similar bundles, will be identical to the bundle under evaluation. This assumption is valid for similarly designed bundles in similar service with the same failure mechanisms. The Weibayes approach provides a statistical failure analysis without large amounts of failure data for the specific bundle under evaluation.

Both Weibull analyses use a median rank regression analysis procedure to determine the Weibull parameters.

5.A.4 Required and Recommended Data to Perform a Weibull Analysis

The minimum required data to perform an RBI analysis of an exchanger bundle is given in Part 5, Table 5.1. Additional information is recommended to determine η and β from a Weibull statistical analysis using a reliability library. This information is used to match criteria from the reliability library and filter the library to a subset of bundles with similar physical design and service. More data provided from the recommended data improves the subset of bundles that will represent the bundle under evaluation. The list of recommended additional data to perform a Weibull analysis is listed in Table 5.A.1.

5.A.5 General Steps to Determine Weibull Parameters from an Exchanger Bundle Reliability Library

The following steps outline the procedure to determine Weibull parameters from a matching cut-set chosen from an exchanger bundle reliability library. If there are sufficient bundle failures of the specific exchanger, a Weibull analysis using only those bundles should be performed.

a) Step 1—Provide the required and recommended bundle failure data or use a reliability library.

   A reliability library is required for evaluation of risk associated with bundle failure. Specific exchanger data are required for each bundle in the reliability library. Minimum basic data required are indicated in Part 5, Table 5.1. Recommended additional data needed for matching/filtering capability using a bundle reliability library are shown in Table 5.A.1.

b) Step 2—Determine the specific bundle failures or matching criteria cut-set [1].

   A group of bundles with similar characteristics is selected to create the data set for the Weibull analysis using the bundle reliability library and filtered using the data defined in Section 5.A.4; Part 5, Table 5.1; and Table 5.A.1. The bundle reliability library if filtered to isolate one specific damage mechanism and to create an acceptable Weibull plot. It is important to note that exchanger bundles experience several damage mechanisms including corrosion, pitting, cracking, erosion/corrosion, vibration damage, mechanical failure, and tube end thinning. Failure data as well as "no-failure" data (suspensions) are used in the plotting of the Weibull curve.

c) Step 3—Perform the Goodness of Fit Test.

   The bundle data will not plot properly if the Weibull plot is created from a broad cut-set of the bundle reliability failure library. This is often caused by including multiple failure mechanisms in the plot and requires further filtering of the matching criteria to isolate the failures for one mechanism. A goodness of fit test is required to determine whether the subset of data accurately represents the bundle.

   The two approaches for goodness of fit test for the data are $pve\%$ and r^2 methods, outlined in the *New Weibull Handbook* [21]. In general, a $pve\%$ of $>$ 20 % is adequate for small failure sample sizes ($<$ 20), and $pve\%$ fit improves at it approaches 100.

d) Step 4—Determine Weibull Parameters from the Matching Cut-set.

   The Weibull parameters β and η are obtained after the goodness of fit test has been applied in accordance with the *Weibull Handbook* methodology [21]. The standard method and best practice for estimating the Weibull parameters β and η for small- to moderate-sized data sets is a median rank

[1] Cut-sets are the unique combinations of component failures that can cause system failure. Cut-sets are user-defined partial data sub-sets of a heat exchanger bundle reliability library that share common attributes such as tube material, exchanger type, process unit, and shellside or tubeside fluids.

regression curve fitting using the time-to-failure as the dependent variable (X onto Y). Commercial software is available for performing a Weibull statistical analysis.

NOTE Most statisticians use confidence bounds on data to account for statistical distribution of the data. A 90 % lower bound confidence (LBC) interval is recommended using Fisher matrix bounds [19]. A 90 % LBC interval provides a 90 % confidence that the data point will fall to the right of the line on a Weibull plot.

5.A.6 Example Determination of Weibull Parameters Using Weibayes Analysis with a Reliability Library

Exchanger bundle 191-X-25A was evaluated using a bundle reliability failure library to match the following criteria.

a) Tubeside fluid category—Crude.

b) Controlling damage mechanism—General corrosion.

c) Tubeside operating temperature range between 350 °F and 500 °F.

d) TEMA type AES.

e) Exchanger type—liquid/liquid process exchanger.

f) Sulfur content greater than 1 %.

Of the nine bundles matching the criteria in the library in Table 5.A.2, five were failures and four were suspensions (bundles in service without failure reported). Three records were inspection records for the specific bundle under evaluation (191-X-25A). The remaining data was obtained for similar service bundles in the reliability library.

The data from Table 5.A.2 was plotted as a Weibull distribution in Figure 5.A.1 and calculated Weibull parameters for this matching bundle set were:

$\beta = 2.568$ slope parameter

$\eta = 20.45$ characteristic life in years

The goodness of fit test parameter, $pve\%$, is shown in Figure 5.A.1 to be 99.9, which implies that the data properly fits a Weibull distribution.

POF as a function of time is determined for the cut-set data using Part 5, Equation (5.55).

$$P_{\text{f,adj}}^{\text{tube}} = 1 - \exp\left[-\left(\frac{t}{\eta_{\text{mod}}}\right)^{\beta}\right]$$
$$P_{\text{f,adj}}^{\text{tube}} = 1 - \exp\left[-\left(\frac{t}{20.45}\right)^{2.568}\right] \tag{5.A.1}$$

NOTE The difference in η is only used in the Weibull analysis for the previous bundles.

Table 5.A.2 shows 191-X-25A bundle failures experienced after 18 and 22 years. The third bundle (T3) was in service for 16 years without failure (suspension). The modified characteristic life may be recalculated using Part 5, Equation (5.63) as demonstrated below:

$$\eta_{\text{mod}} = \left(\frac{1}{r} \sum_{i=1}^{N} t_{i,\text{dur}}^{\beta} \right)^{\frac{1}{\beta}}$$

$$\eta_{\text{mod}} = \left[\frac{(22)^{2.568} + (18)^{2.568} + (16)^{2.568}}{2} \right]^{\frac{1}{2.568}} = 22.16 \text{ years} \tag{5.A.2}$$

The characteristic life for the specific bundle experience is higher than the 20.45-year characteristic life calculated using the matching bundles from the reliability library (Figure 5.A.1).

It should be noted that this method assumes that the operating conditions for the bundle have not changed for the time period being evaluated and has not been redesigned. Changes in metallurgy, process conditions, or bundle design should be considered to determine if the entire past bundle history is representative of the current bundle under evaluation.

5.A.7 Nomenclature

The following lists the nomenclature used in Section 5.A.1.

P_f^{tube}	is the probability of the bundle failure, failures/yr
$pve\%$	is a goodness of fit test method for the data
r^2	is a goodness of fit test method for the data
t	is time, years
β	is the Weibull shape parameter that represents the slope of the line on a POF vs time plot
η	is the Weibull characteristic life parameter that represents the time at which 62.3 % of the bundles are expected to fail, years

5.A.8 Tables

Table 5.A.1—Minimum Required Data to Determine Weibull Parameters

Bundle Attribute General Data	Comments/Example Input
Exchanger type	Exchanger type or function, e.g. steam generator, steam reboiler, vaporizer
Tube type	Type of tube (e.g. plain, finned tube, or twisted tube)
Tube specification	Tube material specification and grade from TEMA datasheet and/or ASME manufacturer's form (e.g. SA-179, SA-213-TP304)
Tube material	Tube material type (e.g. carbon steel, 2.25 % Cr, 304L/321/347 SS, 2205 duplex SS, 904L, Alloy 800, Nickel 200, titanium Grade 2, aluminum alloy)
Process unit	Process unit type (e.g. amine treating, crude distillation unit, delayed coker, hydrogen reforming, sour water stripper, tail gas treater, ethylene, polypropylene, styrene)
Fluid name	Fluid name or description [e.g. crude, effluent, heavy gas oil (HGO)]
Fluid category	Fluid category (e.g. heavy crude feed, medium distillate, rich amine, H_2S, HF, well water, CO_2)

Table 5.A.2—Example—Matching Bundles from Reliability Library

Bundle Tag #	In-service Duration (years)	Failure Reported
191-X-25A-T1	18	Yes
191-X-25A-T2	22	Yes
191-X-25A-T3	16	No
E101-A-T1	10	Yes
E322-A-T1	12	No
E322-A-T2	13	No
HE-115-T1	14	Yes
HE-115-T2	25	No
PR6419-T1	8	Yes

5.A.9 Figures

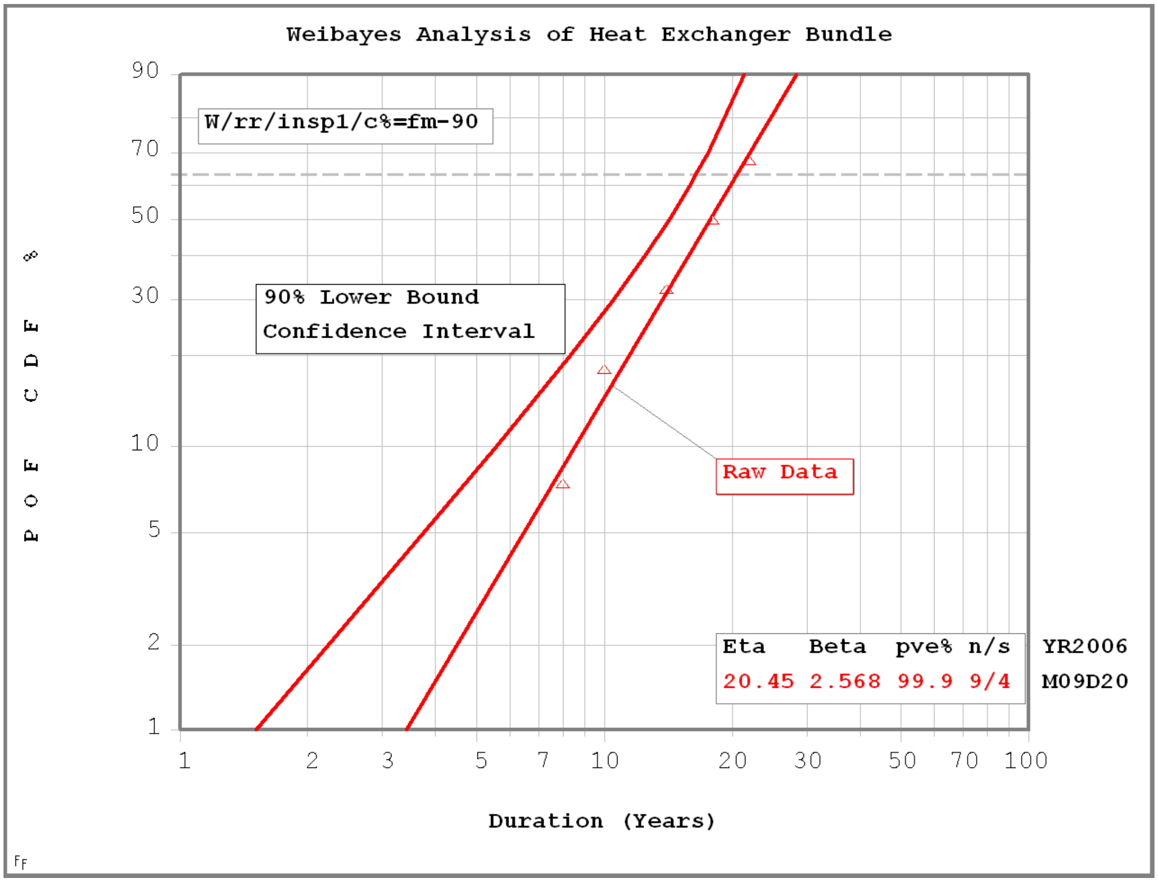

Figure 5.A.1—Weibull Plot of Similar Bundle Data

Part 5, Annex 5.B—Bibliography

5.B.1 General 1
5.B.2 Tables 1

Annex 5.B—Bibliography

5.B.1 General

The references for Part 5 of this document are provided in Section 5.B.2 of this annex.

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