



## PART 3 CONTENTS

## RISK-BASED INSPECTION METHODOLOGY 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 three-volume set presenting the API 581 Risk-Based Inspection methodology. The other two Parts are Part 1—Inspection Planning Methodology and Part 2—Probability of Failure Methodology.

The COF methodology presented in [Part 3](#) determines the COF that is used with the POF ([Part 2](#)) to provide a risk ranking and inspection plan ([Part 1](#)) for a component subject to process and environmental conditions typically found in the refining, petrochemical, and exploration and production industries. The consequence calculated using the procedures in [Part 3](#) 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 for the Level 2 COF 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, *Part 1—Sizing, Selection, and Installation of Pressure-relieving Devices*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 1—Inspection Planning Methodology*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 2—Probability of Failure Methodology*, American Petroleum Institute, Washington, DC.

API Recommended Practice 581, *Risk-Based Inspection Methodology, Part 5—Methodology for Special Equipment*, American Petroleum Institute, Washington, DC.

### 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 [Part 3](#) 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. A Level 2 COF methodology is provided in [Section 5](#), which is intended to be more rigorous and can be applied to a wider range of hazardous fluids. A special COF methodology is provided for ASTs and is covered 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, vapor cloud explosions (VCEs)], combined with computer modeling 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 using computer modeling 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 releases are considered since they can still result in serious consequences. Consequence from chemical splashes and high-temperature steam burns are determined based on serious injuries to personnel. Physical explosions and BLEVE can also cause serious personnel injuries and component damage.
- d) FC includes losses due to business interruption and costs associated with environmental releases. Business interruption consequence is estimated as a function of the flammable and nonflammable consequence area results. Environmental consequence is determined directly from the mass available for release or from the release rate.

### 3.3 Collateral Damage

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

### 3.4 Overview of COF Methodology

#### 3.4.1 General

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

#### 3.4.2 Level 1 Consequence Analysis

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

- a) The fluid phase upon release can be a liquid or a gas, depending on the storage phase and the phase expected to occur upon release to the atmosphere. In general, no consideration is given to the cooling effects of flashing liquid, rainout, jet liquid entrainment, or two-phase releases.
- b) Fluid properties for representative fluids containing mixtures are based on average values (e.g. MW, NBP, density, specific heats, AIT).
- c) Probabilities of ignition, as well as the probabilities of other release events (VCE, pool fire, jet fire, etc.) have been pre-determined for each of the representative fluids as a function of temperature, fluid AIT, and release type. These probabilities are constants, that is, totally independent of the release rate.
- d) The effects of BLEVEs are not included in the assessment.
- e) The effects of pressurized nonflammable explosions, such as those possible when nonflammable pressurized gases (e.g. air or nitrogen) are released during a vessel rupture, are not included in the assessment.

- f) Meteorological conditions were assumed and used in the dispersion calculations that form the basis for the consequence analysis table lookup (see [Annex 3.A](#)).
- g) Consequence areas do not consider the release of a toxic product during a combustion reaction (e.g. burning chlorinated hydrocarbons producing phosgene; hydrochloric acid producing chlorine gas; amines producing hydrogen cyanide; sulfur producing sulfur dioxide).

### 3.4.3 Level 2 Consequence Analysis

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

- a) The specific fluid is not represented adequately within the list of reference fluid groups provided, including cases where the fluid is a wide-range boiling mixture or where the fluid's toxic consequence is not represented adequately by any of the reference fluid groups.
- b) The stored fluid is close to its critical point, in which case the ideal gas assumptions for the vapor release equations are invalid.
- c) The effects of two-phase releases, including liquid jet entrainment as well as rainout, need to be included in the assessment.
- d) The effects of BLEVEs are to be included in the assessment.
- e) The effects of pressurized nonflammable explosions, such as possible when nonflammable pressurized gases (e.g. air or nitrogen) are released during a vessel rupture, are to be included in the assessment.
- f) The meteorological assumptions (see [Annex 3.A](#)) used in the dispersion calculations (that form the basis for the Level 1 consequence analysis table lookups) do not represent the site data.

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

## 3.5 COF Methodology

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

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

## 3.6 Safety, Financial and Injury-based COF

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

## 3.7 Use of Atmospheric Dispersion Modeling

Calculation of the consequence areas associated with several event outcomes (flash fires, VCEs) associated with releases of flammable and toxic fluids require the use of hazards analysis software capable of performing

atmospheric dispersion analysis (cloud modeling). Assumptions and additional background for the Level 1 dispersion modeling calculations are provided in [Annex 3.A](#). Additional information on the use of cloud dispersion modeling is provided in [Section 5.7.5](#).

### 3.8 Tables

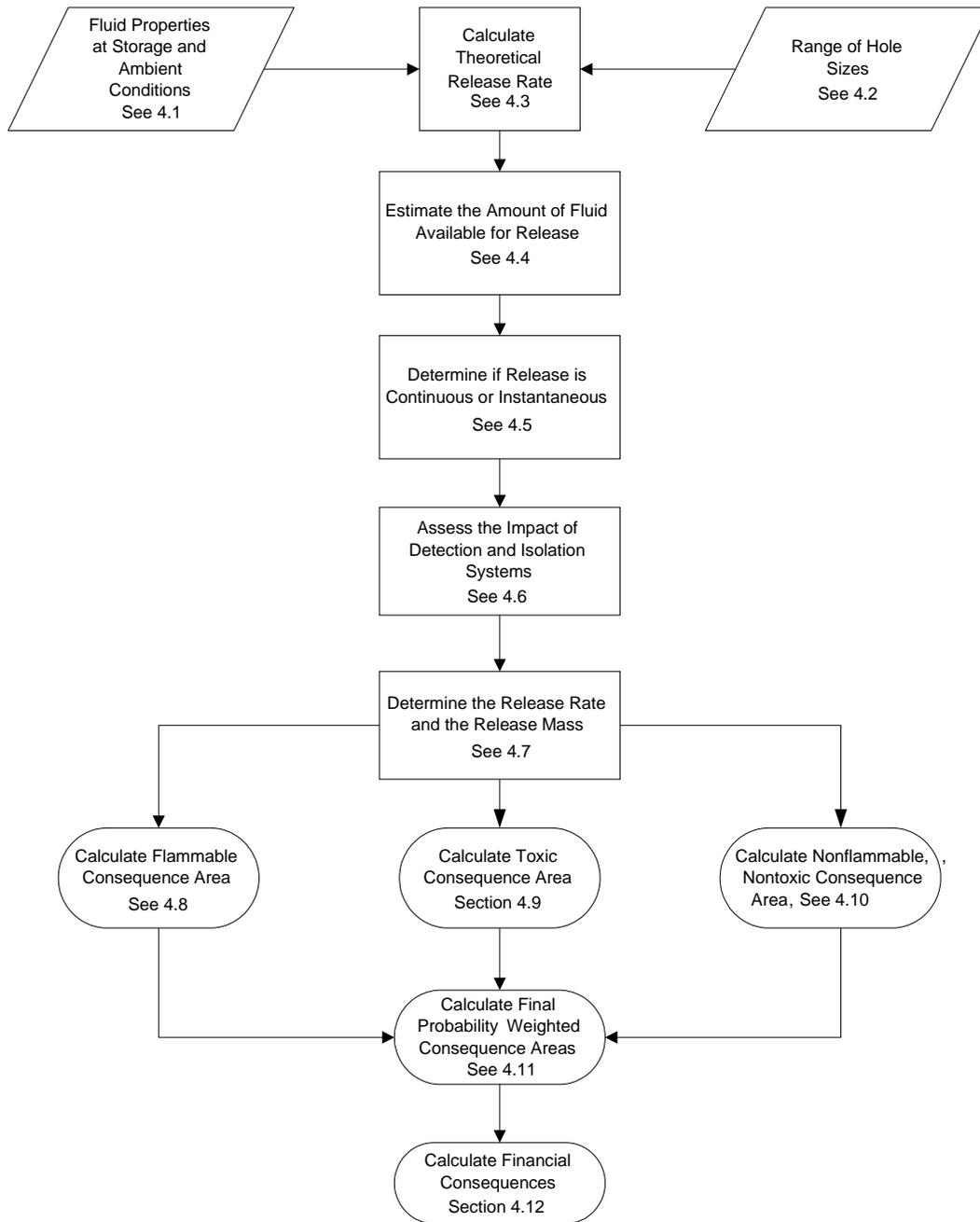
**Table 3.1—Steps in Consequence Analysis**

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

b) Stored vapor or gas:

- 1) NBP;
- 2) MW;
- 3) ideal gas specific heat capacity ratio,  $k$ ;
- 4) constant pressure specific heat,  $C_p$ ;
- 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 material following the release to atmosphere, and either the MW or density is used in determining the release rate, depending on whether a liquid or gas, respectively, is released.

#### 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 chosen whenever the fluid is nonflammable and nontoxic but would still present a hazard to personnel that may come in contact with 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 \(3.1\)](#).

$$k = \frac{C_p}{C_p - R} \quad (3.1)$$

The constant specific heat capacity,  $C_p$ , may be evaluated using the equations provided in [Table 4.2](#).

#### 4.1.5 Flammable Fluid Types

In the initial development of the Level 1 methodology, the results of the consequence analysis were correlated with equations and presented in lookup tables. As the consequence area results were reviewed, it became clear that adjustments had to be made to smooth out the results at the instantaneous to continuous release transition and as the operating temperature approached the autoignition for each fluid (see [Section 4.8.5](#) and [Section 4.8.6](#)).

- a) TYPE 0 Fluids—For the initial set of reference fluids, the consequence area equations were not smoothed and there remained step changes in the equations. Instead, adjustment factors and blending factors were applied to the consequence area equations. These initial fluids are designated here as TYPE 0 and can be found in [Table 4.1](#).
- b) TYPE 1 Fluids—Instantaneous to continuous blending was performed during development of subsequent reference fluids and the resulting consequence area equations accounted for the adjustments. As a result, instantaneous to continuous blending factors need not be 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 strongly dependent on the phase (i.e. gas, liquid, or two-phase) of the fluid after it is released into the environment. Most releases from pressurized units are 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/vapor. 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 should 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 vapor. 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,  $\rho_l$  [lb/ft<sup>3</sup> ( kg/m<sup>3</sup>)], can be estimated from [Table 4.2](#);
    - autoignition temperature, AIT [°R (K)], can be estimated from [Table 4.2](#).
  - 2) For a stored vapor:
    - molecular weight, 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](#);
    - autoignition temperature, 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. Limiting the number of release hole sizes allows for an analysis that is manageable, yet still reflects the range of possible outcomes.

The release hole sizes shown in [Table 4.4](#) are based on the component type and geometry as described in [Annex 3.A](#). In addition, the release hole sizes are limited to a maximum diameter of 16 in. This diameter represents a practical maximum value for a release calculation because catastrophic failures of components generally do not involve disintegration of the equipment item.

### 4.2.2 Calculation of Release Hole Sizes

The following steps are repeated for each release hole size; typically four release hole sizes are evaluated.

- 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  $n^{\text{th}}$  release hole size from [Part 2, Table 3.1](#), and the total generic failure frequency from this table or from [Equation \(3.2\)](#).

$$gff_{total} = \sum_{n=1}^4 gff_n \quad (3.2)$$

## 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 correct release rate equation must be chosen, based on

the phase of the material when it is inside the equipment item and its discharge regime (sonic or subsonic), as the material is released.

The initial phase of the hazardous material is the phase of the stored fluid prior to coming into contact with the atmosphere (i.e. flashing and aerosolization is not included at this point). For two-phase systems (condensers, phase separators, evaporators, reboilers, etc.), some judgment as to the handling of the model needs to be taken into account. In most cases, choosing liquid as the initial state inside the equipment is more conservative and may be preferred. One exception may be for two-phase piping systems. In this case, the upstream spill inventory should be considered so that if a majority of the upstream material can be released as vapor, then a vapor phase should be modeled. The results should be checked accordingly for conservatism. Items 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 <sup>[1]</sup> and may be calculated using Equation (3.3).

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

In Equation (3.3), the discharge coefficient,  $C_d$ , for fully turbulent liquid flow from sharp-edged orifices is in the range of  $0.60 \leq C_d \leq 0.65$ . A value of  $C_d = 0.61$  is recommended <sup>[17]</sup>. 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.

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

### 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 [nominally, 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<sup>[1]</sup>.

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).

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

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].

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

- 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].

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

- 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  $0.61 \leq C_d \leq 1.0$ . 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  $d_n$ .

$$A_n = \frac{\pi d_n^2}{4} \quad (3.8)$$

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's inventory is combined with inventory from other attached components that can 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 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 \(3.9\)](#).

$$mass_{inv} = \sum_{i=1}^N mass_{comp,i} \quad (3.9)$$

- 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,  $mass_{add,n}$ , that is calculated based on 3 minutes of leakage from the component's inventory group. This  $mass_{add,n}$  is calculated assuming the same flow rate from the leaking component but is limited to a 203 mm (8 in.) release hole size. The  $mass_{add,n}$  is calculated for each release hole size using [Equation \(3.10\)](#).

$$mass_{add,n} = 180 \cdot \min[W_n, W_{max8}] \quad (3.10)$$

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

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

$$mass_{avail,n} = \min \left[ \left\{ mass_{comp} + mass_{add,n} \right\}, mass_{inv} \right] \quad (3.11)$$

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,  $mass_{comp}$ , 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,  $mass_{comp,i}$ .
- d) STEP 4.4—Calculate the fluid mass in the inventory group,  $mass_{inv}$ , using [Equation \(3.9\)](#).
- e) STEP 4.5—Calculate the flow rate from a 8 in. (203 mm) diameter hole,  $W_{max8}$ , using [Equations \(3.3\)](#), [\(3.6\)](#), or [\(3.7\)](#), as applicable, with  $A_n = A_g = 50.3 \text{ in.}^2 (32,450 \text{ mm}^2)$ . 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,  $mass_{add,n}$ , 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,  $mass_{avail,n}$ , 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  $\frac{10,000 \text{ lbs}}{180 \text{ s}} = 55.6 \text{ lb/s}$ . 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 extremely 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,
- 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,  $fact_{di}$ .
- 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 \(3.12\)](#)].

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

#### 4.7.2 Instantaneous Release Mass

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

$$mass_n = \min \left[ \{ rate_n \cdot ld_n \}, \{ mass_{avail,n} \} \right] \quad (3.13)$$

In this equation, the leak duration,  $ld_n$ , cannot exceed the maximum duration  $ld_{max,n}$ , 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,  $ld_n$ .

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

#### 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 (3.13), where the theoretical release rate,  $W_n$ , is from STEP 3.2.

NOTE 1: the release reduction factor,  $fact_{di}$ , 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,  $mass_{avail,n}$ , 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,  $ld_{max,n}$ , 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,  $mass_{avail,n}$ , 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 goes up significantly. (The probabilities of ignition and other event tree probabilities for the Level 1 COF are presented in Annex 3.A). As a result, there is an abrupt change in the Level 1 consequence results between a continuous release and an instantaneous release. An instantaneous release is defined as any release larger than 4,536 kg (10,000 lb) in 3 minutes, which is equivalent to a release rate of 25.2 kg/s (55.6 lb/s). A continuous release of 25.5 kg/s would have a much lower consequence than an instantaneous release at 25.2 kg/s of the same material. Therefore, the Level 1 COF includes a blending of the calculated results of the continuous and instantaneous releases (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.

$$CA_{f,n}^{CONT} = a(rate_n)^b \quad (3.15)$$

- 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.

$$CA_{f,n}^{INST} = a(mass_n)^b \quad (3.16)$$

#### 4.8.2.2 Development of Generic Equations

Equation (3.15) and Equation (3.16) were employed 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<sup>2</sup>) [37.8 kW/m<sup>2</sup>] (jet fire, pool fire, and fireball);
  - 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<sup>2</sup>) [12.6 kW/m<sup>2</sup>] (jet fire, fireball, and pool fire);
  - 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, which, 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,  $fact_{mit}$ , 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 \(3.18\)](#).

$$eneff_n = 4 \cdot \log_{10} [C_{4A} \cdot mass_n] - 15 \quad (3.18)$$

NOTE: the adjustment defined by [Equation \(3.18\)](#) 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 \(3.19\)](#).

$$fact_n^{IC} = \min \left[ \left\{ \frac{rate_n}{C_5} \right\}, 1.0 \right] \quad (3.19)$$

When instantaneous equation constants that are not provided in [Table 4.8](#) and [Table 4.9](#) for the reference fluid, the blending factor is defined in [Equation \(3.20\)](#).

$$fact_n^{IC} = 0.0 \quad (3.20)$$

- b) For Instantaneous Releases—Blending is not required for instantaneous releases [4,536 kg (10,000 lb) released in less than 3 minutes, or a release rate of 55.6 lb/s (25.2 kg/s)]. The blending factor,  $fact_n^{IC}$ , for an instantaneous release is defined in [Equation \(3.21\)](#).

$$fact_n^{IC} = 1.0 \quad (3.21)$$

The blended release area is calculated using [Equation \(3.22\)](#).

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).

$$CA_n^{IC-blend} = CA_n^{INST} \cdot fact_n^{IC} + CA_n^{CONT} (1 - fact_n^{IC}) \quad (3.22)$$

#### 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 (3.23).

$$CA^{AIT-blend} = CA^{AIL} fact^{AIT} + CA^{AINL} (1 - fact^{AIT}) \quad (3.23)$$

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

$$fact^{AIT} = 0 \quad \text{for } T_s + C_6 \leq AIT \quad (3.24)$$

$$fact^{AIT} = \frac{(T_s - AIT + C_6)}{2 \cdot C_6} \quad \text{for } T_s + C_6 > AIT > T_s - C_6 \quad (3.25)$$

$$fact^{AIT} = 1 \quad \text{for } T_s - C_6 \geq AIT \quad (3.26)$$

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 (3.27).

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

The equation for probability weighting of the personnel injury consequence areas is given by Equation (3.28).

$$CA_{f,inj}^{flam} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{inj,n}^{flam}}{gff_{total}} \right) \quad (3.28)$$

In Equation (3.27) and Equation (3.28), 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,  $fact_{mit}$ , from [Table 4.10](#).
- b) STEP 8.2—For each release hole size, calculate the energy efficiency correction factor,  $eneff_n$ , using [Equation \(3.18\)](#).
- 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),  $CA_{cmd,n}^{AINL-CONT}$ .

- 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.

$$a = a_{cmd}^{AINL-CONT} \quad (3.29)$$

$$b = b_{cmd}^{AINL-CONT} \quad (3.30)$$

- 2) Use [Equation \(3.31\)](#) to calculate the consequence area.

$$CA_{cmd,n}^{AINL-CONT} = a(rate_n)^b \cdot (1 - fact_{mit}) \quad (3.31)$$

- e) STEP 8.5—For each release hole size, calculate the component damage consequence areas for Autoignition Likely, Continuous Release (AIL-CONT),  $CA_{cmd,n}^{AIL-CONT}$ .

- 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.

$$a = a_{cmd}^{AIL-CONT} \quad (3.32)$$

$$b = b_{cmd}^{AIL-CONT} \quad (3.33)$$

- 2) Use [Equation \(3.34\)](#) to calculate the consequence area.

$$CA_{cmd,n}^{AIL-CONT} = a(rate_n)^b \cdot (1 - fact_{mit}) \quad (3.34)$$

- f) STEP 8.6—For each release hole size, calculate the component damage consequence areas for Autoignition Not Likely, Instantaneous Release (AINL-INST),  $CA_{cmd,n}^{AINL-INST}$ .

- 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.

$$a = a_{cmd}^{AINL-INST} \quad (3.35)$$

$$b = b_{cmd}^{AINL-INST} \quad (3.36)$$

- 2) Use [Equation \(3.37\)](#) for the consequence area.

$$CA_{cmd,n}^{AIL-INST} = a (mass_n)^b \cdot \left( \frac{1 - fact_{mit}}{eneff_n} \right) \quad (3.37)$$

- g) STEP 8.7—For each release hole size, calculate the component damage consequence areas for Autoignition Likely, Instantaneous Release (AIL-INST),  $CA_{cmd,n}^{AIL-INST}$ .

- 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.

$$a = a_{cmd}^{AIL-INST} \quad (3.38)$$

$$b = b_{cmd}^{AIL-INST} \quad (3.39)$$

- 2) Use [Equation \(3.40\)](#) to calculate the consequence area.

$$CA_{cmd,n}^{AIL-INST} = a (mass_n)^b \cdot \left( \frac{1 - fact_{mit}}{eneff_n} \right) \quad (3.40)$$

- h) STEP 8.8—For each release hole size, calculate the personnel injury consequence areas for Autoignition Not Likely, Continuous Release (AINL-CONT),  $CA_{inj,n}^{AINL-CONT}$ .

- 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.

$$a = a_{inj}^{AINL-CONT} \quad (3.41)$$

$$b = b_{inj}^{AINL-CONT} \quad (3.42)$$

- 2) Calculate the consequence area using [Equation \(3.43\)](#).

$$CA_{inj,n}^{AINL-CONT} = \left[ a \cdot (rate_n)^b \right] \cdot (1 - fact_{mit}) \quad (3.43)$$

- i) STEP 8.9—For each release hole size, calculate the personnel injury consequence areas for Autoignition Likely, Continuous Release (AIL-CONT),  $CA_{inj,n}^{AIL-CONT}$ .

- 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.

$$a = a_{inj}^{AIL-CONT} \quad (3.44)$$

$$b = b_{inj}^{AIL-CONT} \quad (3.45)$$

- 2) Calculate the consequence area using [Equation \(3.46\)](#).

$$CA_{inj,n}^{AIL-CONT} = \left[ a \cdot (rate_n)^b \right] \cdot (1 - fact_{mit}) \quad (3.46)$$

j) STEP 8.10—For each release hole size, calculate the personnel injury consequence areas for Autoignition Not Likely, Instantaneous Release (AINL-INST),  $CA_{inj,n}^{AINL-INST}$ .

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.

$$a = a_{inj}^{AINL-INST} \quad (3.47)$$

$$b = b_{inj}^{AINL-INST} \quad (3.48)$$

2) Calculate the consequence area using [Equation \(3.49\)](#).

$$CA_{inj,n}^{AINL-INST} = \left[ a \cdot (mass_n)^b \right] \cdot \left( \frac{1 - fact_{mit}}{eneff_n} \right) \quad (3.49)$$

k) STEP 8.11—For each release hole size, calculate the personnel injury consequence areas for Autoignition Likely, Instantaneous Release (AIL-INST),  $CA_{inj,n}^{AIL-INST}$ .

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.

$$a = a_{inj}^{AIL-INST} \quad (3.50)$$

$$b = b_{inj}^{AIL-INST} \quad (3.51)$$

2) Calculate the consequence area using [Equation \(3.52\)](#).

$$CA_{inj,n}^{AIL-INST} = \left[ a \cdot (mass_n)^b \right] \cdot \left( \frac{1 - fact_{mit}}{eneff_n} \right) \quad (3.52)$$

l) STEP 8.12—For each release hole size, calculate the instantaneous/continuous blending factor,  $fact_n^{IC}$ , using [Equations \(3.19\)](#), [\(3.20\)](#), or [\(3.21\)](#), 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,  $fact_n^{AIT}$ , using [Equations \(3.24\)](#), [\(3.25\)](#), or [\(3.26\)](#), as applicable.

n) STEP 8.14—For TYPE 0 fluids, calculate the continuous/instantaneous blended consequence areas for TYPE 0 fluid components using [Equations \(3.53\)](#) through [\(3.56\)](#) 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,  $fact_n^{IC}$ , 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.

$$CA_{cmd,n}^{AIL} = CA_{cmd,n}^{AIL-INST} \cdot fact_n^{IC} + CA_{cmd,n}^{AIL-CONT} \cdot (1 - fact_n^{IC}) \quad (3.53)$$

$$CA_{inj,n}^{AIL} = CA_{inj,n}^{AIL-INST} \cdot fact_n^{IC} + CA_{inj,n}^{AIL-CONT} \cdot (1 - fact_n^{IC}) \quad (3.54)$$

$$CA_{cmd,n}^{AINL} = CA_{cmd,n}^{AINL-INST} \cdot fact_n^{IC} + CA_{cmd,n}^{AINL-CONT} \cdot (1 - fact_n^{IC}) \quad (3.55)$$

$$CA_{inj,n}^{AINL} = CA_{inj,n}^{AINL-INST} \cdot fact_n^{IC} + CA_{inj,n}^{AINL-CONT} \cdot (1 - fact_n^{IC}) \quad (3.56)$$

- o) STEP 8.15—Calculate the AIT blended consequence areas for all components using Equations (3.57) and (3.58) based on the consequence areas determined in STEP 8.14 and the AIT blending factors,  $fact^{AIT}$  calculated in STEP 8.13. The resulting consequence areas are the component damage and personnel injury flammable consequence areas,  $CA_{cmd,n}^{flam}$  and  $CA_{inj,n}^{flam}$ , for each release hole sizes selected in STEP 2.2.

$$CA_{cmd,n}^{flam} = CA_{cmd,n}^{AIL} \cdot fact^{AIT} + CA_{cmd,n}^{AINL} \cdot (1 - fact^{AIT}) \quad (3.57)$$

$$CA_{inj,n}^{flam} = CA_{inj,n}^{AIL} \cdot fact^{AIT} + CA_{inj,n}^{AINL} \cdot (1 - fact^{AIT}) \quad (3.58)$$

- p) STEP 8.16—Determine the final consequence areas (probability weighted on release hole size) for component damage and personnel injury using Equation (3.59) and Equation (3.60) based on the consequence areas from STEP 8.15.

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

$$CA_{f,inj}^{flam} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{inj,n}^{flam}}{gff_{total}} \right) \quad (3.60)$$

## 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, hydrogen fluoride (HF), ammonia, and chlorine pose only a toxic hazard. On the other hand, some toxic

materials such as hydrogen sulfide (H<sub>2</sub>S) 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<sub>2</sub>S), ammonia (NH<sub>3</sub>), 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,  $mfrac^{tox}$ , that is present in the release fluid.

$$rate_n^{tox} = mfrac^{tox} \cdot W_n \quad (3.61)$$

$$mass_n^{tox} = mfrac^{tox} \cdot mass_n \quad (3.62)$$

For pure toxic fluids ( $mfrac^{tox} = 1.0$ ), the toxic release rate,  $rate_n^{tox}$ , is equal to the release rate,  $W_n$ , as calculated in [Section 4.3](#) and the toxic release mass,  $mass_n^{tox}$ , 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,  $fact_{di}$ , to account for detection and isolation systems is not applied to toxic releases as it is to flammable releases (see [Section 4.6](#)).

#### 4.9.6 Estimation of Toxic Consequence Area for HF Acid and H<sub>2</sub>S

- The background for the development of the toxic consequence equations for HF acid and H<sub>2</sub>S 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.
- The toxic consequence areas for continuous releases of HF or H<sub>2</sub>S as a function of the release rate may be calculated using [Equation \(3.63\)](#).

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

$$CA_{inj,n}^{tox-CONT} = C_8 \cdot ([C_{4B} \cdot rate_n^{tox}]^c \cdot 10^d) \quad (3.63)$$

NOTE 1: for continuous releases, the toxic release rate,  $rate_n^{tox}$ , 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 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<sub>2</sub>S as a function of the release rate may be calculated using Equation (3.64).

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

$$CA_{inj,n}^{tox-INST} = C_8 \cdot ([C_{4B} \cdot mass_n^{tox}]^c \cdot 10^d) \quad (3.64)$$

NOTE 2: for instantaneous releases, the toxic release mass,  $mass_n^{tox}$ , is used as the input to Equation (3.64). The constants,  $c$  and  $d$  to be used in Equation (3.64) 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 (3.65).

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

NOTE 1: for continuous releases, the toxic release rate,  $rate_n^{tox}$ , is used as the input to Equation (3.65). The constants  $e$  and  $f$  for Equation (3.65) are provided in Table 4.12 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 (3.66).

$$CA_{inj,n}^{tox-INST} = e \left( mass_n^{tox} \right)^f \quad (3.66)$$

NOTE 2: for instantaneous releases, the toxic release mass,  $mass_n^{tox}$ , is used as the input to Equation (3.66). The constants  $e$  and  $f$  for Equation (3.66) 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 ( $\text{AlCl}_3$ )—Powder.
  - 2) Carbon Monoxide ( $\text{CO}$ )—Gas only.
  - 3) Hydrogen Chloride ( $\text{HCl}$ )—Gas only.
  - 4) Nitric Acid—Gas or liquid.
  - 5) Nitrogen Dioxide ( $\text{NO}_2$ )—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  $\text{AlCl}_3$ ) using [Equation \(3.65\)](#) 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  $\text{H}_2\text{S}$  this is 100 ppm, for  $\text{NH}_3$  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](#));
- c) maximum leak duration,  $ld_{max,n}$  listed in [Table 4.7](#).

$$ld_n^{tox} = \min \left( 3600, \left\{ \frac{mass_n}{W_n} \right\}, \{ 60 \cdot ld_{max,n} \} \right) \quad (3.67)$$

#### 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 multi-component 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 his or her 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 \(3.68\)](#) is used to calculate the probability weighted toxic consequence area.

$$CA_{f,inj}^{tox} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{inj,n}^{tox}}{gff_{total}} \right) \quad (3.68)$$

#### 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 (3.67).
- b) STEP 9.2—Determine the toxic percentage of the toxic component,  $mfrac^{tox}$ , in the release material. If the release fluid is a pure fluid,  $mfrac^{tox} = 1.0$ .

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,  $rate_n^{tox}$ , and release mass,  $mass_n^{tox}$ , to be used in the toxic analysis using Equation (3.61) and Equation (3.62).
- d) STEP 9.4—For each release hole size, calculate the toxic consequence area for each of the release hole sizes.

- 1) HF Acid and H<sub>2</sub>S—Calculate  $CA_{inj,n}^{tox}$  using Equation (3.63) for a continuous release or Equation (3.64) 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 (3.65) for a continuous release or Equation (3.66) 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 (3.65) 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 (3.68).

### 4.10 Determine Nonflammable, Nontoxic Consequence

#### 4.10.1 General

Consequences associated with the release of nonflammable, nontoxic materials (NFNT) 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<sup>[2]</sup> 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 (3.69).

$$CA_{inj,n}^{CONT} = C_9 \cdot rate_n \quad (3.69)$$

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 (3.70).

$$CA_{inj,n}^{INST} = C_{10} (mass_n)^{0.6384} \quad (3.70)$$

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 (3.71).

$$fact_n^{IC} = \min \left[ \left\{ \frac{rate_n}{C_5} \right\}, 1.0 \right] \quad (3.71)$$

#### 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; 103.4 kPa, 206.8 kPa, and 413.7 kPa (15 psig, 30 psig, and 60 psig) 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 (3.72) and Equation (3.73).

$$CA_{inj,n}^{CONT} = 0.2 \cdot ax^b \quad (3.72)$$

$$CA_{inj,n}^{INST} = 0.0 \quad (3.73)$$

The constants  $a$  and  $b$  shown in Equation (3.72), 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,  $fact_n^{IC}$ , 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 (3.76).

$$CA_{inj,n}^{leak} = CA_{inj,n}^{INST} \cdot fact_n^{IC} + CA_{inj,n}^{CONT} (1 - fact_n^{IC}) \quad (3.76)$$

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

$$CA_{cmd,n}^{leak} = 0.0 \quad (3.77)$$

#### 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 (3.78) is used to calculate the probability weighted nonflammable, nontoxic consequence area for steam, caustic, or acid releases.

$$CA_{f,inj}^{nft} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{inj,n}^{leak}}{gff_{total}} \right) \quad (3.78)$$

The term  $CA_{inj,n}^{leak}$  in Equation (3.78) 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  $CA_{inj,n}^{CONT}$  using Equation (3.69) and  $CA_{inj,n}^{INST}$  using Equation (3.70).
  - 2) For Acids or Caustics—Calculate  $CA_{inj,n}^{CONT}$  for liquid releases using Equations (3.72), (3.74), and (3.75).  
NOTE 1: data are not provided for an instantaneous release; therefore,  $CA_{inj,n}^{INST} = 0.0$ .
- b) STEP 10.2—For each release hole size, calculate the instantaneous/continuous blending factor,  $fact_n^{IC}$ . For steam, use Equation (3.71). For Acids or Caustics,  $fact_n^{IC} = 0.0$ .
- c) STEP 10.3—For each release hole size, calculate the blended nonflammable, nontoxic personnel injury consequence area for steam or acid leaks,  $CA_{inj,n}^{leak}$ , using Equation (3.88) based on the consequence areas from STEP 10.1 and the blending factor,  $fact_n^{IC}$ , 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):

$$CA_{cmd,n}^{leak} = 0.0 \quad (3.79)$$

- d) STEP 10.4—Determine the final nonflammable, nontoxic consequence areas for personnel injury,  $CA_{inj}^{nfmt}$ , using Equation (3.80) 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:

$$CA_{f,cmd}^{nfmt} = 0.0 \quad (3.80)$$

## 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:

- flammable consequence; see Section 4.8;
- toxic consequence; see Section 4.9;
- nonflammable, nontoxic consequence; see Section 4.10.

### 4.11.2 Final Component Damage Consequence Area

The final component damage consequence area is:

$$CA_{f,cmd} = \max \left[ CA_{f,cmd}^{flam}, CA_{f,cmd}^{tox}, CA_{f,cmd}^{nfmt} \right] \quad (3.81)$$

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

$$CA_{f,cmd} = CA_{f,cmd}^{flam} \quad (3.82)$$

### 4.11.3 Final Personnel Injury Consequence Area

The final personnel injury consequence area is:

$$CA_{inj} = \max \left[ CA_{f,inj}^{flam}, CA_{f,inj}^{tox}, CA_{f,inj}^{nfmt} \right] \quad (3.83)$$

### 4.11.4 Final Consequence Area

The final consequence area is:

$$CA_f = \max \left[ CA_{f,cmd}, CA_{f,inj} \right] \quad (3.84)$$

### 4.11.5 Calculation of Final Consequence Area

- a) STEP 11.1—Calculate the final component damage consequence area,  $CA_{f,cmd}$ , using Equation (3.82).
- b) STEP 11.2—Calculate the final personnel injury consequence area,  $CA_{f,inj}$ , using Equation (3.83).
- c) STEP 11.3—Calculate the final consequence area,  $CA_f$ , using Equation (3.84).

## 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:

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

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

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

The example cost estimates shown in [Table 4.15](#) are based on carbon steel prices obtained in 2001. The  $holecost_n$  may be 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 \(3.86\)](#). The probability weighting utilizes the generic frequencies of the release hole sizes provided in [Part 2, Table 3.1](#).

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

#### 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 \(3.57\)](#) in [Equation \(3.87\)](#).

$$FC_{f,affa} = CA_{f,cmd} \cdot equipcost \quad (3.87)$$

#### 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 on-line spares, so the assumption is made that there is no downtime associated with the failure of these equipment types. The probability weighting of the downtime required to repair damage for a specific equipment item is given by [Equation \(3.88\)](#). The

probability weighting uses the generic frequencies of the release hole sizes provided in [Table 3.1](#) of [Part 2](#).

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

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

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

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

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

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

#### 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,  $injcst$ , 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:

- any existing company standards for such calculations,
- local medical/compensation costs associated with long-term disability,
- legal/settlement costs, and
- indirect costs such as increased regulatory scrutiny, loss of reputation, etc.

The costs associated with personnel injury are calculated using [Equation \(3.91\)](#):

$$FC_{inj} = CA_{inj} \cdot popdens \cdot injcost \quad (3.91)$$

Alternatively, the consequence related to injury,  $C_f^{inj}$ , 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,  $frac_{evap}$ , as a function of the NBP is provided in Table 4.18. As an alternative, the following equation can be used to estimate  $frac_{evap}$ :

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

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

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

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

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

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

#### 4.12.7 Calculation of FC

- a) STEP 12.1—Calculate the cost (consequence in \$) to repair the specific piece of equipment,  $FC_{f,cmd}$ , using Equation (3.86) with the release hole size damage costs from Table 4.15 and GFFs for the release hole sizes from STEP 2.2. The material cost factor,  $matcost$ , is obtained from Table 4.16.
- b) STEP 12.2—Calculate the cost of damage to surrounding equipment in the affected area,  $FC_{f,affa}$ , using Equation (3.87) and component damage consequence area,  $CA_{f,cmd}$ , calculated in STEP 11.1. The equipment cost factor,  $equipcost$ , is the unit equipment replacement cost in \$/ft<sup>2</sup>(\$/m<sup>2</sup>).
- c) STEP 12.3—For each release hole size, calculate the cost of business interruption due to the outage days required to repair the damage to equipment.
  - 1) Calculate the probability weighted repair of the specific piece of equipment using Equation (3.88) and the downtime for each release hole size,  $Outage_n$ , from Table 4.17.
  - 2) Calculate the downtime required to repair the surrounding equipment in the affected area,  $Outage_{affa}$ , using Equation (3.89) and the cost of damage to the surrounding equipment in the affected area,  $FC_{f,affa}$ , calculated in STEP 12.2.
  - 3) Calculate the cost of business interruption,  $FC_{f,prod}$ , using Equation (3.90). The production costs,  $prodcost$ , is the cost of lost production on the unit, \$/day.
- d) STEP 12.4—Calculate the costs associated with personnel injury using Equation (3.91) and the personnel injury consequence area,  $CA_{f,inj}$ , calculated in STEP 11.2. The unit population density,  $popdens$ , is the average number of personnel on the unit per ft<sup>2</sup> (personnel/m<sup>2</sup>). The personnel injury cost,  $injcst$ , is the cost incurred by the company as a result serious injury or fatality of personnel.
- e) STEP 12.5—Calculate the costs associated with environmental cleanup.
  - 1) Estimate the spill volume from each release hole size, using Equation (3.93), the release mass from STEP 7.3, and the fluid liquid density and evaporation fraction obtained from Table 4.18.
  - 2) Calculate the probability weighted environmental cleanup costs,  $FC_{f,enviro}$ , 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  $C_f^{fm}$  using Equation (3.85), which is the sum of the costs determined in STEPs 12.1 through 12.5.

#### 4.13 Determine Safety Consequence

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

$$SC_f^{inj} = CA_f^{inj} \cdot popdens \quad (3.95)$$

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

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

#### 4.13.1 Determination of Population Density

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

$$Pers\#_{avg} = \frac{(Pers\#_1 \cdot Present\%_{n1}) + (Pers\#_2 \cdot Present\%_{n2}) + \dots}{100}$$
~~$$Pers\#_{avg} = (Pers\#_1 + Present\%_{n1}) + (Pers\#_2 + Present\%_{n2}) + \dots \quad (3.96)$$~~

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

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

$$popdens = \frac{Pers\#_{avg}}{Area_n^{safety}} \quad (3.97)$$

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.

#### 4.13.2 Calculation of Safety Consequence

- a) Step 13.1 – Calculate the  $CA_f^{inj}$  using Equation (3.83).
- b) Step 13.2 – Calculate the average personnel,  $Pers\#_{avg}$ , present in the unit using Equation (3.96).

- c) Step 13.3 – Calculate the area the unit covers,  $Area_n^{safety}$ . The  $Area_n^{safety}$  should be defined within the unit boundaries and may include additional areas beyond the unit boundaries that may be impacted. Considering the area within the unit boundaries is acceptable when impacted areas beyond the unit boundaries are sparsely populated.
- d) Step 13.4 - Calculate the unit population density,  $popdens$ , using average population present,  $Pers\#_{avg}$ , and the  $Area_n^{safety}$  using Equation (3.97).
- e) Step 13.5 – Calculate the  $SC_f^{inj}$  using the  $CA_f^{inj}$  and  $popdens$  using Equation (3.95).

#### 4.14 Nomenclature

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

- $a$  is a constant provided for reference fluids for Level 1 consequence analysis
- $a_{cmd}^{AIL-CONT}$  is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
- $a_{inj}^{AIL-CONT}$  is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
- $a_{cmd}^{AIL-INST}$  is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
- $a_{inj}^{AIL-INST}$  is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
- $a_{cmd}^{AINL-CONT}$  is a constant for AINL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
- $a_{inj}^{AINL-CONT}$  is a constant for AINL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
- $a_{cmd}^{AINL-INST}$  is a constant for AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
- $a_{inj}^{AINL-INST}$  is a constant for AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
- $AIT$  is the autoignition temperature of the released fluid, K (°R)
- $A_n$  is the hole area associated with the  $n^{\text{th}}$  release hole size, in.<sup>2</sup> (mm<sup>2</sup>)

$Area_n^{safety}$	is the area being evaluated for a safety consequence, typically a process unit, ft <sup>2</sup> (m <sup>2</sup> )
$b$	is a variable provided for reference fluids for Level 1 consequence analysis for analysis
$b_{cmd}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AIL-CONT}$	is a constant AIL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AIL-INST}$	is a constant AIL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AINL-CONT}$	is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AINL-CONT}$	is a constant AINL continuous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$b_{cmd}^{AINL-INST}$	is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for equipment damage area
$b_{inj}^{AINL-INST}$	is a constant AINL instantaneous release provided for reference fluids for Level 1 consequence analysis for personnel injury area
$c$	is a gas release constant used in HF and H <sub>2</sub> S releases for the COF 1 toxic area analysis
$C_d$	is the release hole coefficient of discharge, unitless
$C_p$	is the specific heat of the released fluid, Btu/lb-°R (J/kg-K)
$CA_f$	is the final consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$C_f^{area}$	is the safety consequence impact area, ft <sup>2</sup> (m <sup>2</sup> )
$C_f^{fin}$	is the financial consequence, \$
$C_f^{inj}$	is the injury consequence, injuries
$CA_{inj,n}^{acid}$	is the personnel injury consequence area for caustic and acid leaks, associated with the $n^{th}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )

$CA^{AIL}$	is the flammable consequence area where autoignition is likely to occur, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AIL}$	is the continuous/instantaneous blended component damage flammable consequence area that is likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AIL-CONT}$	is the component damage flammable consequence area for continuous releases that is likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{AIL-CONT}$	is the personnel injury flammable consequence area for continuous releases that is likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AIL-INST}$	is the component damage flammable consequence area for instantaneous releases that is likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{AIL-INST}$	is the personnel injury flammable consequence area for instantaneous releases that is likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA^{AINL}$	is the flammable consequence area where autoignition is not likely to occur, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AINL}$	is the continuous/instantaneous blended component damage flammable consequence area that is not likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AINL-CONT}$	is the component damage flammable consequence area for continuous releases that is not likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{AINL-CONT}$	is the personnel injury flammable consequence area for continuous releases that is not likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{AINL-INST}$	is the component damage flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{AINL-INST}$	is the personnel injury flammable consequence area for instantaneous releases that is not likely to autoignite, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA^{AIT-blend}$	is the AIT blended flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}$	is the final component damage consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{CONT}$	is the personnel injury consequence area for continuous releases, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,n}^{CONT}$	is the consequence area for a continuous release, ft <sup>2</sup> (m <sup>2</sup> )

$CA_{f,cmd}^{flam}$	is the final probability weighted component damage flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{cmd,n}^{flam}$	is the blended component damage flammable consequence area, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{flam}$	is the final probability weighted personnel injury flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{flam}$	is the blended personnel injury flammable consequence area, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_n^{IC-blend}$	is the continuous/instantaneous blended flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}$	is the final personnel injury consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{INST}$	is the personnel injury consequence area for instantaneous releases, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,n}^{INST}$	is the consequence area for an instantaneous release, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{leak}$	is the personnel injury nonflammable, nontoxic consequence area for steam or acid leaks, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,max}$	is the final maximum consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}^{nflm}$	is the component damage nonflammable, nontoxic consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{nflm}$	is the final probability weighted personnel injury consequence area for nonflammable, nontoxic releases such as steam or acids, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{nflm}$	is the personnel injury nonflammable, nontoxic consequence area, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{stm}$	is the personnel injury consequence area for steam leaks, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}^{tox}$	is the final probability weighted component damage toxic consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{tox}$	is the final probability weighted personnel injury toxic consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{tox-CONT}$	is the personnel injury toxic consequence area for a continuous release, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{inj,n}^{tox-INST}$	is the personnel injury toxic consequence area for an instantaneous release, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )

<i>costfactor</i>	is the cost factor reflecting the change in carbon steel and replacement costs from the 2001
<i>d</i>	Is a gas release constant used in HF and H <sub>2</sub> S releases for the Level 1 toxic consequence area analysis
<i>d<sub>n</sub></i>	is the diameter of the <i>n</i> <sup>th</sup> release hole size, in. (mm)
<i>e</i>	Is a gas release constant used in NH <sub>3</sub> and Cl releases for the Level 1 toxic consequence area analysis
<i>eneff<sub>n</sub></i>	is the energy efficiency correction factor for instantaneous events exceeding a release mass of 10,000 lb (4,536 kg)
<i>envcost</i>	is the environmental cleanup costs, \$/bbl
<i>equipcost</i>	is the process unit replacement costs for component, \$/ft <sup>2</sup> (\$/m <sup>2</sup> )
<i>f</i>	is a gas release constant used in NH <sub>3</sub> and Cl releases for the Level 1 toxic consequence area analysis
<i>fact<sup>AIT</sup></i>	is the AIT consequence area blending factor
<i>fact<sub>di</sub></i>	is the release magnitude adjustment factor, based on the detection and isolations systems present in the unit.
<i>fact<sub>n</sub><sup>IC</sup></i>	is the continuous/instantaneous consequence area blending factor determined for each release hole size, associated with the <i>n</i> <sup>th</sup> release hole size
<i>fact<sub>mit</sub></i>	is the consequence area adjustment factor, based on the mitigation systems present in the unit.
<i>frac<sub>evap</sub></i>	is the fraction of the released liquid pool that evaporates, needed to estimate the volume of material for environmental cleanup
<i>FC<sub>affa</sub></i>	is the financial consequence of damage to surrounding equipment on the unit, \$
<i>FC<sub>cmd</sub></i>	is the financial consequence of component damage, \$
<i>FC<sub>environ</sub></i>	is the financial consequence of environmental cleanup, \$
<i>FC<sub>inj</sub></i>	is the financial consequence as a result of serious injury to personnel, \$
<i>FC<sub>prod</sub></i>	is the financial consequence of lost production on the unit, \$
<i>g</i>	Is a gas release constant used in acid and caustic releases for the Level 1 area consequence analysis

$g_c$	is the gravitational constant = $32.2(lb_m - ft)/(lb_f - s^2) [1.0(kg - m)/(N - s^2)]$
$gff_n$	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
$h$	is a gas release constant for acid and caustic for the Level 1 area consequence analysis
$holecost_n$	is the equipment repair cost, provided for each of the release hole sizes selected, \$
$injcost$	is the cost associated with serious injury or fatality of personnel, \$
$k$	is the release fluid ideal gas specific heat capacity ratio, unitless
$K_{v,n}$	is the liquid flow viscosity correction factor, associated with the $n^{th}$ release hole size, unitless
$ld_{max,n}$	is the maximum leak duration based on isolation and detection systems associated with the $n^{th}$ release hole size, minutes
$ld_n$	is the actual leak duration of the flammable release based on the available mass and the calculated release rate, associated with the $n^{th}$ release hole size, seconds
$ld_n^{tox}$	is the leak duration of the toxic release based on the available mass and the calculated release rate, associated with the $n^{th}$ release hole size, seconds
$mass_{add,n}$	is the mass contributed by the surrounding equipment in the inventory group (limited by $W_{max 8}$ ), associated 3 minutes release of the $n^{th}$ release hole size, lb (kg)
$mass_n$	is the adjusted or mitigated discharge mass used associated with 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)
<del><math>mass_n</math></del>	<del>is the adjusted gas or liquid release rate for detection and isolation systems associated with the <math>n^{th}</math> release hole size, lb (kg)</del>

- $mass_n^{tox}$  is the release mass of toxic component used in the toxic consequence calculation associated with the  $n^{\text{th}}$  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
- $MW$  is the release fluid molecular weight, lb/lb-mol (kg/kg-mol)
- $NBP$  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
- $Outage_{mult}$  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  $n^{\text{th}}$  release hole size, days
- $Pers\#_{avg}$  is the average number of people in a defined area at any given time
- $Pers\#_n$  is the number of personnel present in a defined area for each unit staffing activity
- $Present\%_n$  is the percent of time personnel are present in the defined area for each unit staffing activity, typically developed by reviewing population for a year
- $popdens$  is the population density of personnel or employees in the unit, personnel/m<sup>2</sup> (personnel/ft<sup>2</sup>)
- $P_{atm}$  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
- $prodcost$  is the cost of lost production due to downtime to repair equipment, \$/day
- $R$  is the universal gas constant = 1545 ft-lb<sub>f</sub>/(lb-mol-°R) [8.314 J/(kg-mol-K)]
- $Re_n$  is the Reynolds Number for flow through the release, associated with the  $n^{\text{th}}$  release hole size, unitless

$rate_n$	is the adjusted release rate for detection and isolation systems associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
<del><math>rate_n</math></del>	<del>is the adjusted or mitigated discharge rate associated with the <math>n^{\text{th}}</math> release hole size, lb/s (kg/s)</del>
$rate_n^{\text{tox}}$	is the release mass rate of toxic component used in the consequence calculation, associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$t_n$	is the time to release 10,000 lb of fluid mass, calculated for each of the $n$ release hole sizes selected, seconds
$T_s$	is the storage or normal operating temperature, °R (K)
$vol_n^{\text{env}}$	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
$W_{\text{max}8}$	is the maximum flow rate of additional mass that can be added to the release as contributed from the surrounding equipment in the inventory group, lb/s (kg/s)
$W_n$	is the gas or liquid release rate associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$x_i$	is the mole fraction of the component and $Property_i$ may be the NBP, MW, or density of the individual components in the fluid mixture
$\rho$	is the density, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )
$\rho_{\text{atm}}$	is the atmospheric air density, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )
$\rho_l$	is the liquid density at storage or normal operating conditions, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )
$\rho_v$	is the vapor density, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )

## 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 <sub>1</sub> -C <sub>2</sub>	TYPE 0	Methane, ethane, ethylene, LNG, fuel gas
C <sub>3</sub> -C <sub>4</sub>	TYPE 0	Propane, butane, isobutane, LPG
C <sub>5</sub>	TYPE 0	Pentane
C <sub>6</sub> -C <sub>8</sub>	TYPE 0	Gasoline, naphtha, light straight run, heptane
C <sub>9</sub> -C <sub>12</sub>	TYPE 0	Diesel, kerosene
C <sub>13</sub> -C <sub>16</sub>	TYPE 0	Jet fuel, kerosene, atmospheric gas oil
C <sub>17</sub> -C <sub>25</sub>	TYPE 0	Gas oil, typical crude
C <sub>25+</sub>	TYPE 0	Residuum, heavy crude, lube oil, seal oil
H <sub>2</sub>	TYPE 0	Hydrogen
H <sub>2</sub> S	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 <sub>3</sub>	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 <sub>2</sub>	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 <sub>2</sub> , 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/ft <sup>3</sup> )	NBP (°F)	Ambient State	Ideal Gas Specific Heat Eq.	$C_p$					AIT (°F)
						Ideal Gas Constant <i>A</i>	Ideal Gas Constant <i>B</i>	Ideal Gas Constant <i>C</i>	Ideal Gas Constant <i>D</i>	Ideal Gas Constant <i>E</i>	
C <sub>1</sub> -C <sub>2</sub>	23	15.639	-193	Gas	Note 1	12.3	1.150E-01	-2.87E-05	-1.30E-09	N/A	1036
C <sub>3</sub> -C <sub>4</sub>	51	33.61	-6.3	Gas	Note 1	2.632	0.3188	-1.347E-04	1.466E-08	N/A	696
C <sub>5</sub>	72	39.03	97	Liquid	Note 1	-3.626	0.4873	-2.6E-04	5.3E-08	N/A	544
C <sub>6</sub> -C <sub>8</sub>	100	42.702	210	Liquid	Note 1	-5.146	6.762E-01	-3.65E-04	7.658E-08	N/A	433
C <sub>9</sub> -C <sub>12</sub>	149	45.823	364	Liquid	Note 1	-8.5	1.01E+00	-5.56E-04	1.180E-07	N/A	406
C <sub>13</sub> -C <sub>16</sub>	205	47.728	502	Liquid	Note 1	-11.7	1.39E+00	-7.72E-04	1.670E-07	N/A	396
C <sub>17</sub> -C <sub>25</sub>	280	48.383	651	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	396
C <sub>25+</sub>	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 <sub>2</sub>	2	4.433	-423	Gas	Note 1	27.1	9.270E-03	-1.38E-05	7.650E-09	N/A	752
H <sub>2</sub> S	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 <sub>3</sub>	133.5	152	382	Powder	Note 1	6.49E+01	8.74E+01	1.82E-02	-4.65E-04	N/A	1036
NO <sub>2</sub>	46	58	275	Liquid	—	—	—	—	—	—	N/A
Phosgene	99	86	181	Liquid	—	—	—	—	—	—	N/A

Fluid	MW	Liquid Density (lb/ft <sup>3</sup> )	NBP (°F)	Ambient State	Ideal Gas Specific Heat Eq.	$C_p$					AIT (°F)
						Ideal Gas Constant <i>A</i>	Ideal Gas Constant <i>B</i>	Ideal Gas Constant <i>C</i>	Ideal Gas Constant <i>D</i>	Ideal Gas Constant <i>E</i>	
TDI	174	76	484	Liquid	—	—	—	—	—	—	1148
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  $C_p = A + B \left( \frac{C}{T} \right)^2 + D \left( \frac{E}{T} \right)^2 \sinh \left[ \frac{C}{T} \right] + D \left( \frac{E}{T} \right)^2 \cosh \left[ \frac{E}{T} \right]$  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<sup>-4</sup> Btu/(kg-mol-°R).

NOTE 6 For NOTE 1, R=8.314 J/mol-K; For NOTE 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/m <sup>3</sup> )	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	$C_p$					AIT (°C)
						Ideal Gas Constant <i>A</i>	Ideal Gas Constant <i>B</i>	Ideal Gas Constant <i>C</i>	Ideal Gas Constant <i>D</i>	Ideal Gas Constant <i>E</i>	
C <sub>1</sub> -C <sub>2</sub>	23	250.512	-125	Gas	Note 1	12.3	1.15E-01	-2.87E-05	-1.30E-09	N/A	558
C <sub>3</sub> -C <sub>4</sub>	51	538.379	-21	Gas	Note 1	2.632	0.3188	-1.35E-04	1.47E-08	N/A	369
C <sub>5</sub>	72	625.199	36	Liquid	Note 1	-3.626	0.4873	-2.60E-04	5.30E-08	N/A	284
C <sub>6</sub> -C <sub>8</sub>	100	684.018	99	Liquid	Note 1	-5.146	6.76E-01	-3.65E-04	7.66E-08	N/A	223
C <sub>9</sub> -C <sub>12</sub>	149	734.012	184	Liquid	Note 1	-8.5	1.01E+00	-5.56E-04	1.18E-07	N/A	208
C <sub>13</sub> -C <sub>16</sub>	205	764.527	261	Liquid	Note 1	-11.7	1.39E+00	-7.72E-04	1.67E-07	N/A	202
C <sub>17</sub> -C <sub>25</sub>	280	775.019	344	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	202
C <sub>25+</sub>	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 <sub>2</sub>	2	71.010	-253	Gas	Note 1	27.1	9.27E-03	-1.38E-05	7.65E-09	N/A	400
H <sub>2</sub> S	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 <sub>3</sub>	133.5	2434.798	194	Powder	Note 1	6.49E+01	8.74E+01	1.82E-02	-4.65E-04	N/A	558
NO <sub>2</sub>	90	929.068	135	Liquid	—	—	—	—	—	—	N/A
Phosgene	99	1377.583	83	Liquid	—	—	—	—	—	—	N/A

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

Fluid	MW	Liquid Density (kg/m <sup>3</sup> )	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	$C_p$					AIT (°C)
						Ideal Gas Constant $A$	Ideal Gas Constant $B$	Ideal Gas Constant $C$	Ideal Gas Constant $D$	Ideal Gas Constant $E$	
TDI	174	1217.399	251	Liquid	—	—	—	—	—	—	620
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  $C_p = A + B \left( \frac{C}{T} \right)^2 + D \left( \frac{E}{T} \right)^2$  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 NOTE 2 and 3,  $R=8314$  J/mol-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 <i>unless</i> 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 $\leq 1/4$ in. leaks 10 minutes for $d_2 = \frac{1}{4} > D \leq 1$ in. leaks 5 minutes for $d_3 = 1 > D \leq 4$ in. leaks 60 minutes for $d_4 = D \geq 4$ in. leaks
A	B	30 minutes for $\leq 1/4$ in. leaks 20 minutes for $d_2 = \frac{1}{4} > D \leq 1$ <del><math>d_2 = \min[D, \frac{1}{4} &lt; D \leq 1]</math> in. in</del> leaks 10 minutes for $d_3 = 1 > D \leq 4$ <del><math>d_3 = \min[D, 1 &lt; D \leq 4]</math> in. in</del> leaks 60 minutes for $d_4 = D \geq 4$ <del><math>d_4 = \min[D, D \geq 4]</math> in. in</del> leaks
A	C	40 minutes for $\leq 1/4$ in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \leq 1$ <del><math>d_2 = \min[D, \frac{1}{4} &lt; D \leq 1]</math> in. in</del> leaks 20 minutes for $d_3 = 1 > D \leq 4$ <del><math>d_3 = \min[D, 1 &lt; D \leq 4]</math> in. in</del> leaks 60 minutes for $d_4 = D \geq 4$ <del><math>d_4 = \min[D, 16]</math> in</del> leaks
B	A or B	40 minutes for $\leq 1/4$ in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \leq 1$ <del><math>d_2 = \min[D, \frac{1}{4} &lt; D \leq 1]</math> in. in</del> leaks 20 minutes for $d_3 = 1 > D \leq 4$ <del><math>d_3 = \min[D, 1 &lt; D \leq 4]</math> in. in</del> leaks 60 minutes for $d_4 = D \geq 4$ <del><math>d_4 = \min[D, D \geq 4]</math> in. in</del> leaks
B	C	1 hour for $\leq 1/4$ in. leaks 30 minutes for $d_2 = \frac{1}{4} > D \leq 1$ <del><math>d_2 = \min[D, \frac{1}{4} &lt; D \leq 1]</math> in. in</del> leaks 20 minutes for $d_3 = 1 > D \leq 4$ <del><math>d_3 = \min[D, 1 &lt; D \leq 4]</math> in. in</del> leaks 60 minutes for $d_4 = D \geq 4$ <del><math>d_4 = \min[D, D \geq 4]</math> in. in</del> leaks
C	A, B, or C	1 hour for $\leq 1/4$ in. leaks

		<p>40 minutes for <math>d_2 = \frac{1}{4} &gt; D \leq 1</math> <del><math>d_2 = \min\left[\frac{1}{4}, D \leq 1\right]</math> in-in</del> leaks</p> <p>20 minutes for <math>d_3 = 1 &gt; D \leq 4</math> <del><math>d_3 = \min[D, 1 &lt; D \leq 4]</math> in-in</del> leaks</p> <p>60 minutes for <math>d_4 = D \geq 4</math> <del><math>d_4 = \min[D, D \geq 4]</math> in-in</del> leaks</p>
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**Table 4.7M—Leak Durations Based on Detection and Isolation Systems**

Detection System Rating	Isolation System Rating	Maximum Leak Duration, $ld_{max}$
A	A	<p>20 minutes for <math>\leq 6.4</math> mm leaks</p> <p>10 minutes for <math>d_2 = 6.4 &gt; D \leq 25</math> mm leaks</p> <p>5 minutes for <math>d_3 = 25 &gt; D \leq 102</math> mm leaks</p> <p>60 minutes for <math>d_4 = D \geq 102</math> mm leaks</p>
A	B	<p>30 minutes for <math>\leq 6.4</math> mm leaks</p> <p>20 minutes for <math>d_2 = 6.4 &gt; D \leq 25</math> <del><math>d_2 = \min[D, 6.4 &lt; D \leq 25]</math> mm leaks</del></p> <p>10 minutes for <math>d_3 = 25 &gt; D \leq 102</math> <del><math>d_3 = \min[D, 25 &lt; D \leq 102]</math> mm leaks</del></p> <p>60 minutes for <math>d_4 = D \geq 102</math> <del><math>d_4 = \min[D, D \geq 102]</math></del> mm leaks</p>
A	C	<p>40 minutes for <math>\leq 6.4</math> mm leaks</p> <p>30 minutes for <math>d_2 = 6.4 &gt; D \leq 25</math> <del><math>d_2 = \min[D, 6.4 &lt; D \leq 25]</math> mm leaks</del></p> <p>20 minutes for <math>d_3 = 25 &gt; D \leq 102</math> <del><math>d_3 = \min[D, 25 &lt; D \leq 102]</math> mm leaks</del></p> <p>60 minutes for <math>d_4 = D \geq 102</math> <del><math>d_4 = \min[D, D \geq 102]</math></del> mm leaks</p>
B	A or B	<p>40 minutes for <math>\leq 6.4</math> mm leaks</p> <p>30 minutes for <math>d_2 = 6.4 &gt; D \leq 25</math> <del><math>d_2 = \min[D, 6.4 &lt; D \leq 25]</math> leaks</del></p> <p>20 minutes for <math>d_3 = 25 &gt; D \leq 102</math> <del><math>d_3 = \min[D, 25 &lt; D \leq 102]</math> mm leaks</del></p>

		60 minutes for $d_4 = D \geq 102$ <del><math>d_4 = \min[D, D \geq 102]</math></del> mm leaks
B	C	1 hour for $\leq 6.4$ mm leaks 30 minutes for $d_2 = 6.4 > D \leq 25$ <del><math>d_2 = \min[D, 6.4 &lt; D \leq 25]</math></del> mm leaks 20 minutes for $d_3 = 25 > D \leq 102$ <del><math>d_3 = \min[D, 25 &lt; D \leq 102]</math></del> mm leaks 60 minutes for $d_4 = D \geq 102$ <del><math>d_4 = \min[D, D \geq 102]</math></del> mm leaks
C	A, B, or C	1 hour for $\leq 6.4$ mm leaks 40 minutes for $d_2 = 6.4 > D \leq 25$ <del><math>d_2 = \min[D, 6.4 &lt; D \leq 25]</math></del> mm leaks 20 minutes for $d_3 = 25 > D \leq 102$ <del><math>d_3 = \min[D, 25 &lt; D \leq 102]</math></del> mm leaks 60 minutes for $d_4 = D \geq 102$ <del><math>d_4 = \min[D, D \geq 102]</math></del> 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 <sub>1</sub> -C <sub>2</sub>	TYPE 0	43.0	0.98			280.0	0.95			41.0	0.67			1079	0.62		
C <sub>3</sub> -C <sub>4</sub>	TYPE 0	49.48	1.00			313.6	1.00			27.96	0.72			522.9	0.63		
C <sub>5</sub>	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 <sub>6</sub> -C <sub>8</sub>	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 <sub>9</sub> -C <sub>12</sub>	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 <sub>13</sub> -C <sub>16</sub>	TYPE 0			64.0	0.90			1023	0.92			0.46	0.88			9.2	0.88
C <sub>17</sub> -C <sub>25</sub>	TYPE 0			20.0	0.90			861.0	0.92			0.11	0.91			5.6	0.91
C <sub>25+</sub>	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 <sub>2</sub>	TYPE 0	64.5	0.992			420.0	1.00			61.5	0.657			1430	0.618		
H <sub>2</sub> S	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	
		<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
C <sub>1</sub> -C <sub>2</sub>	TYPE 0	8.669	0.98			55.13	0.95			6.469	0.67			163.7	0.62		
C <sub>3</sub> -C <sub>4</sub>	TYPE 0	10.13	1.00			64.23	1.00			4.590	0.72			79.94	0.63		
C <sub>5</sub>	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 <sub>6</sub> -C <sub>8</sub>	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 <sub>9</sub> -C <sub>12</sub>	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 <sub>13</sub> -C <sub>16</sub>	TYPE 0			12.11	0.90			196.7	0.92			0.086	0.88			1.714	0.88
C <sub>17</sub> -C <sub>25</sub>	TYPE 0			3.785	0.90			165.5	0.92			0.021	0.91			1.068	0.91
C <sub>25+</sub>	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 <sub>2</sub>	TYPE 0	13.13	0.992			86.02	1.00			9.605	0.657			216.5	0.618		
H <sub>2</sub> S	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 <sub>1</sub> -C <sub>2</sub>	TYPE 0	110.0	0.96			745.0	0.92			79.0	0.67			3100	0.63		
C <sub>3</sub> -C <sub>4</sub>	TYPE 0	125.2	1.00			836.7	1.00			57.72	0.75			1769	0.63		
C <sub>5</sub>	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 <sub>6</sub> -C <sub>8</sub>	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 <sub>9</sub> -C <sub>12</sub>	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 <sub>13</sub> -C <sub>16</sub>	TYPE 0			183.0	0.89			2850	0.90			1.3	0.88			26.0	0.88
C <sub>17</sub> -C <sub>25</sub>	TYPE 0			57.0	0.89			2420	0.90			0.32	0.91			16.0	0.91
C <sub>25+</sub>	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 <sub>2</sub>	TYPE 0	165.0	0.933			1117	1.00			118.5	0.652			4193	0.621		
H <sub>2</sub> S	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 <sub>1</sub> -C <sub>2</sub>	TYPE 0	21.83	0.96			143.2	0.92			12.46	0.67			473.9	0.63		
C <sub>3</sub> -C <sub>4</sub>	TYPE 0	25.64	1.00			171.4	1.00			9.702	0.75			270.4	0.63		
C <sub>5</sub>	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 <sub>6</sub> -C <sub>8</sub>	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 <sub>9</sub> -C <sub>12</sub>	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 <sub>13</sub> -C <sub>16</sub>	TYPE 0			34.36	0.89			539.4	0.90			0.242	0.88			4.843	0.88
C <sub>17</sub> -C <sub>25</sub>	TYPE 0			10.70	0.89			458.0	0.90			0.061	0.91			3.052	0.91
C <sub>25+</sub>	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 <sub>2</sub>	TYPE 0	32.05	0.933			228.8	1.00			18.43	0.652			636.5	0.621		
H <sub>2</sub> S	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 Acid and H<sub>2</sub>S**

Continuous Releases Duration (minutes)	HF Acid		H <sub>2</sub> S	
	$c$	$d$	$c$	$d$
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
<b>Instantaneous Releases</b>	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
<b>Instantaneous Releases</b>	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)	<u>Anhydrous</u> Ammonia		Chlorine	
	<i>e</i>	<i>f</i>	<i>e</i>	<i>f</i>
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
<b>Instantaneous Releases</b>	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	
		<i>e</i>	<i>f</i>	<i>e</i>	<i>f</i>
Aluminum chloride (AlCl <sub>3</sub> )	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 <sub>2</sub> )	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	
		<i>e</i>	<i>f</i>	<i>e</i>	<i>f</i>
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	
		<i>e</i>	<i>f</i>	<i>e</i>	<i>f</i>
Aluminum chloride (AlCl <sub>3</sub> )	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 <sub>2</sub> )	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	
		<i>e</i>	<i>f</i>	<i>e</i>	<i>f</i>
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), <i>holecost</i>			
		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**

<b>Material</b>	<b>Cost Factor, <i>matcost</i></b>	<b>Material</b>	<b>Cost Factor, <i>matcost</i></b>
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 "Teflon" 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
Polypropylene Lined (pp)	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	NA	3	7	NA
Heat exchanger	HEXSS, HEXTS	2	3	3	10
	HEXTUBE	NA	NA	NA	NA
Pipe	PIPE-1, PIPE-2	0	NA	NA	1
	PIPE-4	0	1	NA	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	NA
Tank	TANKBOTTOM	5	NA	NA	50
	TANKBOTEDGE	5	NA	NA	50
	COURSE-1 through 10	2	3	3	14
FINFAN	FINFAN_TUBE	0	NA	NA	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: NA—Not applicable means that these hole sizes are not used for these component types. Refer to [Part 3, Annex 3.A, Section 3.A.3.2.](#)

Table 4.18—Fluid Leak Properties

Fluid	MW	Density (lb/ft <sup>3</sup> )	NBP (°F)	Fraction Evaporated in 24 Hours (Note 1) <i>fract<sub>evap</sub></i>
C <sub>1</sub> -C <sub>2</sub>	23	15.639	-193	1.00
C <sub>3</sub> -C <sub>5</sub>	58	36.209	31	1.00
C <sub>6</sub> -C <sub>8</sub>	100	42.702	210	0.90
C <sub>9</sub> -C <sub>12</sub>	149	45.823	364	0.50
C <sub>13</sub> -C <sub>16</sub>	205	47.728	502	0.10
C <sub>17</sub> -C <sub>25</sub>	280	48.383	651	0.05
C <sub>25+</sub>	422	56.187	981	0.02
Acid	18	62.3	212	0.90
H <sub>2</sub>	2	4.433	-423	1.00
H <sub>2</sub> S	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 <sub>2</sub>	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 1: Estimated values.

Table 4.18M—Fluid Leak Properties

Fluid	MW	Density (kg/m <sup>3</sup> )	NBP (°C)	Fraction Evaporated in 24 Hours (Note 1) <i>fract<sub>evap</sub></i>
C <sub>1</sub> -C <sub>2</sub>	23	250.513	-125	1.00
C <sub>3</sub> -C <sub>5</sub>	58	580.012	-1	1.00
C <sub>6</sub> -C <sub>8</sub>	100	684.020	99	0.90
C <sub>9</sub> -C <sub>12</sub>	149	734.014	184	0.50
C <sub>13</sub> -C <sub>16</sub>	205	764.529	261	0.10
C <sub>17</sub> -C <sub>25</sub>	280	775.021	344	0.05
C <sub>25+</sub>	422	900.029	527	0.02
Acid	18	997.950	100	0.90
H <sub>2</sub>	2	71.010	-253	1.00
H <sub>2</sub> S	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 <sub>2</sub>	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 1: Estimated values.

## 4.16 Figures

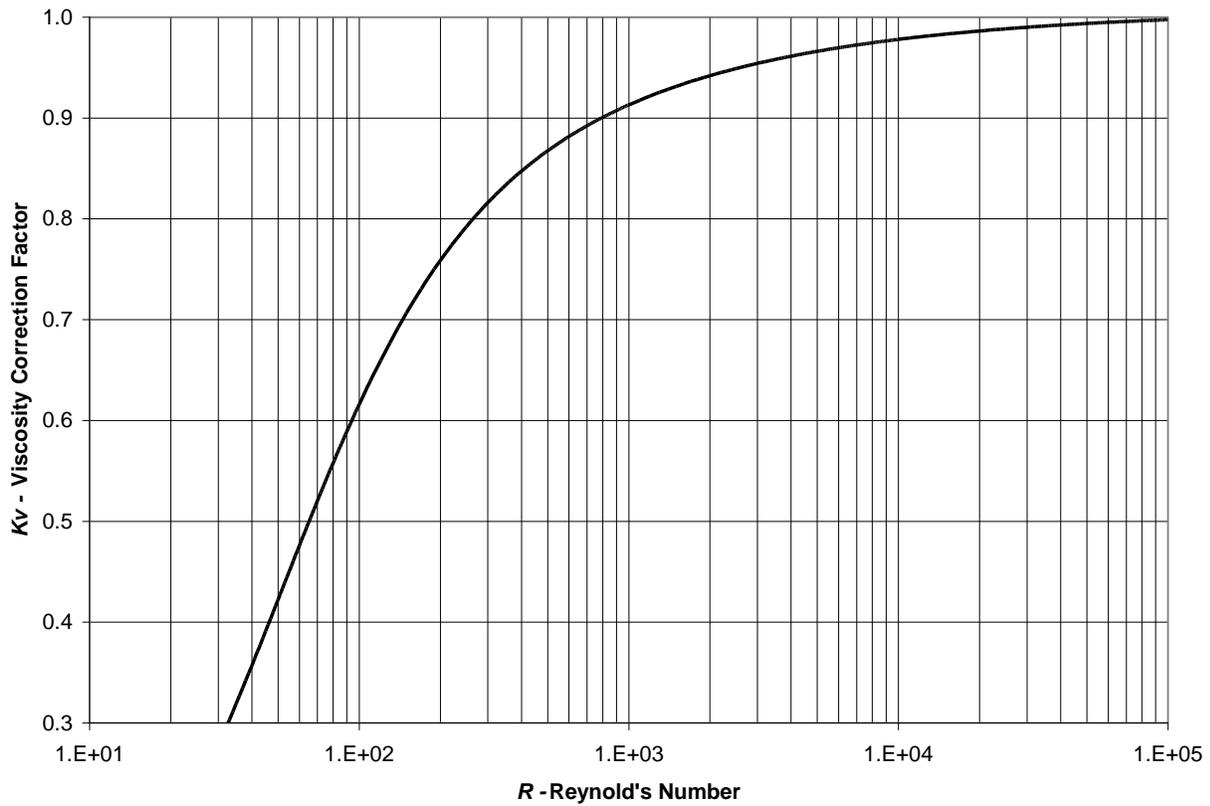


Figure 4.1—Liquid Flow Viscosity Correction Factor,  $K_v$

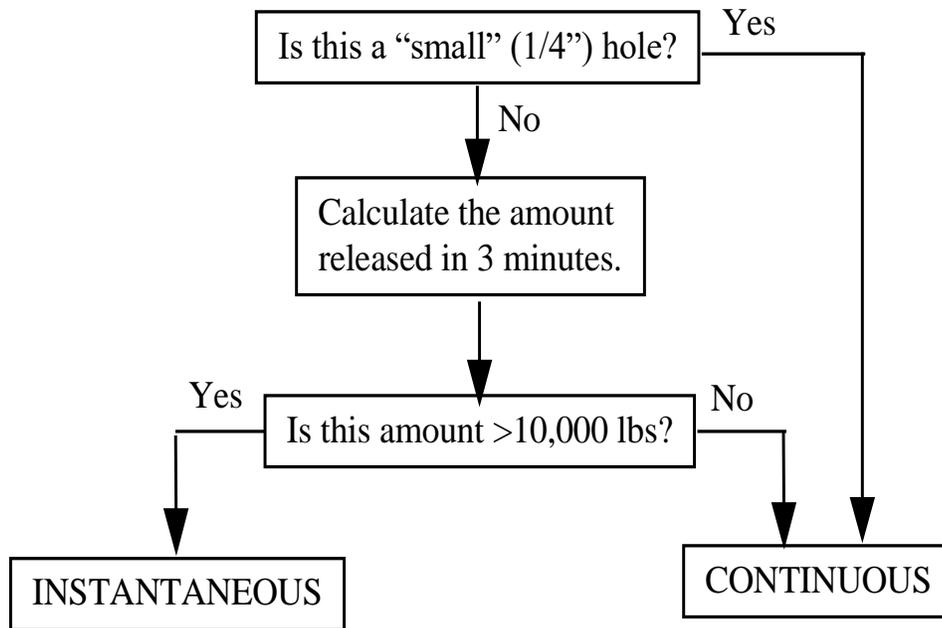
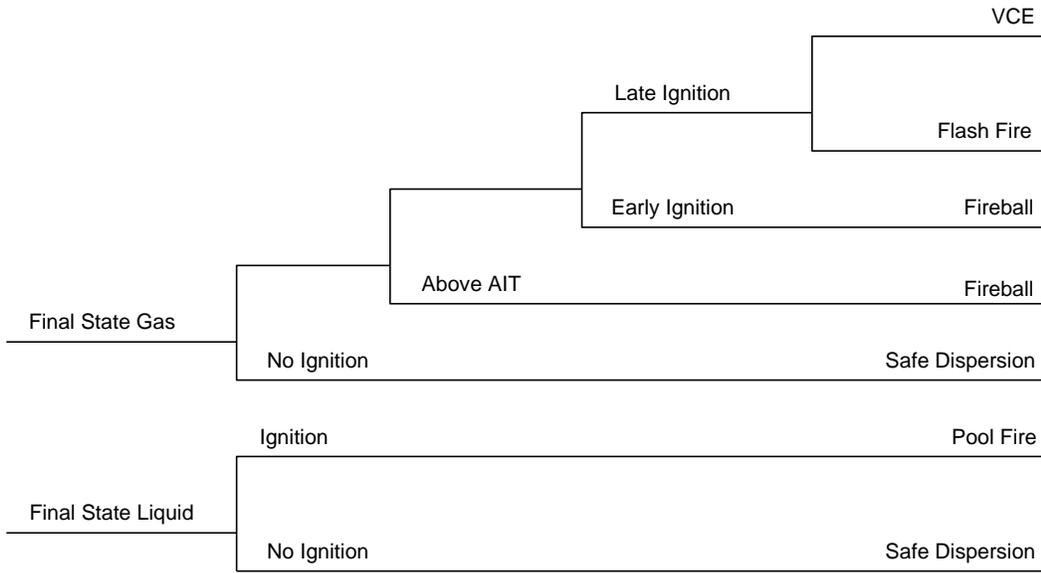
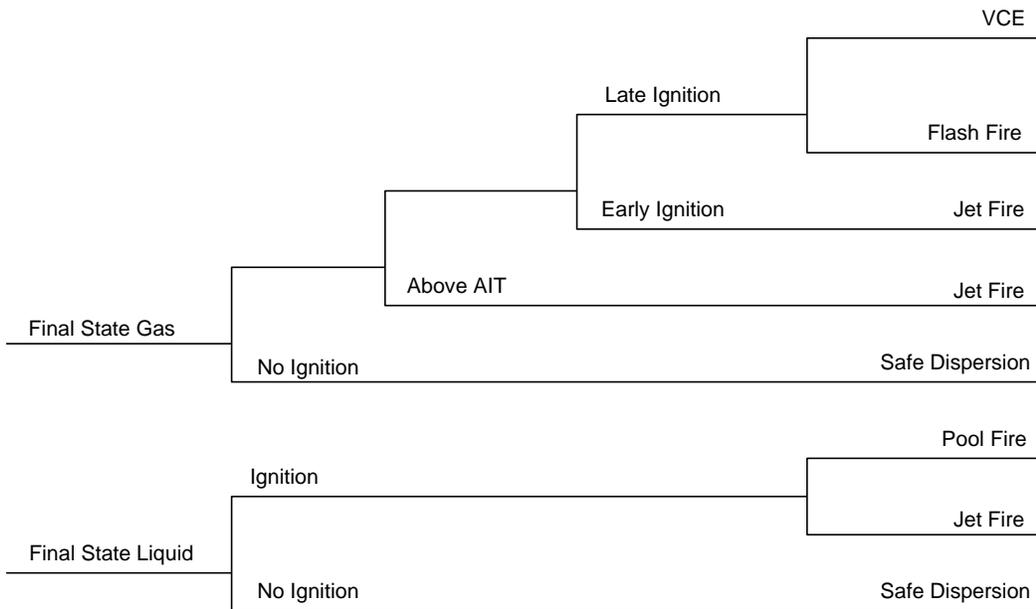


Figure 4.2—Instantaneous and Continuous Determination

**Instantaneous-Type Release**



**Continuous-Type Release**



**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 multi-component 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,  $\rho_l$ .
- f) Liquid viscosity,  $\mu_l$ .
- 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,  $P_{sat_s}$ , at storage temperature.
- m) Flammability limits, LFL and upper flammability limit (UFL).

- n) Heat of combustion,  $HC_s$ .
- o) Toxic limits (e.g. IDLH, ERPG, AELG, 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,  $\rho_l$ ;
- e) density of the vapor,  $\rho_v$ ;
- 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,  $\Delta H_v$ ;
- j) bubble point temperature of liquid,  $T_b$ ;
- 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 multi-component 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 <sup>[3]</sup>, 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,  $P_{sat_s}$ , must be determined.

$$\text{if } P_{sat_s} \geq P_s \geq P_{atm} \Rightarrow \text{release phase is vapor} \quad (3.95)$$

$$\text{if } P_s \geq P_{sat_s} > P_{atm} \Rightarrow \text{release phase is two-phase} \quad (3.96)$$

$$\text{if } P_s \geq P_{atm} > P_{sat_s} \Rightarrow \text{release phase is liquid} \quad (3.97)$$

### 5.3.3 Vapor Release Source

As shown in [Equation \(3.95\)](#), if the saturation pressure of the fluid at storage temperature,  $P_{sat_s}$ , 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 <sup>[4]</sup> 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,  $P_{sat_s}$ , 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,  $P_{sat_s}$ , 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,  $P_{sat_s}$ , 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.
  - 1) For liquid releases, use Equation (3.3).
  - 3) For vapor releases, use Equations (3.6) or (3.7), as applicable.
  - 4) 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 <sup>[5]</sup>.

$$frac_{ro} = 1 - 2 \cdot frac_{fsh} \quad \text{for} \quad frac_{fsh} < 0.5 \quad (3.98)$$

$$frac_{ro} = 0.0 \quad \text{for} \quad frac_{fsh} \geq 0.5 \quad (3.99)$$

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

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:

$$W_n^{pool} = rate_n \cdot frac_{ro} \quad (3.100)$$

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

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

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

## 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,  $erate_b$ , can be estimated using Equation (3.103) as provided by Shaw and Briscoe [10].

$$erate_n = \pi^{1.5} \left[ \frac{X_{surf} \cdot k_{surf} \cdot (T_g - T_b)}{C_{14} \cdot \Delta H_v \sqrt{\pi \cdot \alpha_{surf}}} \right] (2 \cdot g \cdot \dot{V}_{p,n})^{0.5} t_{p,n} \quad (3.103)$$

The surface interaction parameters  $X_{surf}$ ,  $k_{surf}$ , and  $\alpha_{surf}$  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 Cremer and Warner Ltd. [11].

The size of the boiling pool reaches a steady state, when the evaporation rate,  $erate_b$ , 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].

$$r_{p,n} = \sqrt{\frac{2}{3}} \left( \frac{8g \cdot \dot{V}_{p,n}}{\pi} \right)^{.25} t_{p,n}^{0.75} \quad (3.104)$$

### 5.7.4.3 Non-boiling Liquid Pools

If  $T_b > T_g$ , 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,  $P_{b,g}$ , corresponding to the ground temperature. Thus, an additional thermodynamic calculation is required to

determine  $P_{b,g}$ . 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,  $erate_{nb}$ , can be estimated using Equation (3.105) as provided by Shaw and Briscoe [10].

$$erate_n = C_{15} \cdot \left( \frac{P_{b,g} \cdot MW}{RT_s} \right) u_w^{0.78} \cdot r_{p,n}^{1.89} \quad (3.105)$$

The size of the non-boiling pool reaches a steady state when the evaporation rate,  $erate_{b,n}$ , 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<sup>2</sup>, at grade) where the air to fuel mixture is between the LFL and the upper flammability limit (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,  $fact_{di}$ , 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,  $mass_{avail,n}$ , 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,  $ld_{max,n}$ , 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,  $frac_{entl}$ , 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,  $r_{p,n}$ , using Equations (3.103) and (3.104). For non-boiling pools, calculate the evaporation rate,  $erate_n$ , and the pool radius,  $r_{p,n}$ , 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<sup>[14]</sup> 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<sup>[14]</sup> 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, Lee, and Ang in 1990 <sup>[15]</sup> 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 <sup>[16]</sup>. The curve fit for the Cox, Lee, 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,  $mfrac^{flam}$ , must be known to calculate the release rate of flammable material:

$$rate_n^{flam} = rate_n \cdot mfrac^{flam} \quad (3.106)$$

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

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

$$rate_{v,n}^{flam} = rate_n^{flam} \cdot frac_{fsh} \quad (3.108)$$

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 [4,535.9 kg (10,000 lb) release in 3 minutes or less], a maximum value of 25.22 kg/s (55.6 lb/s) should be used for  $rate_{l,n}^{flam}$  or  $rate_{v,n}^{flam}$  in [Equation \(3.109\)](#) and [Equation \(3.110\)](#).

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

where,

$$a = -1.368924E-01$$

$$b = -7.598764E-03$$

$$c = 8.282163E-06$$

$$d = -6.124231E-09$$

$$e = 6.876128E-02$$

$$f = 1.193736E-04$$

$$g = 2.081034E-07$$

$$h = -4.057289E-11$$

(3.109)

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

where,

$$\begin{aligned} a &= -6.053124\text{E-}02 \\ b &= -9.958413\text{E-}03 \\ c &= 1.518603\text{E-}05 \\ d &= -1.386705\text{E-}08 \\ e &= 4.564953\text{E-}02 \\ f &= 7.912392\text{E-}04 \\ g &= -6.489157\text{E-}07 \\ h &= 7.159409\text{E-}10 \end{aligned} \quad (3.110)$$

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).

$$poi_l^{ait} = 1.0 \quad (3.111)$$

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.

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

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.

$$poi_{l,n} = poi_{l,n}^{amb} + (poi_l^{ait} - poi_{l,n}^{amb}) \left( \frac{T_s - C_{16}}{AIT - C_{16}} \right) \quad (3.113)$$

$$poi_{v,n} = poi_{v,n}^{amb} + (poi_v^{ait} - poi_{v,n}^{amb}) \left( \frac{T_s - C_{16}}{AIT - C_{16}} \right) \quad (3.114)$$

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).

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

### 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  $poi_i$ . The probability of delayed ignition given ignition is  $(1 - poi_i)$ .

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,  $poi_{l,n}$ , and a flammable vapor release,  $poi_{v,n}$ , can be estimated using [Equation \(3.116\)](#) and [Equation \(3.117\)](#). As an alternative, Cox, Lee, and Ang <sup>[15]</sup> provides a curve for the probability that an ignition will be an immediate vs a delayed ignition.

$$poi_{l,n} = poi_{l,n}^{amb} + \left( \frac{T_s - C_{16}}{AIT - C_{16}} \right) \cdot (poi^{ait} - poi_{l,n}^{amb}) \quad (3.116)$$

$$poi_{v,n} = poi_{v,n}^{amb} + \left( \frac{T_s - C_{16}}{AIT - C_{16}} \right) \cdot (poi^{ait} - poi_{v,n}^{amb}) \quad (3.117)$$

The probabilities of immediate ignition, given ignition at ambient conditions,  $poi_{l,n}^{amb}$  and  $poi_{v,n}^{amb}$ , 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,  $poi^{ait}$ , 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:

$$poi_{2,n} = frac_{fsh} \cdot poi_{v,n} + (1 - frac_{fsh}) \cdot poi_{l,n} \quad (3.118)$$

### 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,  $pvcedi_{l,n}$  or  $pvcedi_{v,n}$ , 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 \(3.119\)](#).

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

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 \(3.121\)](#).

$$pffdi_{l,n} = 1 - pvcedi_{l,n} \quad (3.120)$$

$$pffdi_{v,n} = 1 - pvcedi_{v,n} \quad (3.121)$$

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 \(3.122\)](#).

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

#### 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 \(3.124\)](#).

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

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

#### 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 \(3.125\)](#).

$$pvce_{v,n} = poi_{v,n} \cdot (1 - poi_{v,n}) \cdot (1 - pvcedi_{v,n}) \quad (3.125)$$

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

$$psafe_{2,n} = (1 - poi_{2,n}) \quad (3.126)$$

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

$$ppool_{l,n} = poi_{l,n} \cdot poi_{l,n} \quad (3.127)$$

## 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:

$$\dot{m}_b = \frac{C_{17} \cdot HC_l}{C_{p_l} (T_b - T_{am}) + \Delta H_v} \quad (3.128)$$

For boiling pools, such as cryogenic liquids or LPGs:

$$\dot{m}_b = \frac{C_{17} \cdot HC_l}{\Delta H_v} \quad (3.129)$$

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

$$\dot{m}_b = \sum_{i=1}^N \text{frac}_{mole,i} \cdot \dot{m}_{b,i} \quad (3.130)$$

### 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,  $\dot{m}_b$ , or:

$$A_{burn_{pf,n}} = \frac{W_n^{pool}}{\dot{m}_b} \quad (3.131)$$

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 5 mm (0.0164 ft), in accordance with The Netherlands Organization for Applied Scientific Research (TNO Yellow Book), 1997 [18], recommendations.

$$A_{max\,pf,n} = \frac{mass_{avail,n}}{C_{18} \cdot frac_{ro} \cdot \rho_l} \quad (3.132)$$

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

$$A_{pf,n} = \min[A_{burn\,pf,n}, A_{max\,pf,n}] \quad (3.133)$$

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<sup>2</sup> may be appropriate for all but the largest releases. From this area, the radius of the pool fire can be determined:

$$R_{pf,n} = \sqrt{\frac{A_{pf,n}}{\pi}} \quad (3.134)$$

#### 5.8.2.4 Flame Length and Flame Tilt

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

$$L_{pf,n} = 110 \cdot R_{pf,n} \left[ \frac{\dot{m}_b}{\rho_{atm} \sqrt{2 \cdot g \cdot R_{pf,n}}} \right]^{0.67} u_s^{-0.21} \quad (3.135)$$

The non-dimensional 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,  $\beta$ , is often quoted in the range of 0.15 to 0.35. A conservative value of 0.35 can be chosen. Therefore:

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

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:

$$I_{th_n}^{pool} = \tau_{atm,n} \cdot Q_{rad_n}^{pool} \cdot F_{cyl_n} \quad (3.139)$$

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]:

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

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

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

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:

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

The vertical view factor can be calculated as follows:

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

The horizontal view factor can be calculated as follows:

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

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

$$X = \frac{L_{pf,n}}{R_{pf,n}} \quad (3.145)$$

$$Y = \frac{xS_n}{R_{pf,n}} \quad (3.146)$$

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

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

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

### 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 12.6 kW/m<sup>2</sup> (4,000 Btu/hr-ft<sup>2</sup>) is used for serious personnel injury. The maximum permissible radiation for component damage is 37.8 kW/m<sup>2</sup> (12,000 Btu/hr-ft<sup>2</sup>).

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,  $xS_{cmd,n}^{pool}$  and  $xS_{inj,n}^{pool}$ , are determined, Equation (3.150) and Equation (3.151) are used to calculate the pool fire consequence areas.

$$CA_{f,cmd,n}^{pool} = \pi \cdot \left( xS_{cmd,n}^{pool} + R_{pf,n} \right)^2 \quad (3.150)$$

$$CA_{f,inj,n}^{pool} = \pi \cdot \left( xS_{inj,n}^{pool} + R_{pf,n} \right)^2 \quad (3.151)$$

### 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 <sup>[17]</sup>. 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 12.6 kW/m<sup>2</sup> (4,000 Btu/hr-ft<sup>2</sup>) for personnel and 37.8 kW/m<sup>2</sup> (12,000 Btu/hr-ft<sup>2</sup>) 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,  $\beta$ , is often quoted in the range of 0.15 to 0.35. A conservative value of 0.35 can be chosen. Therefore:

$$Q_{rad_n}^{jet} = C_{14} \cdot \beta \cdot W_n^{jet} \cdot HC_v \quad (3.152)$$

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:

$$Ith_n^{jet} = \tau_{atm,n} \cdot Q_{rad_n}^{jet} \cdot Fp_n \quad (3.153)$$

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

$$Fp_n = \frac{1}{4\pi \cdot xs_n^2} \quad (3.154)$$

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,  $xS_{cmd,n}^{jet}$  and  $xS_{inj,n}^{jet}$ , are determined, [Equation \(3.155\)](#) and [Equation \(3.156\)](#) are used to calculate the jet fire consequence areas.

$$CA_{f,cmd,n}^{jet} = \pi \cdot xS_{cmd,n}^{jet \ 2} \quad (3.155)$$

$$CA_{f,inj,n}^{jet} = \pi \cdot xS_{inj,n}^{jet \ 2} \quad (3.156)$$

## 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 <sup>[17]</sup> 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,  $mass_{fb}$ , is the fraction of the released mass that contains flammable material and can be determined using [Equation \(3.157\)](#).

$$mass_{fb} = mfrac^{flam} \cdot mass_{avail,n} \quad (3.157)$$

The maximum mass available for release,  $mass_{avail,n}$ , 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:

$$Dmax_{fb} = C_{22} \cdot mass_{fb}^{0.333} \quad (3.158)$$

The center height of the fireball is assumed to be:

$$H_{fb} = 0.75 \cdot Dmax_{fb} \quad (3.159)$$

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

$$t_{fb} = C_{23} \cdot mass_{fb}^{0.333} \quad \text{for } mass_{fb} \leq 66,000 \text{ lbs [29,937 kgs]} \quad (3.160)$$

$$t_{fb} = C_{24} \cdot mass_{fb}^{0.167} \quad \text{for } mass_{fb} > 66,000 \text{ lbs [29,937 kgs]} \quad (3.161)$$

### 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,  $\beta_{fb}$ , is often quoted in the range of 0.25 to 0.4; see Equation (3.162).

$$Q_{rad}^{fball} = \frac{C_{14} \cdot \beta_{fb} \cdot mass_{fb} \cdot HC_l}{\pi \cdot Dmax_{fb}^2 \cdot t_{fb}} \quad (3.162)$$

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

$$\beta_{fb} = C_{25} \cdot P_B^{0.32} \quad (3.163)$$

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:

$$I_{th}^{fball} = \tau_{atm} \cdot Q_{rad}^{fball} \cdot F_{sph} \quad (3.164)$$

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

$$F_{sph} = \frac{(Dmax_{fb})^2}{4C_{fb}^2} \quad (3.165)$$

where

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

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,  $xS_{cmd}^{fball}$  and  $xS_{inj}^{fball}$ , are determined, Equation (3.167) and Equation (3.168) are used to calculate the fireball consequence areas.

$$CA_{f.cmd}^{fball} = \pi \cdot (xS_{cmd}^{fball})^2 \quad (3.167)$$

$$CA_{f,inj}^{fball} = \pi \cdot (xS_{inj}^{fball})^2 \quad (3.168)$$

## 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 <sup>[25]</sup> 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,  $\eta$ . 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,  $\eta$ , with a range of between  $0.03 \leq \eta \leq 0.19$  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).

$$W_{TNT} = \frac{\eta \cdot mass_{vce} \cdot HC_s}{HC_{TNT}} \quad (3.169)$$

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 4648 J/kg (2000 Btu/lb).

- 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 curve 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):

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

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

$$\bar{R}_{HS,n} = C_{27} \cdot \frac{xS_n^{vce}}{W_{TNT}^{1/3}} \quad (3.171)$$

#### 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].

$$Pr = -23.8 + 2.92 \cdot \ln[C_{28} \cdot P_{SO,n}] \quad (3.172)$$

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,  $xS_{cmd,n}^{vce}$  and  $xS_{inj,n}^{vce}$ , are determined, Equation (3.173) and Equation (3.174) are used to calculate the VCE consequence areas.

$$CA_{f,cmd,n}^{vce} = \pi \cdot (xS_{cmd,n}^{vce})^2 \quad (3.173)$$

$$CA_{f,inj,n}^{vce} = \pi \cdot (xS_{inj,n}^{vce})^2 \quad (3.174)$$

## 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,  $CA_{inj,n}^{flash}$ , 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,  $CA_{cmd,n}^{flash}$ , is limited to 25 % of the area for serious injury to personnel.

$$CA_{f,cmd,n}^{flash} = 0.25 \cdot CA_{inj,n}^{flash} \quad (3.175)$$

### 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 \(3.177\)](#).

$$CA_{f,cmd,n}^{flam} = \left( p_{pool,n} \cdot CA_{f,cmd,n}^{pool} + p_{jet,n} \cdot CA_{f,cmd,n}^{jet} + p_{fball,n} \cdot CA_{f,cmd,n}^{fball} + \right. \\ \left. p_{vce,n} \cdot CA_{f,cmd,n}^{vce} + p_{flash,n} \cdot CA_{f,cmd,n}^{flash} \right) \quad (3.176)$$

$$CA_{f,inj,n}^{flam} = \left( p_{pool,n} \cdot CA_{f,inj,n}^{pool} + p_{jet,n} \cdot CA_{f,inj,n}^{jet} + p_{fball,n} \cdot CA_{f,inj,n}^{fball} + \right. \\ \left. p_{vce,n} \cdot CA_{f,inj,n}^{vce} + p_{flash,n} \cdot CA_{f,inj,n}^{flash} \right) \quad (3.177)$$

### 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 \(3.178\)](#).

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

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

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

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,  $mfrac^{flam}$ . 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,  $rate_n^{flam}$ , using Equation (3.106). Also calculate the liquid portion,  $rate_{l,n}^{flam}$ , and the vapor portion,  $rate_{v,n}^{flam}$ , 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,  $poi_{l,n}^{amb}$ , using Equation (3.109) and the value of  $rate_{l,n}^{flam}$  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,  $poi_{v,n}^{amb}$ , using Equation (3.110) and the value of  $rate_{v,n}^{flam}$  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,  $poi_l^{ait}$ , and the vapor,  $poi_v^{ait}$ , at the AIT using Equation (3.111) and Equation (3.112).

- 4) Calculate the probability of ignition for the liquid,  $poi_{l,n}$ , and the vapor,  $poi_{v,n}$ , 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,  $poi_{l,n}^{amb}$  and  $poi_{v,n}^{amb}$ , 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,  $poi_{l,n}$ , and the vapor portion of the release,  $poi_{v,n}$ , using Equation (3.128) and Equation (3.129). Use a value for the probability of immediate ignition at the AIT,  $poi^{ait} = 1.0$ .
  - 3) For two-phase releases, calculate the probability of immediate ignition given ignition,  $poi_{2,n}$ , at normal storage temperatures using Equation (3.118) and the flash fraction,  $frac_{fsh}$ , 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  $pvcedi_{l,n}$ ; for a vapor it is  $pvcedi_{v,n}$ .
  - 2) For two-phase releases, calculate the probability of VCE, given delayed ignition,  $pvcedi_{2,n}$ , using Equation (3.119) and the flash fraction,  $frac_{fsh}$  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:

$$ppool_{v,n} = 0.0 \quad (3.180)$$

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

$$pjet_{v,n} = poi_{v,n} \cdot poii_{v,n} \quad (3.181)$$

- 3) Probability of a VCE given a release:

$$pvce_{v,n} = poi_{v,n} \cdot (1 - poii_{v,n}) \cdot (1 - pvcedi_{v,n}) \quad (3.182)$$

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

$$pflash_{v,n} = poi_{v,n} \cdot poii_{v,n} \quad (3.183)$$

- 5) Probability of a fireball:

$$pfball_{v,n} = 0.0 \quad (3.184)$$

- 6) Probability of safe dispersion given a release:

$$psafe_{v,n} = 1 - poi_{v,n} \quad (3.185)$$

- k) STEP 8.11—For each hole size, calculate the component damage consequence area of a pool fire,  $CA_{f,cmd,n}^{pool}$ , and the personnel injury consequence area,  $CA_{f,inj,n}^{pool}$ , 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,  $\dot{m}_b$ , 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,  $Aburn_{pf,n}$ , 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,  $A_{pf,n}$ , using [Equation \(3.133\)](#).

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

- 5) Calculate the radius of the pool fire,  $R_{pf,n}$ , using [Equation \(3.134\)](#) and the length of the pool fire,  $L_{pf,n}$ , using [Equation \(3.135\)](#). Also, calculate the pool flame tilt,  $\theta_{pf,n}$ , using [Equation \(3.137\)](#).
- 6) Calculate the amount of heat radiated from the pool fire,  $Qrad_n^{pool}$ , using [Equation \(3.138\)](#).

- 7) A radiation limit of 12,000 Btu/hr-ft<sup>2</sup> (37.8 kW/m<sup>2</sup>) is used for component damage consequence area. For personnel injury, 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) is used. These radiation limits are used to determine the safe distances,  $xS_{cmd,n}^{pool}$  and  $xS_{inj,n}^{pool}$ , 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,  $\tau_{atm,n}$ , and the view factor,  $F_{cyl,n}$ , 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<sup>2</sup> (37.8 kW/m<sup>2</sup>) for component damage and 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) 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,  $CA_{f,cmd,n}^{pool}$ , and the personnel injury consequence area,  $CA_{f,inj,n}^{pool}$ , using Equation (3.150) and Equation (3.151).
- I) STEP 8.12—For each hole size, calculate the component damage consequence area of a jet fire,  $CA_{l,cmd,n}^{jet}$ , and the personnel injury consequence area,  $CA_{l,inj,n}^{jet}$ , of a jet fire.
- 1) Calculate the amount of heat radiated from the jet fire,  $Q_{rad,n}^{jet}$ , 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<sup>2</sup> (37.8 kW/m<sup>2</sup>) is used for component damage consequence area. For personnel injury, 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) is used. These radiation limits are used to determine the safe distances,  $xS_{cmd,n}^{jet}$  and  $xS_{inj,n}^{jet}$ , 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  $\tau_{atm,n}$ , and the view factor,  $F_{p,n}$ , 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<sup>2</sup> (37.8 kW/m<sup>2</sup>) for component damage and 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) 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,  $CA_{f,cmd,n}^{jet}$ , and the personnel injury consequence area,  $CA_{f,inj,n}^{jet}$  using Equation (3.155) and Equation (3.156).
- m) STEP 8.13—For the rupture case, calculate the component damage consequence area,  $CA_{f,cmd,n}^{fball}$ , and the personnel injury consequence area,  $CA_{f,inj,n}^{fball}$ , 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,  $mfrac^{flam}$ , obtained in STEP 8.1, and the inventory mass available for release,  $mass_{avail,n}$ , determined in STEP 4.7.
  - 2) Calculate the maximum diameter,  $Dmax_{fb}$ , 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,  $Qrad^{fball}$ , using Equation (3.162).
  - 5) For the component damage consequence area, API 581 uses a radiation limit of 12,000 Btu/hr-ft<sup>2</sup> (37.8 kW/m<sup>2</sup>). For personnel injury, 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) is used. These radiation limits are used to determine the safe distances,  $xS_{cmd}^{fball}$  and  $xS_{inj}^{fball}$ , from the fireball using the following four-step iterative procedure.
    - i) Guess at an acceptable distance from the fireball,  $xS^{fball}$ .
    - ii) Calculate the atmospheric transmissivity,  $\tau_{atm}$ , and the spherical view factor,  $F_{sph}$ , using Equation (3.140) and Equation (3.165). Both of these parameters are functions of the distance from the fireball chosen above,  $xS^{fball}$ .
    - iii) Calculate the received thermal heat flux,  $I_{th}^{fball}$ , at the distance chosen using Equation (3.164) and compare it to the acceptable radiation limit 12,000 Btu/hr-ft<sup>2</sup> (37.8 kW/m<sup>2</sup>) for component damage and 4,000 Btu/hr-ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) 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,  $\eta$ , 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,  $xS_{cmd,n}^{vce}$ , accordingly, and repeat the above steps until the probit value is equal to 5.0.
- 5) Calculate the personal injury consequence area,  $CA_{f,inj,n}^{vce}$ , using Equation (3.174).

- o) STEP 8.15—For each of the hole sizes, calculate the component damage consequence area,  $CA_{f,cmd,n}^{flash}$ , and the personnel injury consequence area,  $CA_{f,inj,n}^{flash}$ , 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,  $CA_{f,inj,n}^{flash}$ .
  - 2) The component damage consequence area for the flash fire,  $CA_{f,cmd,n}^{flash}$ , is 25 % of personnel injury consequence area  $CA_{f,inj,n}^{flash}$ , in accordance with [Equation \(3.175\)](#).
- p) STEP 8.16—For each hole size, determine the component damage and personnel injury flammable consequence areas,  $CA_{f,cmd,n}^{flam}$  and  $CA_{f,inj,n}^{flam}$ , 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,  $CA_{f,cmd}^{flam}$ , and personnel injury,  $CA_{f,inj}^{flam}$ , 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<sub>50</sub>;
- 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 non-fatal long-term health issues will arise.

### 5.9.2.2 Probit Analysis

Probit equations <sup>[29]</sup> 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—AEG-3

AEGs 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.

AEGs are published for three levels of exposure—AEG-1, AEG-2, and AEG-3—each one representing increasing levels of danger to the exposed personnel. The most life-threatening level, AEG-3, is used when comparing it against the concentrations as calculated by the cloud dispersion model. The AEG-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 AEG-3, but at or above AEG-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<sub>50</sub>

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<sub>50</sub> 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 AEG 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,  $ld_{max,n}$  listed in [Table 4.7](#).

$$ld_n^{tox} = \min \left[ 3600, \left\{ \frac{mass_n}{W_n} \right\}, \left\{ 60 \cdot ld_{max,n} \right\} \right] \quad (3.186)$$

### 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).

$$ptox_n = psafe_n \quad (3.187)$$

### 5.9.5 Consequences of Releases Containing Multiple Toxic Chemicals

Consequence results for releases of multi-component 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,  $CA_{inj,n}^{tox}$ .

$$CA_{f,inj,n}^{tox} = ptox_n \cdot CA_{f,n}^{cloud} \quad (3.188)$$

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,  $CA_{cmd,n}^{tox}$ , 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).

$$tox_{lim}^{mod} = \frac{tox_{lim}}{molfrac^{tox}} \quad (3.189)$$

For example, a hydrocarbon stream contains 5 mole% H<sub>2</sub>S. H<sub>2</sub>S 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:

$$tox_{lim}^{mod} = \frac{100 \text{ ppm}}{0.05} = 2000 \text{ ppm} \quad (3.190)$$

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).

$$CA_{f,inj}^{tox} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{f,inj,n}^{tox}}{gff_{total}} \right) \quad (3.191)$$

In Equation (3.191), the total GFF is as calculated in STEP 2.2.

### 5.9.8 Calculation of Toxic Consequence Areas

- STEP 9.1—Determine the mole fraction of the release rate that contains a toxic component,  $molefrac^{tox}$ .
- STEP 9.2—Calculate the release duration,  $ld_n^{tox}$ , using Equation (3.186).
- 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.
- STEP 9.4—Determine the modified toxic limit,  $tox_{lim}^{mod}$ , using Equation (3.189).
- 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,  $CA_{f,inj,n}^{tox}$ , 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<sup>[31]</sup> and modified here to convert to an equivalent TNT.

$$W_{TNT} = C_{29} \cdot V_s \cdot \left( \frac{P_s - P_{atm}}{k - 1} \right) \quad (3.192)$$

#### 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,  $xS_{cmd}^{pexp}$ , and personnel injury,  $xS_{inj}^{pexp}$ , from which a consequence area can be calculated per Equation (3.193) and Equation (3.194).

$$CA_{f,cmd}^{pexp} = \pi \cdot (xS_{cmd}^{pexp})^2 \quad \text{for rupture case only} \quad (3.193)$$

$$CA_{f,inj}^{pexp} = \pi \cdot (xS_{inj}^{pexp})^2 \quad \text{for rupture case only} \quad (3.194)$$

### 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 \(3.195\)](#).

$$W_{TNT} = C_{30} \cdot n_v RT_s \cdot \ln \left[ \frac{P_s}{P_{atm}} \right] \quad (3.195)$$

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,  $xS_{cmd}^{bleve}$ , and personnel injury,  $xS_{inj}^{bleve}$ , from which a consequence area can be calculated per [Equation \(3.196\)](#) and [Equation \(3.197\)](#).

$$CA_{f,cmd}^{bleve} = \pi \cdot (xS_{cmd}^{bleve})^2 \quad \text{for rupture case only} \quad (3.196)$$

$$CA_{f,inj}^{bleve} = \pi \cdot (xS_{inj}^{bleve})^2 \quad \text{for rupture case only} \quad (3.197)$$

### 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 \(3.199\)](#).

$$CA_{f,cmd,n}^{nfmt} = pnfnt \cdot \max\left(CA_{f,cmd,n}^{pexp}, CA_{f,cmd,n}^{bleve}\right) \quad (3.198)$$

$$CA_{f,inj,n}^{nfmt} = pnfnt \cdot \max\left(CA_{f,inj,n}^{pexp}, CA_{f,inj,n}^{bleve}, CA_{f,inj,n}^{leak}\right) \quad (3.199)$$

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.

$$CA_{f,cmd}^{nfmt} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{f,cmd,n}^{nfmt}}{gff_{total}} \right) \quad (3.200)$$

$$CA_{f,inj}^{nfmt} = \left( \frac{\sum_{n=1}^4 gff_n \cdot CA_{f,inj,n}^{nfmt}}{gff_{total}} \right) \quad (3.201)$$

### 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,  $CA_{f,inj,n}^{leak}$ , 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,  $CA_{f,cmd}^{pexp}$ , and the personnel injury consequence area,  $CA_{f,inj}^{pexp}$ , 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,  $xS_{cmd}^{bleve}$ , from the BLEVE using the following four-step iterative procedure.
    - i) Guess at an acceptable component damage distance from the BLEVE,  $xS_{cmd}^{bleve}$ .
    - ii) Calculate the Hopkinson-scaled distance,  $\bar{R}_{HS}$ , using Equation (3.171). This parameter is a function of the distance from the BLEVE chosen above,  $xS_{cmd}^{bleve}$ .
    - iii) Calculate the side-on overpressure,  $P_{SO}$ , at the Hopkinson-scaled distance,  $\bar{R}_{HS}$ , using Equation (3.170).
    - iv) Adjust the distance,  $xS_{cmd}^{bleve}$ , 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,  $CA_{f,cmd}^{bleve}$ , 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,  $xS_{inj}^{bleve}$ , from the BLEVE using the following five-step iterative procedure.
    - i) Guess at an acceptable personnel injury distance from the BLEVE,  $xS_{inj}^{bleve}$ .
    - ii) Calculate the Hopkinson-scaled distance,  $\bar{R}_{HS}$ , using Equation (3.171). This parameter is a function of the distance from the BLEVE chosen above,  $xS_{inj}^{bleve}$ .
    - iii) Calculate the side-on overpressure,  $P_{SO}$ , at the Hopkinson-scaled distance,  $\bar{R}_{HS}$ , using Equation (3.170).
    - iv) Calculate the probit value,  $Pr$ , using Equation (3.172).
    - v) Adjust the distance,  $xS_{inj}^{bleve}$ , accordingly, and repeat the above steps until the probit value is equal to 5.0.
  - 7) Calculate the personal injury consequence area,  $CA_{f,inj}^{bleve}$ , 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  $CA_{f,cmd,n}^{nfmt}$ , and personnel injury area is  $CA_{f,inj,n}^{nfmt}$ .
- e) STEP 10.5—Calculate the final, probability weighted nonflammable, nontoxic consequence areas,  $CA_{f,cmd}^{nfmt}$  and  $CA_{f,inj}^{nfmt}$ , 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:

- flammable consequences (see Section 5.8);
- toxic consequences (see Section 5.9);
- 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.

$$CA_{f,cmd} = CA_{f,cmd}^{flam} + \max \left[ psafe \cdot CA_{f,cmd}^{safe}, CA_{f,cmd}^{nfmt} \right] \quad (3.202)$$

### 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.

$$CA_{f,inj} = CA_{f,inj}^{flam} + \max \left[ psafe \cdot CA_{f,inj}^{safe}, CA_{f,inj}^{tox}, CA_{f,inj}^{nfmt} \right] \quad (3.203)$$

### 5.11.4 Final Consequence Area

The final consequence area is:

$$CA_f = \max \left[ CA_{f,cmd}, CA_{f,inj} \right] \quad (3.204)$$

### 5.11.5 Calculation for Final Consequence Area

- a) STEP 11.1—Calculate the final component damage consequence area,  $CA_{f,cmd}$ , using Equation (3.202).
- b) STEP 11.2—Calculate the final personnel injury consequence area,  $CA_{f,inj}$ , using Equation (3.203).

## 5.12 Determine the FC

### 5.12.1 General

The FC is determined accordance with the Level 1 consequence analysis; see Section 4.12.7.

### 5.12.2 Calculation of FC

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.

$Aburn_{pf,n}$	is the pool fire area based on burning rate, associated with the $n^{\text{th}}$ release hole size, $\text{ft}^2$ ( $\text{m}^2$ )
$AIT$	is the autoignition temperature of the released fluid, $^{\circ}\text{R}$ (K)
$Amax_{pf,n}$	is the maximum pool fire area based on a pool depth of 0.0164 ft (5 mm), associated with the $n^{\text{th}}$ release hole size, $\text{ft}^2$ ( $\text{m}^2$ )
$A_{pf,n}$	is the pool fire surface area, associated with the $n^{\text{th}}$ release hole size, $\text{ft}^2$ ( $\text{m}^2$ )
$BP_s$	is the boiling point temperature of the stored fluid at normal operating conditions, $^{\circ}\text{R}$ (K)
$CA_f$	is the final consequence area, $\text{ft}^2$ ( $\text{m}^2$ )
$CA_{f,cmd}^{bleve}$	is the component damage consequence area for a BLEVE associated with the rupture case, $\text{ft}^2$ ( $\text{m}^2$ )
$CA_{f,inj}^{bleve}$	is the personnel injury consequence area for a BLEVE associated with the rupture case, $\text{ft}^2$ ( $\text{m}^2$ )
$CA_{f,n}^{cloud}$	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 $n^{\text{th}}$ release hole size, $\text{ft}^2$ ( $\text{m}^2$ )

$CA_{f,cmd}^{fball}$	is the component damage consequence area for a fireball associated with the rupture case, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{fball}$	is the personnel injury consequence area for a fireball associated with the rupture case, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}^{flam}$	is the final overall component damage flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{flam}$	is the component damage flammable consequence area associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{flam}$	is the final overall personnel injury flammable consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{flam}$	is the personnel injury flammable consequence area associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{flash}$	is the component damage consequence area for a flash fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{flash}$	is the personnel injury consequence area for a flash fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{jet}$	is the component damage consequence area for a jet fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{jet}$	is the personnel injury consequence area for a jet fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{leak}$	is the personnel injury nonflammable, nontoxic consequence area for steam or acid leaks, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}^{nfmt}$	is the final probability weighted component damage consequence area for nonflammable, nontoxic releases, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{nfmt}$	is the final probability weighted personnel injury consequence area for nonflammable, nontoxic releases, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{nfmt}$	is the personnel injury nonflammable, nontoxic consequence area, associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd}^{pexp}$	is the component damage consequence area for a physical explosion associated with the rupture case only, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{pexp}$	is the personnel injury consequence area for a physical explosion associated with the rupture case only, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{pool}$	is the component damage consequence area for a pool fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )

$CA_{f,inj,n}^{pool}$	is the personnel injury consequence area for a pool fire associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{safe}$	is the component damage consequence area for a safe release associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{safe}$	is the personnel injury consequence area for a safe release associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj}^{tox}$	is the final overall personnel injury toxic consequence area, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{tox}$	is the personnel injury toxic consequence area associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,cmd,n}^{vce}$	is the component damage consequence area for a VCE associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$CA_{f,inj,n}^{vce}$	is the personnel injury consequence area for a VCE associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$C_{fb}$	is the distance from the center of the fireball to the target, ft (m)
$Cp_l$	is the specific heat of the pool liquid, J/kg-K (Btu/lb-°R)
$Dmax_{fb}$	is the maximum diameter of the fireball, ft (m)
$erate_n$	is the liquid pool mass evaporation rate associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$fact_{di}$	is the release magnitude reduction factor, based on the detection and isolations systems present in the unit
$Fcyl_n$	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 $n^{\text{th}}$ release hole size, unitless
$Fp_n$	is the radiation view factor for a point source associated with the $n^{\text{th}}$ release hole size, ft <sup>2</sup> (m <sup>2</sup> )
$frac_{fsh}$	is the mass fraction of the stored fluid that flashes to vapor upon release to the atmosphere
$frac_l$	is the mass fraction liquid of the stored fluid under storage conditions
$frac_{mole,i}$	is the mole fractions for the $i^{\text{th}}$ component in the fluid mixture
$frac_{ro}$	is the rainout mass fraction

$frac_v$	is the mass fraction vapor of the stored fluid under storage conditions
$Fsph$	is the view factor for a spherical shape, unitless
$Fv_n$	is the vertical radiation view factor for a cylindrical shape associated with the $n^{\text{th}}$ release hole size, unitless
$g$	is the acceleration due to gravity on earth at sea level = 32.2 ft/s <sup>2</sup> (9.81 m/s <sup>2</sup> )
$g_c$	is the gravitational constant = $1.0(kg - m)/(N - s^2) [32.2(lb_m - ft)/(lb_f - s^2)]$
$gff_n$	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
$H_{fb}$	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 $\approx$ 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 <sup>2</sup> (W/m <sup>2</sup> )
$Ith_n^{jet}$	is the radiant heat flux received at a distant receiver location from a jet fire associated with the $n^{\text{th}}$ release hole size, Btu/hr-ft <sup>2</sup> (W/m <sup>2</sup> )
$Ith_n^{pool}$	is the radiant heat flux received at a distant receiver location from a pool fire associated with the $n^{\text{th}}$ release hole size, Btu/hr-ft <sup>2</sup> (W/m <sup>2</sup> )
$k$	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 <sup>2</sup> (W/m <sup>2</sup> )
$ld_{max,n}$	is the maximum leak duration associated with the $n^{\text{th}}$ 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 $n^{\text{th}}$ 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 $n^{\text{th}}$ release hole size, seconds

$L_{pf,n}$	is the pool fire flame length, associated with the $n^{\text{th}}$ release hole size, ft (m)
$LFL$	is the lower flammability limit for the fluid
$\dot{m}_b$	is the burning flux rate of a pool fire, lb/ft <sup>2</sup> -s (kg/m <sup>2</sup> -s)
$\dot{m}_{b,i}$	is the burning flux rate of a pool fire for the $i^{\text{th}}$ component in the fluid mixture in the pool fire, lb/ft <sup>2</sup> -s (kg/m <sup>2</sup> -s)
$mass_{avail,n}$	is the available mass for release for each of the release hole sizes selected, associated with the $n^{\text{th}}$ release hole size, lb (kg)
$mass_{fb}$	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
$molfrac^{tox}$	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)
$pfbal_n$	is the probability of a fireball given a release associated with the $n^{\text{th}}$ release hole size
$pfbal_{v,n}$	is the probability of a fireball given a vapor release associated with the $n^{\text{th}}$ 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 $n^{\text{th}}$ 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 $n^{\text{th}}$ release hole size
$pflash_n$	is the probability of a flash fire given a release associated with the $n^{\text{th}}$ release hole size
$pflash_{v,n}$	is the probability of a flash fire given a vapor release associated with the $n^{\text{th}}$ release hole size
$pjet_n$	is the probability of a jet fire given a release associated with the $n^{\text{th}}$ release hole size

$p_{jet_{v,n}}$	is the probability of a jet fire given a vapor release associated with the $n^{\text{th}}$ release hole size
$p_{nfn_{n}}$	is the probability of nonflammable, nontoxic event given a release associated with the $n^{\text{th}}$ hole size
$poi$	is the probability of ignition given a release
$poi_t^{ait}$	is the maximum probability of ignition for a liquid release at or above the $AIT$
$poi_v^{ait}$	is the maximum probability of ignition for a vapor release at or above the $AIT$
$poi_{l,n}^{amb}$	is the probability of ignition given a liquid release at ambient temperature associated with the $n^{\text{th}}$ release hole size
$poi_{v,n}^{amb}$	is the probability of ignition given a vapor release at ambient temperature associated with the $n^{\text{th}}$ release hole size
$poi_{l,n}$	is the probability of ignition given a liquid release associated with the $n^{\text{th}}$ release hole size
$poi_{v,n}$	is the probability of ignition given a vapor release associated with the $n^{\text{th}}$ release hole size
$poi_{2,n}$	is the probability of ignition given a two-phase release associated with the $n^{\text{th}}$ release hole size
$poi_i$	is the probability of immediate ignition given ignition
$poi_t^{ait}$	is the probability of immediate ignition given ignition if the fluid were to be released at or above its $AIT$ , assumed = 1.0
$poi_{l,n}^{amb}$	is the probability of immediate ignition given ignition if a liquid were to be released at ambient temperature associated with the $n^{\text{th}}$ release hole size
$poi_{v,n}^{amb}$	is the probability of immediate ignition given ignition if a vapor were to be released at ambient temperature associated with the $n^{\text{th}}$ release hole size
$poi_{l,n}$	is the probability of immediate ignition given ignition of a liquid release associated with the $n^{\text{th}}$ release hole size
$poi_{v,n}$	is the probability of immediate ignition given ignition of a vapor release associated with the $n^{\text{th}}$ release hole size
$poi_{2,n}$	is the probability of immediate ignition given ignition of a two-phase release associated with the $n^{\text{th}}$ release hole size
$ppool_{l,n}$	is the probability of a pool fire given a release of a flammable liquid associated with the $n^{\text{th}}$ release hole size

$ppool_n$	is the probability of a pool fire given a release associated with the $n^{\text{th}}$ release hole size
$ppool_{v,n}$	is the probability of a pool fire given a release of a flammable vapor associated with the $n^{\text{th}}$ release hole size
$psafe_n$	is the probability of a safe release given a release associated with the $n^{\text{th}}$ release hole size
$psafe_{v,n}$	is the probability of a safe release given a vapor release associated with the $n^{\text{th}}$ 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 $n^{\text{th}}$ release hole size
$ptox_n$	is the probability of a toxic release given a release associated with the $n^{\text{th}}$ release hole size
$pvce_n$	is the probability of a VCE given a release associated with the $n^{\text{th}}$ release hole size
$pvce_{l,n}$	is the probability of a VCE given a release of a flammable vapor associated with the $n^{\text{th}}$ release hole size
$pvce_{v,n}$	is the probability of a VCE given a vapor release associated with the $n^{\text{th}}$ release hole size
$pvcedi$	is the probability of VCE given a delayed ignition
$pvcedi_{l,n}$	is the probability of VCE given a delayed ignition of a release of a flammable liquid associated with the $n^{\text{th}}$ release hole size
$pvcedi_{v,n}$	is the probability of VCE given a delayed ignition of a release of a flammable vapor associated with the $n^{\text{th}}$ release hole size
$P_{atm}$	is the atmospheric pressure, psia (kPa)
$P_{b,g}$	is the bubble point pressure of the released fluid at the ground temperature, psia (kPa)
$P_B$	is the component or equipment burst pressure, 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 $n^{\text{th}}$ 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)

$Q_{rad}^{fball}$	is the total energy flux radiated from a fireball, Btu/hr-ft <sup>2</sup> (W/m <sup>2</sup> )
$Q_{rad}_n^{jet}$	is the total energy radiated from a jet fire associated with the $n^{\text{th}}$ release hole size, Btu/hr (W)
$Q_{rad}_n^{pool}$	is the total energy flux radiated from a pool fire associated with the $n^{\text{th}}$ release hole size, Btu/hr-ft <sup>2</sup> (W/m <sup>2</sup> )
$r_{p,n}$	is the pool radius, calculated for each of the $n$ release hole sizes selected, ft (m)
$R$	is the universal gas constant = 1545 ft-lb/(lb-mol-°R) [8314 J/(kg-mol-K)]
$R_{pf,n}$	is the pool fire radius, calculated for each of the $n$ release hole sizes selected, ft (m)
$RH$	is the atmospheric relative humidity, %
$rate_{l,n}^{flam}$	is the flammable liquid portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$rate_n^{flam}$	is the flammable portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$rate_{v,n}^{flam}$	is the flammable vapor portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$rate_n$	is the adjusted or mitigated discharge rate used in the consequence calculation associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$rate_n^{tox}$	is the toxic portion of the adjusted or mitigated discharge rate used in the consequence calculation associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$\bar{R}_{HS,n}$	is the Hopkinson's scaled distance used in the blast calculations associated with the $n^{\text{th}}$ release hole size, lb/ft <sup>1/3</sup> (m/kg <sup>1/3</sup> )
$SC_f$	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
$t_{fb}$	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.
$tox_{lim}^{mod}$	is the modified toxic exposure limit to account for cloud modeling of mixtures, ppm
$T_{atm}$	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)
$u_{s,n}$	is the non-dimensional wind speed associated with the $n^{\text{th}}$ release hole size, unitless
$u_w$	is the wind speed measured at 6 ft off of grade, ft/s (m/s)
$UFL$	is the upper flammability limit for the fluid
$\dot{V}_{p,n}$	is the volumetric vapor rate leaving the pool surface associated with the $n^{\text{th}}$ release hole size, $\text{m}^3/\text{s}$ ( $\text{ft}^3/\text{s}$ )
$V_s$	is the equipment stored vapor volume, $\text{ft}^3$ ( $\text{m}^3$ )
$W_n^{jet}$	is the portion of the release rate that forms a jet associated with the $n^{\text{th}}$ release hole size, lb/s (kg/s)
$W_n$	is the theoretical release rate associated with the $n^{\text{th}}$ 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 $n^{\text{th}}$ 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)
$xS_{cmd}^{bleve}$	is the safe distance from a BLEVE for component damage associated with the rupture case, ft (m)
$xS_{inj}^{bleve}$	is the safe distance from a BLEVE for personnel injury associated with the rupture case, ft (m)
$xS^{fball}$	is the safe distance from the flame surface of a fireball, ft (m)
$xS_{cmd}^{fball}$	is the safe distance from a fireball for component damage associated with the rupture case, ft (m)
$xS_{inj}^{fball}$	is the safe distance from a fireball for personnel injury associated with the rupture case, ft (m)

$xS_{cmd,n}^{jet}$	is the safe distance from the jet fire flame surface for component damage associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_{inj,n}^{jet}$	is the safe distance from the jet fire flame surface for personnel injury associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_n^{jet}$	is the safe distance from the jet fire flame surface associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_n$	is the safe distance from the flame surface to the target location associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_{cmd}^{pexp}$	is the safe distance from a physical explosion for component damage associated with the rupture case, ft (m)
$xS_{inj}^{pexp}$	is the safe distance from a physical explosion for personnel injury associated with the rupture case, ft (m)
$xS_{cmd,n}^{pool}$	is the safe distance from the pool fire flame surface for component damage associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_{inj,n}^{pool}$	is the safe distance from the pool fire flame surface for personnel injury associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_n^{pool}$	is the safe distance from the pool fire flame surface associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_{cmd,n}^{vce}$	is the safe distance from the VCE for component damage associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_{inj,n}^{vce}$	is the safe distance from the VCE for personnel injury associated with the $n^{\text{th}}$ release hole size, ft (m)
$xS_n^{vce}$	is the safe distance from the VCE associated with the $n^{\text{th}}$ release hole size, ft (m)
$X_{surf}$	is the surface roughness factor, unitless
$\alpha_{surf}$	is the thermal diffusivity of the surface under the liquid pool, ft <sup>2</sup> /s (m <sup>2</sup> /s)
$\beta$	is the fraction of combustion power radiated from a flame
$\beta_{fb}$	is the fraction of combustion power radiated from a fireball
$\Delta H_v$	is the latent heat of vaporization of the liquid in the pool, Btu/lb (J/kg)
$\eta$	is the explosion yield factor, unitless
$\rho_{atm}$	is the atmospheric air density, lb/ft <sup>3</sup> (kg/m <sup>3</sup> )

- $\rho_l$  is the liquid density at storage or normal operating conditions, lb/ft<sup>3</sup> (kg/m<sup>3</sup>)
- $\rho_v$  is the vapor density at storage or normal operating conditions, lb/ft<sup>3</sup> (kg/m<sup>3</sup>)
- $\theta_{pf,n}$  is the pool fire flame tilt associated with the  $n^{\text{th}}$  release hole size, radians
- $\tau_{atm}$  is the atmospheric transmissivity, unitless
- $\tau_{atm,n}$  is the atmospheric transmissivity associated with the  $n^{\text{th}}$  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.	<ol style="list-style-type: none"> <li>1. Determine pool fire size</li> <li>2. Calculate burning rate</li> <li>3. Calculate flame length and tilt</li> <li>4. Determine radiant energy emitted</li> <li>5. Determine energy received at distant points (need view factor and atmospheric transmissivity)</li> <li>6. Calculate safe distance</li> </ol>
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.	<ol style="list-style-type: none"> <li>1. Calculate flame length</li> <li>2. Determine radiant energy emitted</li> <li>3. Determine energy received at distant points (need view factor and atmospheric transmissivity)</li> <li>4. Calculate safe distance</li> </ol>
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.	<ol style="list-style-type: none"> <li>1. Determine available flammable mass</li> <li>2. Determine fireball diameter, height and duration</li> <li>3. Determine radiant energy emitted</li> <li>4. Determine energy received at distant points (need view factor and atmospheric transmissivity)</li> <li>5. Calculate safe distance</li> </ol>
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.	<ol style="list-style-type: none"> <li>1. Determine if cloud source is continuous (plume) or instantaneous (puff)</li> <li>2. Utilize cloud dispersion model to determine the grade level area of flammable material (greater than LFL) that is in the source cloud</li> </ol>
Vapor cloud explosions [5], [6], [7], [17], [18], [21], [22], [4]		<ol style="list-style-type: none"> <li>1. Determine if cloud source is continuous (plume) or instantaneous (puff)</li> <li>2. Utilize cloud dispersion model to determine the amount of flammable material (between LFL and UFL) that is in the source cloud</li> <li>3. Determine equivalent amount of TNT</li> <li>4. Calculate overpressure as a function of distance</li> <li>5. Calculate safe distance</li> </ol>
BLEVEs [17], [18], [26]	Occur upon rupture of a vessel containing a superheated but pressurized liquid that flashes to vapor upon release to atmosphere	<ol style="list-style-type: none"> <li>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</li> <li>2. Calculate overpressure as a function of distance</li> <li>3. Calculate safe distance</li> </ol>
Physical explosions [17], [18], [33], [30]	Occur upon rupture of a vessel containing a pressurized flammable or nonflammable vapor	<ol style="list-style-type: none"> <li>1. Determine equivalent amount of TNT that is a function of the storage pressure and volume of vapor</li> <li>2. Calculate overpressure as a function of distance</li> <li>3. Calculate safe distance</li> </ol>
Toxic releases	Occurs upon release of toxic fluid to the atmosphere through a hole or due to a rupture	<ol style="list-style-type: none"> <li>1. Determine if cloud source is continuous (plume) or instantaneous (puff)</li> <li>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</li> </ol>

**Table 5.2—Surface Interaction Parameters with Liquid Pools**

Surface	Thermal Conductivity, $k_{surf}$ (Btu/hr-ft-°R)	Thermal Diffusivity, $\alpha_{surf}$ (ft <sup>2</sup> /s)	Surface Roughness, $X_{surf}$ (unitless)
Concrete (Note 1)	0.53	$4.48 \times 10^{-6}$	1.0
Soil (average)	0.56	$4.94 \times 10^{-6}$	3.0
Soil (sandy, dry)	0.15	$2.13 \times 10^{-6}$	3.0
Soil (moist, 8 % water, sandy)	0.34	$3.62 \times 10^{-6}$	3.0

NOTE 1 Use as default.  
NOTE 2 Cremer and Warner Ltd. <sup>[11]</sup>.

**Table 5.2M—Surface Interaction Parameters with Liquid Pools**

Surface	Thermal Conductivity, $k_{surf}$ (W/m-K)	Thermal Diffusivity, $\alpha_{surf}$ (m <sup>2</sup> /s)	Surface Roughness, $X_{surf}$ (unitless)
Concrete (Note 1)	0.92	$4.16 \times 10^{-7}$	1.0
Soil (average)	0.96	$4.59 \times 10^{-7}$	3.0
Soil (sandy, dry)	0.26	$1.98 \times 10^{-7}$	3.0
Soil (moist, 8 % water, sandy)	0.59	$3.36 \times 10^{-7}$	3.0

NOTE 1 Use as default.  
NOTE 2 Cremer and Warner Ltd. <sup>[11]</sup>.

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 $poi_n^{amb}$	At AIT $poi_n^{ait}$	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

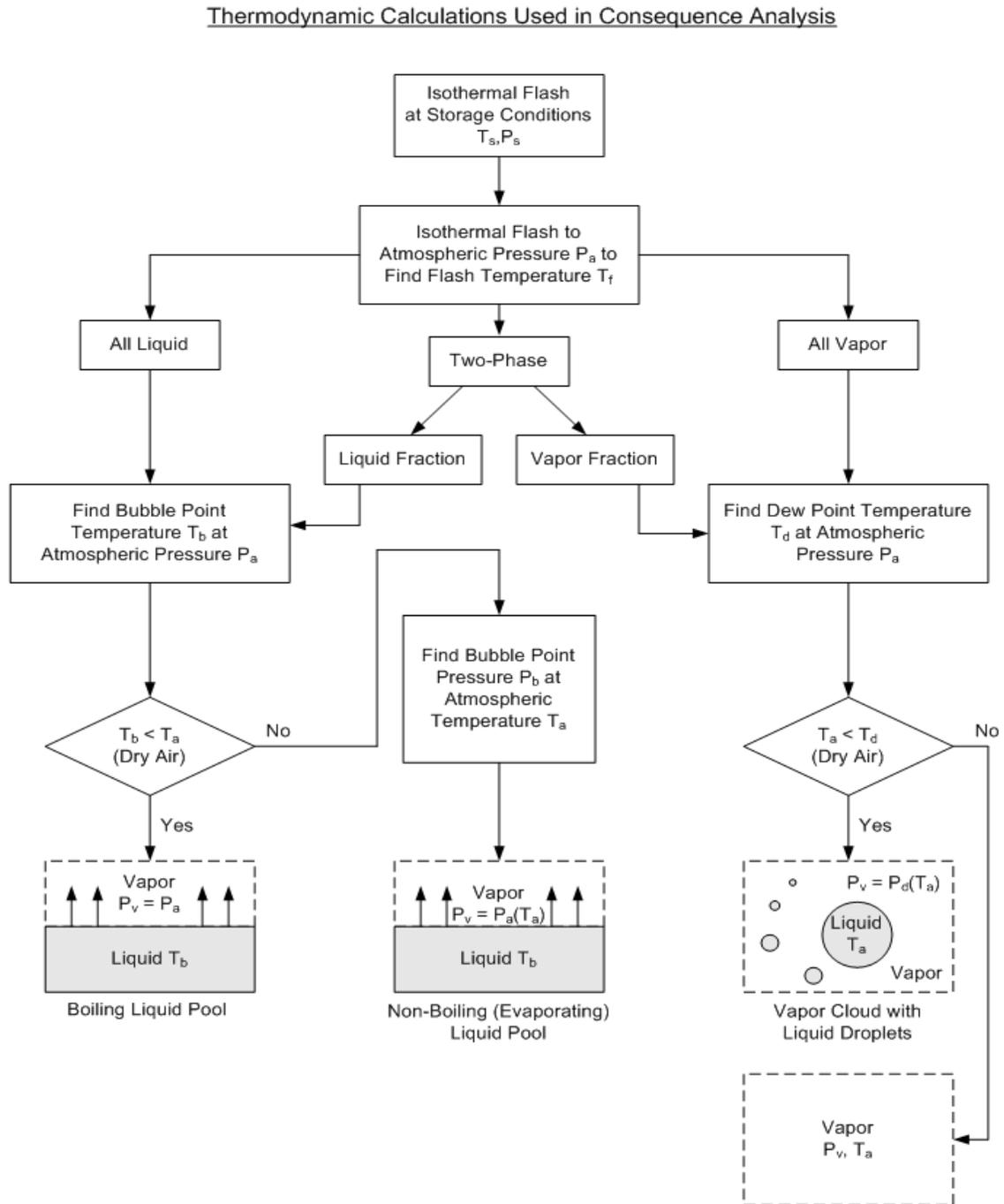


Figure 5.1—Source Term Modeling—Thermodynamic Modeling

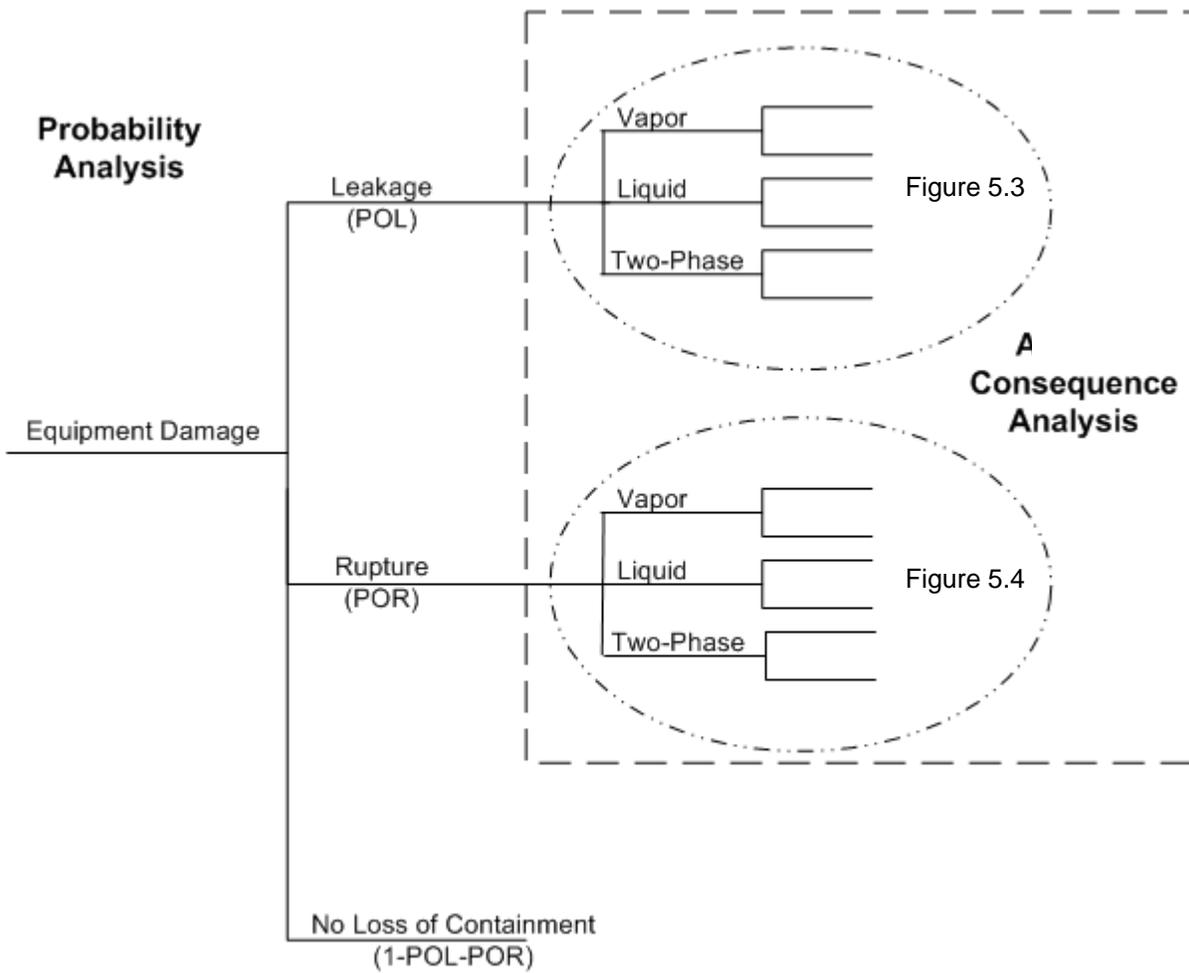
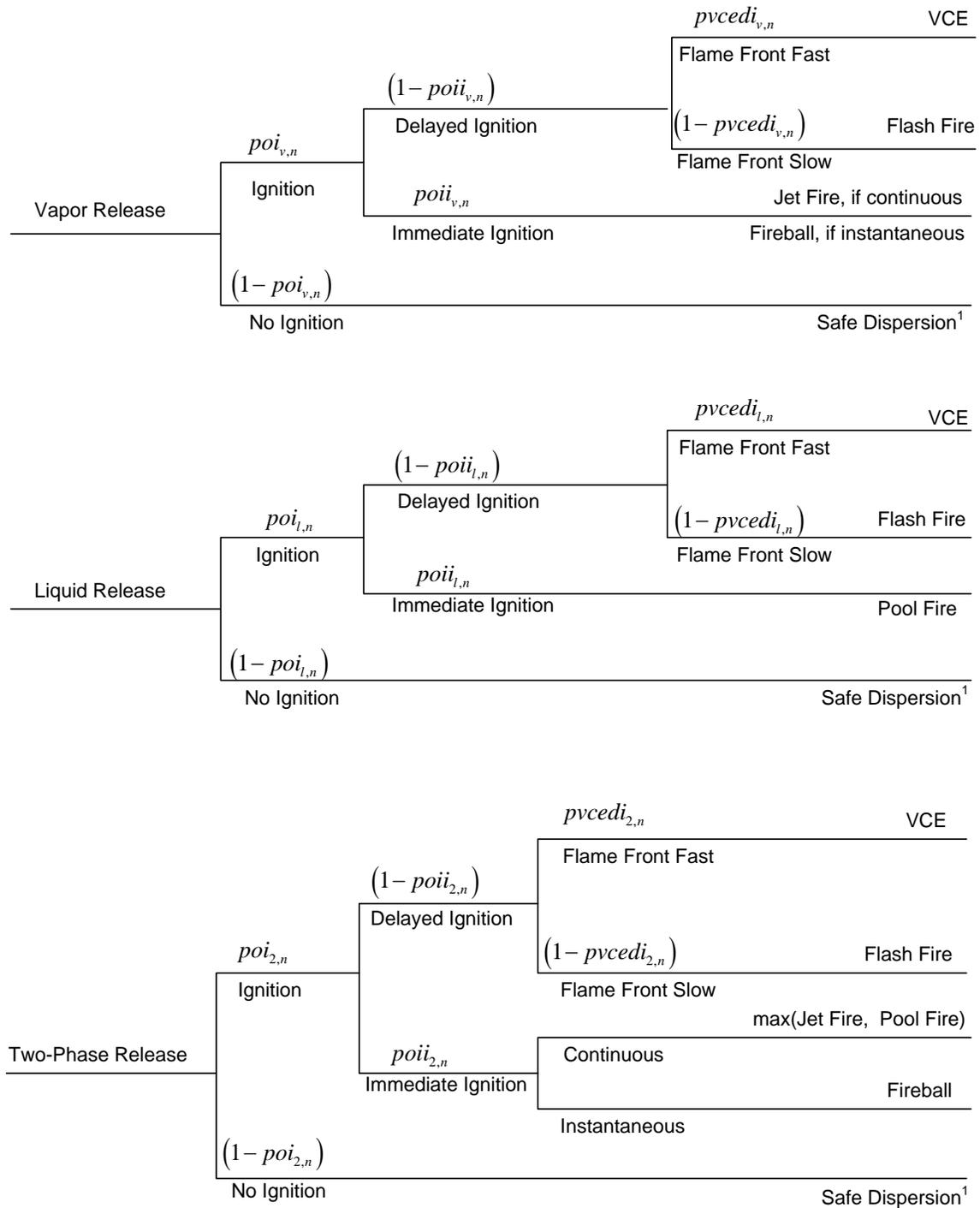
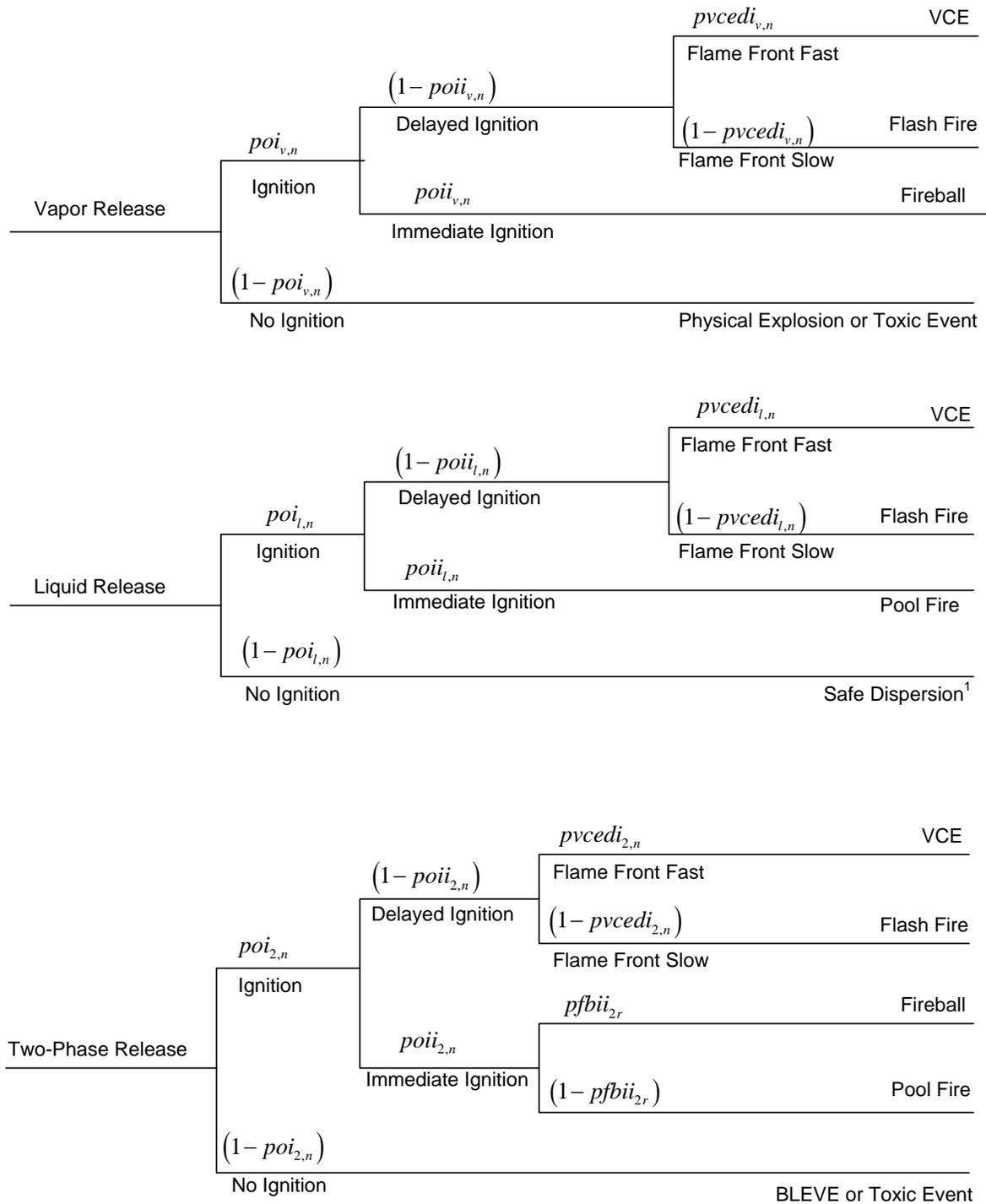


Figure 5.2—Overall Event Tree



<sup>1</sup> 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**



<sup>1</sup> 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**

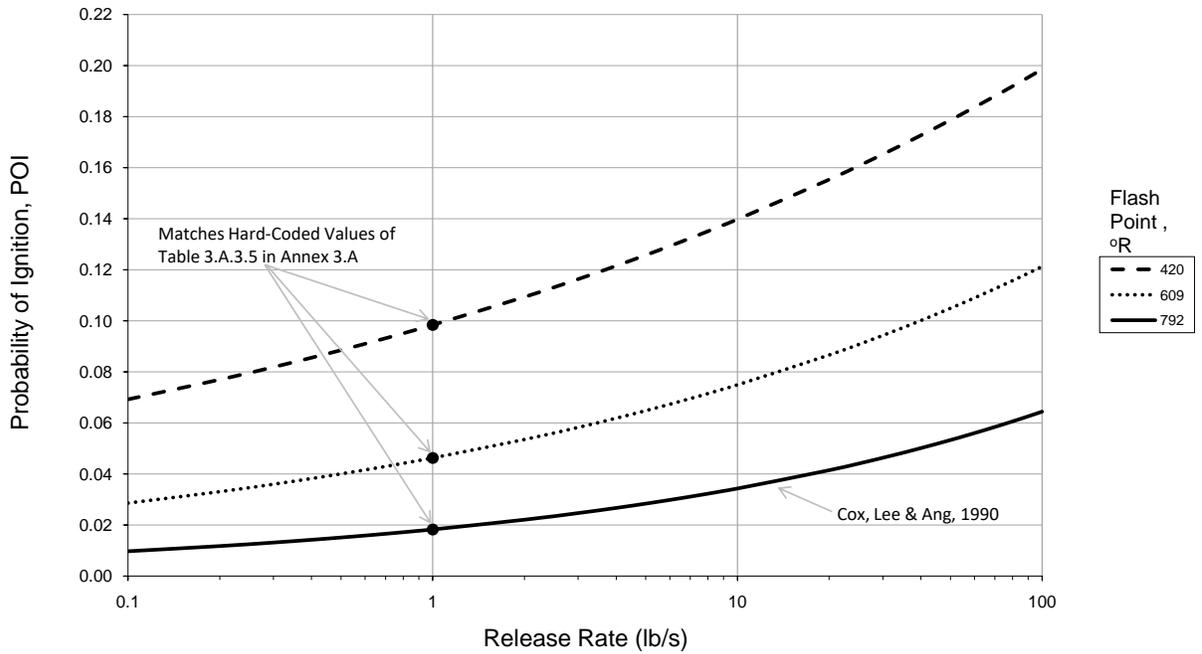


Figure 5.5—Probability of Ignition for Liquids (U.S. Customary Units)

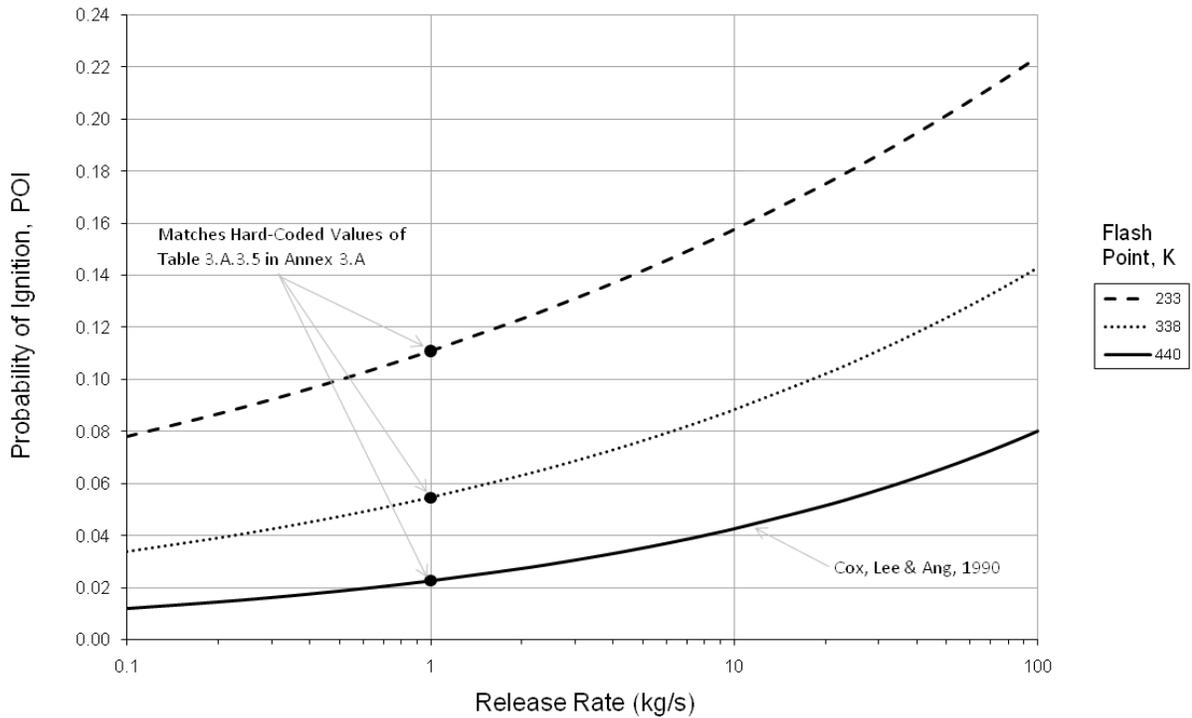
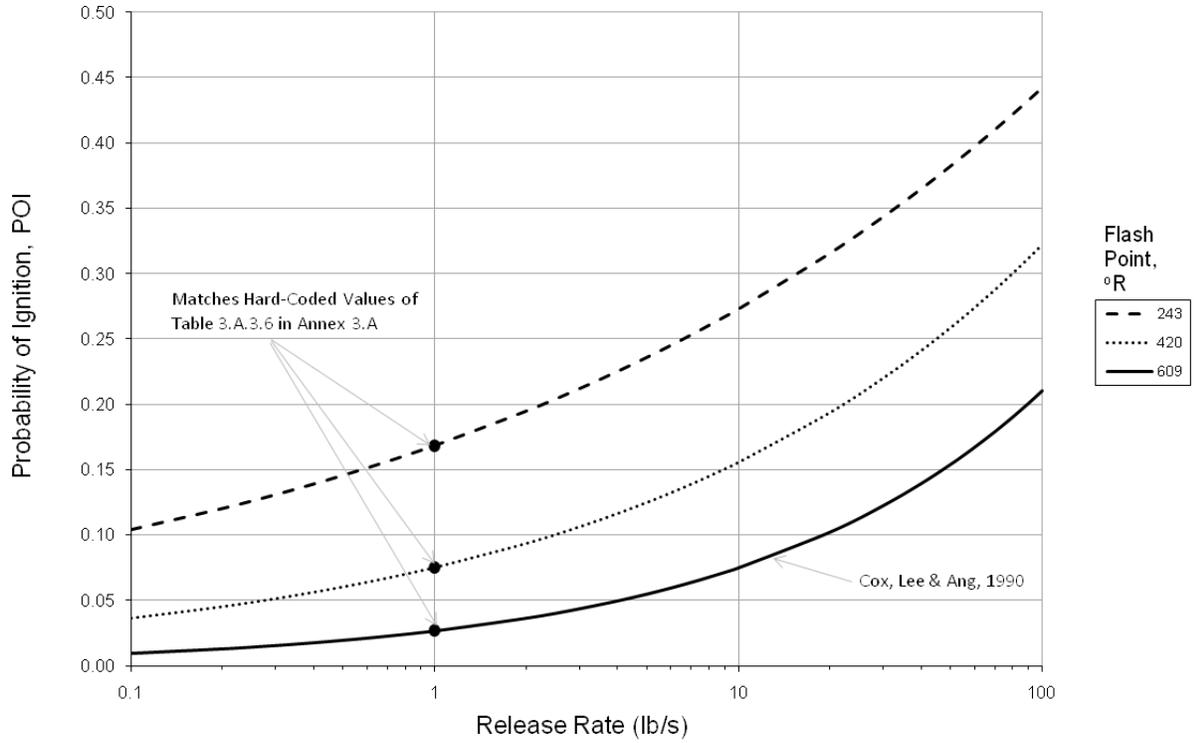
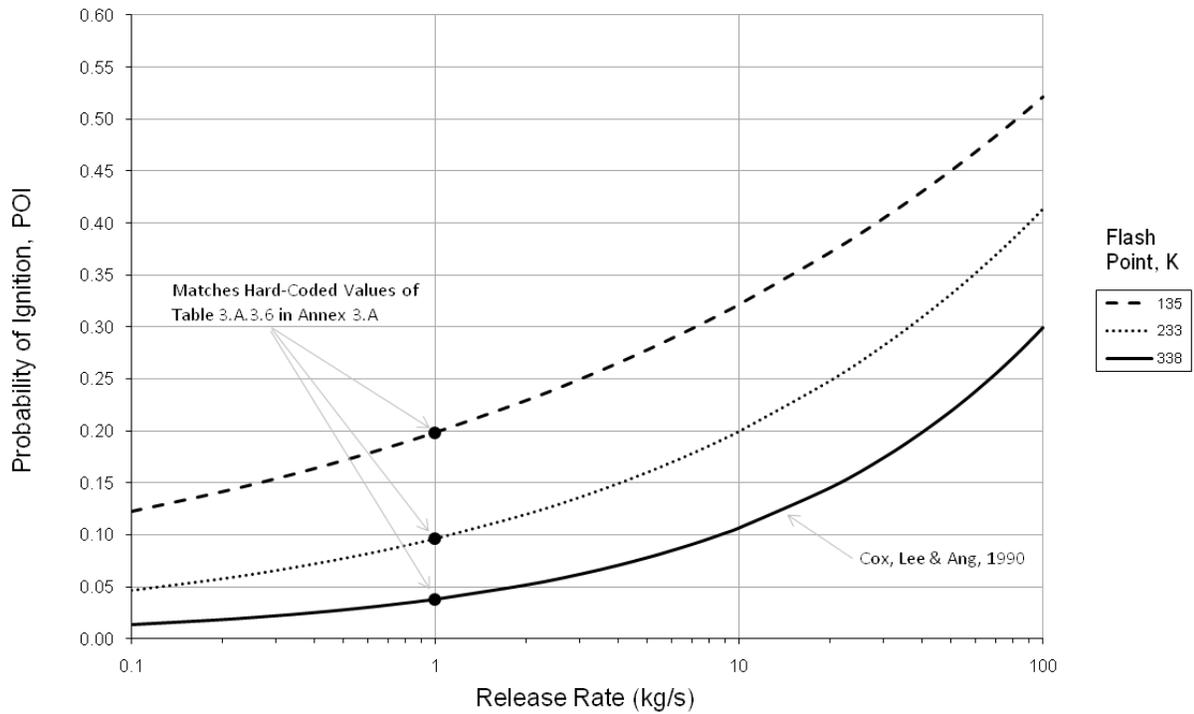


Figure 5.5M—Probability of Ignition for Liquids (Metric Units)



**Figure 5.6—Probability of Ignition for Vapors (U.S. Customary Units)**



**Figure 5.6M—Probability of Ignition for Vapors (Metric Units)**