Risk-Based Inspection Methodology
Part 3—Consequence of Failure Methodology
Annex 3.A Contents

Risk-Based Inspection Methodology
Part 3—Consequence of Failure Methodology
Annex 3.A—Basis for Consequence Methodology

3.A.1 General

The consequence analysis is performed to aid in establishing a relative ranking of equipment items on the basis of risk. The consequence methodologies presented in Part 3 of this document are intended as simplified methods for establishing relative priorities for inspection programs. If more accurate consequence estimates are needed, the analyst should refer to more rigorous analysis techniques, such as those used in quantitative risk assessments.

This Annex provides background and supplemental information to the specific procedures for conducting the consequence analysis provided in Part 3.

3.A.2 References

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

API Recommended Practice 581, *Risk-Based Inspection Methodology*, *Part 3—Consequence of Failure Methodology*, American Petroleum Institute, Washington, DC.

API, *A Survey of API Members' Aboveground Storage Tank Facilities*, 1994.

OFCM, Directory of Atmospheric Transport and Diffusion Consequence Assessment Models (FC-I3-1999), published by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) with the assistance of SCAPA members.

3.A.3 Level 1 Consequence Methodology

3.A.3.1   Representative Fluid and Associated Properties

3.A.3.1.1   Overview

In the Level 1 consequence analysis, a representative fluid that most closely matches the fluid contained in the pressurized system being evaluated is selected from the representative fluids shown in Table 3.A.3.1. Because very few refinery and chemical plant streams are pure materials, the selection of a representative fluid involves making assumptions. The assumptions and the sensitivity of the results are dependent on the type of consequences being evaluated. If assumptions are not valid or the fluid in question is not properly represented by the fluids provided in Table 3.A.3.1, a Level 2 consequence analysis is recommended using the methodology in Part 3, Section 5.

3.A.3.1.2   Choice of Representative Fluids for Mixtures

3.A.3.1.2.1   General

For mixtures, the choice of the representative material should primarily be based on the normal boiling point and the molecular weight, and secondly on the density. If these values are unknown, an estimated property value for the mixture can be calculated using Equation (3.A.1) to assist in representative fluid selection using mole fraction weighting.

$$Property_{mix} = \sum x_i \cdot Property_i \qquad\qquad (3.A.1)$$

It is important to note that the flammable consequence results are not highly sensitive to the exact material selected, provided the molecular weights are similar, because air dispersion properties and heats of combustion are similar for all hydrocarbons with similar molecular weights. This is particularly true for straight chain alkanes, but becomes less true as the materials become less saturated or aromatic. Therefore, caution should be used when applying the Level 1 consequence analysis table lookups to materials (such as aromatics, chlorinated hydrocarbons, etc.) not explicitly defined in the representative fluid groups of Table 3.A.3.1. In such cases, it is recommended that a Level 2 consequence analysis be performed using a fluid property solver to determine the consequences of release.

3.A.3.1.2.2   Example

As an example of determining the various properties of mixtures, by applying Equation (3.A.1), a material containing 10 mol% C_3, 20 mol% C_4, 30 mol% C_5, 30 mol% C_6, and 10 mol% C_7 would have the following average key properties:

a)   MW = 74.8;

b)   AIT = 629.8 °F (322.1 °C) ;

c)   NBP = 102.6 °F (39.2 °C);

d)   density = 38.8 lb/ft^3 (621.5 kg/m^3).

The best selection from the materials in the representative fluids list of Table 3.A.3.1 would be C_5, since the property of first importance is the NBP, and C_5 has a NBP of 97 °F (36 °C), which is lower than the calculated NBP of our example mixture. It is non-conservative to select a representative fluid with a higher NBP than the fluid being considered, e.g. C_6-C_8 when modeling a fluid with a weighted NBP of 210 °F (99 °C).

3.A.3.1.2.3   Example with a Mixture

If a mixture contains inert materials such as CO_2 or water, the choice of representative fluid should be based on the flammable/toxic materials of concern, excluding these materials. This is a conservative assumption that will result in higher COF results, but it is sufficient for risk prioritization. For example, if the material is 93 mol% water and 7 mol% C_{20}, using C_{20} and the corresponding inventory of the hydrocarbon provides a conservative COF. A Level 2 consequence methodology may be used to more accurately model the release.

3.A.3.1.2.4   Toxic Mixture

If the mixture contains toxic components and a toxic consequence analysis is required, a flammable representative fluid is still required, even when the toxic component is a small fraction of the mixture. In this situation, the representative fluid is selected, as described in Section 3.A.3.1.2.1 and Equation (3.A.1).

3.A.3.1.3   Fluid Properties

Representative fluid properties for the Level 1 consequence analysis are provided in Table 3.A.3.1. The properties of fluids (or individual components of mixtures) can be found in standard chemical reference books.

3.A.3.2   Release Hole Size Selection

3.A.3.2.1   Overview

Part 2 of this document defines release hole sizes that represent small, medium, large, and rupture cases for various components or equipment types. This predefined set of release hole sizes are based on failure size distributions observed in piping and pressure vessels. The range of release hole sizes were chosen to address potential on-site and off-site consequences. For on-site effects, small and medium hole size cases usually dominate the risk due to a higher likelihood and potential for on-site consequences.

For off-site effects, medium and large hole size cases dominate risk. To address both on-site and off-site consequences and provide discrimination between components, four release hole sizes per component are used. The following sections discuss the criteria for selecting release hole sizes for specific equipment types.

3.A.3.2.2 Piping

Piping uses the standard four release hole sizes ($1/4$-in., 1-in., 4-in., and rupture), provided that the diameter of the leak is less than or equal to the diameter of the pipe. For example, an NPS 1 pipe has $1/4$-in. and rupture release hole sizes, because the diameter is equal to a 1-in. release hole size. An NPS 4 pipe will have $1/4$-in., 1-in., and rupture release hole sizes because the diameter is equal to a 4-in. hole size.

3.A.3.2.3 Pressure Vessels

The standard four release hole sizes are assumed for all sizes and pressure vessel types. Equipment types included in this general classification are as follows.

a) Vessel—standard pressure vessels such as knock-out (KO) drums, accumulators, and reactors.

b) Filter—standard types of filters and strainers.

c) Column—distillation columns, absorbers, strippers, etc.

d) Heat exchanger shell—shell side of reboilers, condensers, heat exchangers.

e) Heat exchanger tube—tube side of reboilers, condensers, heat exchangers.

f) Fin/fan coolers—fin/fan-type heat exchangers.

3.A.3.2.4 Pumps

Pumps are assumed to have $1/4$-in., 1-in., and 4-in. possible release hole sizes. If the suction line is less than NPS 4, the release hole size should be the full diameter of the suction line. The use of three release hole sizes for pumps is consistent with historical failure data and ruptures are not modeled for pumps.

3.A.3.2.5 Compressors

Both centrifugal and reciprocating compressors use 1-in. and 4-in. (or suction line full bore rupture, whichever is smaller) release hole sizes. The selection of only two release hole sizes is consistent with historical failure data.

3.A.3.3 Fluid Inventory Available for Release

3.A.3.3.1 Overview

The consequence analysis requires an upper-limit for the amount of fluid inventory that is available for release from a component. In theory, the total amount of fluid that can be released is the amount that is held within pressure containing equipment between isolation valves that can be quickly closed. In reality, emergency operations can be performed over time to close manual valves, de-inventory sections, or otherwise stop a leak. In addition, piping restrictions and differences in elevation can serve to slow or stop a leak. The inventory calculation as presented here is used as an upper limit and does not indicate that this amount of fluid would be released in all leak scenarios.

The Level 1 COF methodology is based on a procedure that determines the mass of fluid that could realistically be released in the event of a leak. When a component or equipment type is evaluated, the inventory of the component is combined with inventory from associated equipment that can contribute fluid mass to the leaking component. These items together form an *Inventory Group*. The procedure calculates the release mass as the lesser of the:

a) mass of the component plus a 3-minute release through the hole to a maximum rupture hole size of 8 in. using the calculated release rate;

b) total mass of the inventory group.

A 3-minute release time is based on the dynamics of a large leak scenario, where the leaking component will de-inventory and adjacent equipment provides additional inventory for the leak. Large leaks are detected within a few minutes because of the operational indications that a leak exists. The amount of time that a large leak or rupture will be fed is expected to range from 1 to 5 minutes, with 3 minutes selected as the midpoint of the range.

The 3-minute assumption is not as applicable to small leaks, since it is far less likely that small leaks will persist long enough to empty the inventory from the leaking component and additional inventory from other components in the inventory group. In these situations, plant detection, isolation, and mitigation techniques will limit the duration of the release so that the actual mass released to atmosphere will be significantly less than the available mass as determined above.

Calculating the inventories for equipment and piping can be done using the guidelines provided in Section 3.A.3.3.2 through Section 3.A.3.3.4.

3.A.3.3.2 Liquid Inventory

Liquid inventories for components are calculated using the assumptions presented in Table 3.A.3.2 (normal operating levels should be used, if known). Common equipment and piping groups for liquid systems include:

a) the bottom half of a distillation column, reboiler, and the associated piping;

b) accumulators and liquid outlet piping;

c) feed pipeline;

d) storage tanks and outlet piping;

e) series of heat exchangers and associated piping.

Once the liquid inventory groups are established, the inventory for each component is added to obtain the total group inventory. The liquid inventory determined in this manner is used for each component in the group.

3.A.3.3.3 Vapor Inventory

Common equipment and piping groups for vapor systems include:

a) the top half of the distillation column, overhead piping, and the overhead condenser;

b) vent header line, KO pot, and exit line.

The inventory for vapor systems is governed by the flow or charge rate through the system rather than inventory. A method for determining inventory is to use the flow rate for a specified time (e.g. 60 minutes) to calculate release mass. If this rate is not known, the upstream group liquid inventory can be used since flashing occurs from the liquid system. Using the upstream group liquid inventory will result in a conservative inventory calculation.

3.A.3.3.4 Two-phase Systems

Two-phase systems can be modeled as a liquid or vapor. The conservative assumption is that the release occurs in the lower portion of the component and results in a liquid release. If the upstream system is primarily liquid, only the liquid inventory can be calculated and this limits the conservativeness of modeling a two-phase system as liquid. Conversely, if the upstream inventory is primarily vapor, the vapor inventory can be calculated with an adjustment for the liquid portion.

3.A.3.4   Determination of the Release Type (Instantaneous or Continuous)

Different analytical models and methods are used to estimate the effects of an instantaneous versus a continuous type of release. The COF can differ greatly, depending on the analytical model chosen to represent a release. Therefore, it is very important that a release is properly categorized into one of the two release types.

An example of the importance of proper model selection is a vapor cloud explosion (VCE). A review of historical data on fires and explosions shows that *unconfined* VCEs are more likely to occur for an instantaneous vapor release than a continuous release. An instantaneous release is defined as the release of more than 10,000 lb (4,536 kg) of mass in a short period of time. Using this definition for a continuous release reflects the tendency for mass released in a short period of time, less than 10,000 lb (4,536 kg), to result in a flash fire rather than a VCE.

In the Level 1 consequence procedure, the continuous release model uses a lower probability for a VCE following a leak and the probability of a VCE is a function of release type, not release rate. Level 1 consequence procedure event probabilities are provided in Tables 3.A.3.3 through 3.A.3.6. The Level 2 procedure determines event probabilities as a function of release type and release rate; see Part 3, Section 5.8.1 for determining event probabilities for a Level 2 consequence procedure.

3.A.3.5   Determination of Flammable and Explosive Consequences

3.A.3.5.1   Overview

Consequence is measured in terms of the area affected by the ignition of a flammable release. There are several potential consequence outcomes for any release involving a flammable material; however, a single combined COF is calculated as the probability weighted average of all possible consequence outcomes. The probability of a consequence outcome is different from, and should not be confused with, the probability of failure discussed in Part 2, which involves evaluation of the component damage state that affects equipment integrity.

The probability of a consequence outcome is the probability that a specific physical phenomenon (outcome) will be observed after the release has occurred. Potential release consequence outcomes for flammable materials are:

a)   safe dispersion,

b)   jet fire,

c)   VCE,

d)   flash fire,

e)   fireball,

f)   liquid pool fire.

A description of each event outcome is provided in Part 3, Section 5.8.

3.A.3.5.2   Assumptions and Limitations

The consequence procedure is a simplified approach to a relatively complex discipline. A large number of assumptions are implicit in the procedure in addition to the assumptions that would be part of a more in-depth analysis. This section is intended to highlight a few of the more important assumptions related to the simplified approach, but does not attempt a comprehensive discussion.

a)   The consequence area does not reflect where the damage occurs. Jet and pool fires tend to have damage areas localized around the point of the release, but VCE and flash fires may result in damage far from the release point.

b) The use of a fixed set of conditions for meteorology and release orientations was chosen to represent a conservative basis for the consequence modeling. Meteorological and release orientations are site and situation specific. Quantitative risk assessment calculations allow for customization due to actual site condition since it significantly impacts the results.

c) The probabilities associated with potential release event outcomes can be situation and site specific. Standardized event trees, including ignition probabilities, were chosen to reflect typical conditions expected for the refining and petrochemical industries. Quantitative risk assessment calculations allow for customization of event probabilities since they significantly impact the results.

3.A.3.5.3 Basis for Flammable Consequence Area Tables

3.A.3.5.3.1 General

For representative fluids shown in Table 3.A.3.1, flammable consequences are determined by using the equations presented in lookup tables, allowing the RBI analyst to establish approximate consequence measures using the following information:

a) representative fluid and properties;

b) release type (continuous or instantaneous) and phase of dispersion;

c) release rate or mass, depending on the type of dispersion and the effects of detection, isolation, and mitigation measures.

3.A.3.5.3.2 Predicting Probabilities of Flammable Outcomes

Each flammable event outcome is the result of a chain of events. Event trees, as shown in Figure 3.A.3.1, are used to visually depict the possible chain of events that lead to each outcome. The event trees also are used to show how various individual event probabilities should be combined to calculate the probability for the chain of events.

For a given release type, the two main factors that define the outcome of the release of flammable material are the probability of ignition and the timing of ignition. The three possibilities depicted in the outcome event trees are no ignition, early ignition, and late ignition. The event tree outcome probabilities used in the Level 1 consequence analysis for all release types are presented in Tables 3.A.3.3 through 3.A.3.6 according to the release type and representative fluid. Each row within the tables contains probabilities for the potential outcome, according to the representative fluid. Event trees developed for standard risk analyses were used to develop the relative outcome probabilities. Ignition probabilities were based on previously developed correlations. In general, ignition probabilities are a function of the following fluid parameters.

a) AIT.

b) Flash temperature.

c) NFPA Flammability Index.

d) Flammability range (difference between upper and lower flammability limits).

Fluids that are released well above their AITs will have markedly different ignition probabilities (Table 3.A.3.3 and Table 3.A.3.4) than those released near or below their AITs (Table 3.A.3.5 and Table 3.A.3.6).

3.A.3.5.3.3   Calculating Consequences for Each Outcome

A set of materials were run through a hazards analysis screening to determine the consequence areas for all potential outcomes. The consequence areas were then plotted as a function of release rate or mass to generate graphs. When plotted on a log/log scale, the consequence curves formed straight lines that were fit to an equation relating consequence area to the release rate or mass. The consequence equations are presented in the following generic form:

$$CA_f = x(rate)^y \qquad\qquad for\ a\ continuous\ release \qquad\qquad (3.A.2)$$

$$CA_f = x(mass)^y \qquad\qquad for\ an\ instantaneous\ release \qquad\qquad (3.A.3)$$

The consequence of a release of flammable materials is not strongly dependent on the duration of the release because most fluids reach a steady state size, or footprint, within a short period of time if released into the atmosphere. The only exception to this generalization is a pool fire resulting from the continuous release of a liquid. If flammable liquids are released in a continuous manner, the consequences associated with a pool fire will depend on the duration and the total mass of the release.

3.A.3.5.3.4   Calculation of the Combined Consequence Area

An equation that represents a single consequence area for the combination of possible outcomes can be derived for each of the four combinations of release types and final phase cases. The combined consequence area is determined by a two-step process.

a)   STEP 1—Multiply the consequence area for each outcome [calculated from Equation (3.A.2)] by the associated event tree probabilities (taken from the appropriate Tables 3.A.3.3 through 3.A.3.6). If the impact criterion uses only a portion of the consequence area (for instance, flash fires use only 25 % of the area within the LFL for equipment damage), include this in the probability equation.

b)   STEP 2—Sum all of the consequence-probability products found in STEP 1.

The equation that summarizes the result of the process is as follows:

$$CA_{f,comb} = \sum p_i CA_{f,i} \qquad\qquad (3.A.4)$$

The procedure for combining consequence equations for all the potential outcomes was performed for a set of representative fluids (see Table 3.A.3.1). The results of this exercise are the equations given in Part 3, Tables 4.8 and 4.9.

3.A.3.5.3.5   Consequence Analysis Dispersion Modeling

The computer modeling necessary to determine consequence areas associated with cloud dispersion (flash fires, VCEs, toxic releases) requires specific input regarding meteorological and release conditions. For the Level 1 consequence analysis, meteorological conditions representative of the Gulf Coast annual averages were used. These conditions can also be used when performing a Level 2 consequence analysis. The meteorological input assumptions were as follows:

a)   atmospheric temperature 70 °F (21 °C);

b)   relative humidity 75 %;

c)   wind speed 8 mph (12.9 km/h);

d)   Stability Class D;

e)   surface roughness parameter 1.2 in. (30.5 mm) for typical for processing plants.

Additional constants were used as part of the Level 1 consequence analysis as follows.

a) Initial pressure typical of medium-pressure processing conditions with a refinery 100 psig (0.69 MPa).

b) Initial temperatures representing a range from low-temperature [below autoignition, i.e. 68 °F (20 °C)] to high-temperature (near autoignition) conditions.

c) Range of release hole sizes from 0.25 in. to 16 in. (6.35 mm to 406 mm) diameter for continuous events.

d) Range of release masses from 100 lb to 100,000 lb (45.4 kg to 453,592 kg).

e) Both vapor and liquid releases from a component containing saturated liquid, with release orientation horizontal downwind at an elevation of 10 ft over a concrete surface.

Analysis has shown that these assumptions are satisfactory for a wide variety of plant conditions. Where these assumptions are not suitable, the analyst should consider performing a Level 2 consequence analysis.

3.A.3.6 Determination of Toxic Consequences

3.A.3.6.1 Overview

As with the flammable consequence analysis, dispersion analysis has been performed to evaluate the consequence areas associated with the release of toxic fluids to the atmosphere. The assumptions made for the cloud dispersion modeling are as described in Section 3.A.3.5.3.5. Toxic consequences are determined by using the equations presented in lookup tables similar to the flammable consequence analysis described in Section 3.A.3.5.

3.A.3.6.2 Background for Calculation of Toxic Consequences

The development of the toxic consequence area equations for the Level 1 consequence analysis considers exposure time and concentration. These two components combine to result in an exposure that is referred to as the toxic dose. The degree of injury from a toxic release is directly related to the toxic dose. Level 1 consequence methodology relates dose to injury using probits.

For toxic vapor exposure, the probit (a shortened form of probability unit) is represented as follows:

$$Pr = A + B \cdot \ln\left[C^n t\right]$$

(3.A.5)

Example constants for the probit equation are provided in Part 3, Table 4.14 for various toxic fluids. A single fixed probability of fatality (50 % probability of fatality) is used to determine the toxic impact. This level corresponds to a probit value of 5.0.

3.A.3.6.3 Toxic Continuous Releases

A cloud dispersion model is used to analyze a continuous release (plume model) to the atmosphere. The cloud footprint or plan area is approximated as the shape of an ellipse, as shown in Figure 3.A.3.2, and is calculated using Equation (3.A.6).

$$A = \pi a b$$

(3.A.6)

3.A.3.6.4 Toxic Instantaneous Releases

For instantaneous releases (puff model), the dispersion of the cloud over time is shown in Figure 3.A.3.3. The plan area covered by the cloud is conservatively assumed to be an ellipse, except that the y-distance (a) is taken as one-half of the maximum cloud width as determined from the dispersion results. As part of a Level

2 consequence methodology, cloud dispersion modeling software exists that provides a more accurate plot area as a function of concentration than the elliptical area assumptions made above.

3.A.3.6.5   Development of Toxic Consequence Areas for HF Acid

3.A.3.6.5.1   General

Hydrofluoric acid (HF) is typically stored, transferred, and processed in liquid form. However, the toxic impact associated with a release of liquid HF into the atmosphere is due to the dispersion of the toxic vapor cloud. A toxic vapor cloud of HF can be produced by flashing of the liquid upon release or evaporation from a liquid pool. For the Level 1 consequence analysis, the initial state of HF is assumed to be liquid; the models for calculating the toxic impact areas for HF liquid releases take into account the possibility of flashing and pool evaporation. For HF releases, the Level 1 consequence analysis uses the following guidelines to determine the release rate or mass of mixtures containing HF.

a)   The mass fraction of HF is calculated if the released material contains HF as a component in a mixture.

b)   The liquid release rate (or mass) of the HF component is used to calculate the toxic impact area.

c)   The release rate is calculated for a continuous release of the fluid using the closest matching representative fluid and with the equations provided in Part 3, Section 4.3. If the released fluid contains a toxic component, the toxic release rate is calculated as the product of the toxic component mass fraction and the release rate for the mixture.

A consequence analysis software program (PHAST) was used to generate a range of release rates and durations to obtain graphs of toxic consequence areas. Release durations of instantaneous (less than 3 minutes), 5 minutes (300 seconds), 10 minutes (600 seconds), 30 minutes (1800 seconds), 40 minutes (2400 seconds), and 1 hour (3600 seconds) were evaluated to obtain toxic consequence areas for varying release rates. Toxic impact criteria used was for a probit value of 5.0 using the probit Equation (3.A.5) and probit values listed in Part 3, Table 4.14 for HF.

3.A.3.6.5.2   Continuous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.7).

$$CA_f = C_8 \cdot 10^{\left(c \cdot \log_{10}[C_4 \cdot rate] + d\right)}$$

(3.A.7)

For continuous releases, the values of the constants c and d are functions of the release duration and provided for HF in Part 3, Table 4.11.

3.A.3.6.5.3   Instantaneous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.4 could be correlated as functions of release mass for instantaneous releases in accordance with Equation (3.A.8).

$$CA_f = C_8 \cdot 10^{\left(c \cdot \log_{10}[C_4 \cdot mass] + d\right)}$$

(3.A.8)

For instantaneous releases, the values of the constants c and d are provided for HF and H$_2$S in Part 3, Table 4.11.

3.A.3.6.6 Development of Toxic Consequence Areas for H₂S

3.A.3.6.6.1 General

H_2S is processed as a vapor or when processed under high pressures, quickly flashes upon release due to its low boiling point. In either case, the release of H_2S to the atmosphere results in the quick formation of a toxic vapor cloud. For H_2S releases, the Level 1 consequence analysis uses the following guidelines to determine the release rate or mass of mixtures containing H_2S.

a)   If the released material contains H_2S as a component in a mixture, the mass fraction of H_2S is obtained, and If the initial state of the material is a vapor, the mass fraction of H_2S is used to obtain the vapor discharge rate (or mass) of only H_2S; this rate (or mass) is used to determine the impact area.

b)   If the initial state of the material is a liquid, the mass fraction of H_2S is used to obtain the vapor flash rate (or mass) of only the H_2S; this rate (or mass) is used to determine the impact.

c)   If the initial phase of a material being released is 1 wt% H_2S in gas oil, the material has the potential for both toxic and flammable outcomes from the vapor and flammable outcomes from the liquid. Therefore, the following procedure is followed, using C_{17}-C_{25} as the representative material.

  1)   Calculate the liquid discharge rate for C_{17}-C_{25} as described in Part 3, Section 4.3.

  2)   When estimating flammable consequences, calculate the potential flammable consequence areas as in Part 3, Section 4.3 and take the worst case between:

   i)   the flammable effects of C_{17}-C_{25} using 100 % of the release rate,

   ii)   the flammable effects of H_2S based on 1 % of the release rate.

  3)   Calculate the toxic effects of H_2S, using 1 % of the release rate.

For instantaneous releases, use the above procedure, substituting inventory mass for release rate.

The release durations used to model the consequences of the H_2S release were identical to those assumed for HF acid as discussed in Section 3.A.3.6.5.2.

3.A.3.6.6.2 Continuous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.7).

The values of the constants c and d are functions of the release duration and provided for H_2S in Part 3, Table 4.11.

3.A.3.6.6.3 Instantaneous Releases

The results of the dispersion analyses showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.4 could be correlated as functions of release mass for instantaneous releases in accordance with Equation (3.A.8).

For instantaneous releases, the values of the constants c and d are provided for H_2S in Part 3, Table 4.11.

3.A.3.6.7 Development of Toxic Consequence Areas for Ammonia

3.A.3.6.7.1 General

To estimate the consequence area for ammonia, the dispersion analyses was performed using a saturated liquid at ambient temperature [5 °F (24 °C)], with liquid being released from a low pressure storage tank. The tank head was set at 10 ft (3.05 m).

3.A.3.6.7.2   Continuous Releases

To determine an equation for the continuous area of a release of ammonia, four release hole sizes ($^1/_4$ in., 1-in., 4-in., and 16-in.) were run for various release durations (10, 30, and 60 minutes). Again, toxic consequences were calculated using a software package containing atmospheric dispersion routines.

Toxic impact criteria used was for a probit value of 5.0 using the probit Equation (3.A.5) and probit values listed in Part 3, Table 4.17 for ammonia. The results showed that the clouds modeled in accordance with the approximated shapes of Section 3.A.3.6.3 could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.9).

$$CA_f = e\left(rate\right)^f$$ (3.A.9)

For continuous releases, the values of the constants e and f are functions of the release duration and provided for Ammonia in Part 3, Table 4.12.

3.A.3.6.7.3   Instantaneous Releases

For instantaneous release cases, four release masses of ammonia were modeled (10, 100, 1,000, and 10,000 lb), and the relationship between release mass and consequence area to a probit value of 5.0 were correlated. The results in ft^2 for ammonia are provided in Equation (3.A.10).

$$CA_f = 14.17\left(mass\right)^{0.9011}$$ (3.A.10)

3.A.3.6.8   Development of Toxic Consequence Areas for Chlorine

3.A.3.6.8.1   General

To estimate the consequence area for chlorine, the dispersion analyses were performed using the identical procedure for ammonia as described in Section 3.A.3.6.7.1 and Section 3.A.3.6.7.2.

3.A.3.6.8.2   Continuous Releases

The results of the cloud modeling for chlorine showed that the consequence areas could be correlated as functions of release rate for continuous releases in accordance with Equation (3.A.9).

For continuous releases, the values of the constants e and f are functions of the release duration and provided for chlorine in Part 3, Table 4.12.

3.A.3.6.8.3   Instantaneous Releases

For instantaneous release cases, the consequence areas in ft^2 for chlorine could be correlated using Equation (3.A.11).

$$A = 14.97\left(mass\right)^{1.117}$$ (3.A.11)

3.A.3.6.9   Development of Toxic Consequence Areas for Common Chemicals

3.A.3.6.9.1   General

Procedures to perform Level 1 consequence analysis have been completed for 10 additional toxic chemicals:

a)   aluminum chloride ($AlCl_3$);

b)   carbon monoxide (CO);

c)   hydrogen chloride (HCl);

d)   nitric acid;

e)   nitrogen dioxide (NO_2);

f)   phosgene;

g)   toluene diisocyanate (TDI);

h)   ethylene glycol monoethyl ether (EE);

i)   ethylene oxide (EO);

j)   propylene oxide (PO).

The Level 1 consequence analysis equations for these chemicals have been developed using the same approach as for ammonia and chlorine, described in Section 3.A.3.6.7 and Section 3.A.3.6.8.

3.A.3.6.9.2   Continuous Releases

For continuous releases, the consequence area can be approximated as a function of duration using Equation (3.A.9) with the constants e and f provided in Part 3, Table 4.12.

3.A.3.6.9.3   Instantaneous Releases

Toxic consequences of an instantaneous release for the toxic chemicals listed in Section 3.A.3.6.9.1 estimated smaller (or 0) affected areas than equivalent continuous releases. A conservative curve was calculated using a short duration continuous release toxic consequence curve instead of a less conservative instantaneous release area.

3.A.3.7   Nomenclature

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

a is one-half of the cloud width (minor axis), taken at its largest point (within the 50 % probability of fatality dose level)

A is a constant for the probit equation

b is one-half of the downwind dispersion distance (major axis), taken at the 50 % probability of fatality dose level

B is a constant for the probit equation

c is a constant for the specific consequence area equations for HF acid and H_2S

C is the toxic concentration in the probit equation, ppm

CA_f is the consequence area, ft² (m²)

$CA_{f,comb}$ is the combined/probability weighted consequence area, ft^2 (m^2)

$CA_{f,i}$ is the individual outcome consequence area for the ith event outcome, ft^2 (m^2)

d is a constant for the specific consequence area equations for HF acid and H$_2$S

e is the constant for the specific consequence area equations for ammonia and chlorine

f is the exponent for the specific consequence area equations for ammonia and chlorine

$mass$ is the release mass, lb (kg)

n is the exponent in the probit equation

p_i is the specific event probability for the ith event outcome; see Tables 3.A.3.3, 3.A.3.4, 3.A.3.5, or 3.A.3.6

Pr is the probit value, typically 5.0, which is defined as 50 % probability

$rate$ is the release rate, lb/s (kg/s)

t is the toxic dosage in the probit equation, seconds

x is the constant for the generic consequence area equation

y   is the exponent for the generic consequence area equation

3.A.3.8 Tables

Table 3.A.3.1—List of Representative Fluids Available for Level 1 Consequence Methodology

Representative Fluid	Examples of Applicable Materials	Molecular Weight	Normal Boiling Point		Autoignition Temperature	
			°C	°F	°C	°F
C_1-C_2	Methane, ethane, ethylene, LNG, fuel gas	23	−125	−193	558	1,036
C_3-C_4	Propane, butane, isobutane, LPG	51	−21	−6.3	369	696
C_5	Pentane	72	36	97	284	544
C_6-C_8	Gasoline, naphtha, light straight run, heptane	100	99	210	223	433
C_9-C_{12}	Diesel, kerosene	149	184	364	208	406
C_{13}-C_{16}	Jet fuel, kerosene, atmospheric gas oil	205	261	502	202	396
C_{17}-C_{25}	Gas oil, typical crude	280	344	651	202	396
C_{25+}	Residuum, heavy crude, lube oil, seal oil	422	527	981	202	396
Water	Water	18	100	212	N/A	N/A
Steam	Steam	18	100	212	N/A	N/A
Acid	Acid, caustic	18	100	212	N/A	N/A
H_2	Hydrogen only	2	−253	−423	400	752
H_2S	Hydrogen sulfide only	34	−59	−75	260	500
HF	Hydrogen fluoride	20	20	68	17,760	32,000
CO	Carbon monoxide	28	−191	−312	609	1,128
DEE	Diethyl ether	74	35	95	160	320
HCl	Hydrogen chloride	36	−85	−121	N/A	N/A
Nitric acid	Nitric acid	63	121	250	N/A	N/A
NO_2	Nitrogen dioxide	90	135	275	N/A	N/A
Phosgene	Phosgene	99	83	181	N/A	N/A
TDI	Toluene diisocyanate	174	251	484	620	1,148
Methanol	Methanol	32	65	149	464	867
PO	Propylene oxide	58	34	93	449	840
Styrene	Styrene	—	—	—	—	—
EEA	Ethylene glycol monoethyl ether acetate	132	156	313	379	715
EE	Ethylene glycol monoethyl ether	90	135	275	235	455
EG	Ethylene glycol	62	197	387	396	745
EO	Ethylene oxide	44	11	51	429	804

Table 3.A.3.2—Assumptions Used When Calculating Liquid Inventories Within Equipment

Equipment Description	Component Type	Examples	Default Liquid Volume Percent
Process columns (may be treated as two or three items) — top half — middle section — bottom half	COLTOP COLMID COLBTM	Distillation columns, FCC main fractionator, splitter tower, debutanizer, packed columns (see Note 1), liquid/liquid columns (see Note 2)	25 % 25 % 37 % These default values are typical of trayed distillation columns and consider liquid holdup at the bottom of the vessel as well as the presence of chimney trays in the upper sections
Accumulators and drums	DRUM	OH accumulators, feed drums, HP/LP separators, nitrogen storage drums, steam condensate drums, three-phase separators (see Note 3)	50 % liquid Typically, two-phase drums are liquid level controlled at 50 %
KO pots and dryers	KODRUM	Compressor KOs, fuel gas KO drums, flare drums, air dryers (see Note 5)	10 % liquid Much less liquid inventory expected in KO drums
Compressors	COMPC COMPR	Centrifugal and reciprocating compressors	Negligible, 0 %
Pumps	PUMP1S PUMP2S PUMPR	Pumps	100 % liquid
Heat exchangers	HEXSS HEXTS	Shell and tube exchangers	50 % shell-side, 25 % tube-side
Fin fan air coolers	FINFAN TUBE FINFAN HEADER	Total condensers, partial condensers, vapor coolers, and liquid coolers (see Note 4)	25 % liquid
Filters	FILTER		100 % full
Piping	PIPE-xx		100 % full, calculated for Level 2 methodology
Reactors	REACTOR	Fluid reactors (see Note 6), fixed-bed reactors (see Note 7), mole-sieves	15 % liquid

NOTE 1   Packed columns will typically contain much less liquid traffic than trayed columns. Typical liquid volume percentages for packed columns are 10 % to 15 %.

NOTE 2   For liquid/liquid columns, such as amine contactors, caustic contactors, and lube or aromatics extractors, where a solvent or other fluid is brought into direct contact with the process fluid (e.g. TEG and BTX in an aromatics extractor), the liquid volume percentage will be much higher. Consideration should be given to the amount of each fluid in the vessel and whether or not the fluid composition includes both fluids in the mixture composition.

NOTE 3   For three-phase separators, such as desalters and OH drums with water boots, the liquid volume percentage may be lower than 50 %, depending on how much of the second liquid phase (typically water) is present and whether or not the fluid composition includes both liquid phases in the mixture composition.

NOTE 4   Most air coolers are two-phase and only partially condense vapors. Even A/Cs that totally condense the vapor stream require the majority of the heat transfer area (and volume) to cool the vapors to their dew point and condense to liquid. Typically, only the final pass (less rows of tubes than other passes) will be predominately liquid. A liquid volume percentage of 25 % should still be conservative for all A/Cs except liquid coolers where a liquid volume of 100% should be used.

NOTE 5   For flue gas KO drums and air dryers, the LV% is typically negligible. Consideration should be given to reducing the liquid volume percentage to 0 %.

NOTE 6   Fluidized reactors can have up to 15 % to 25 % of the available vessel volume taken up by catalyst. The remaining available volume is predominately vapor. A liquid volume of 15 % should still be conservative.

NOTE 7   Fixed-bed reactors can have up to 75 % of the available vessel volume taken up by hardware and catalyst. The remaining volume will typically be 50 % liquid and 50 % vapor. An assumed liquid volume of 15 % of the overall available vessel volume should still be conservative.

Table 3.A.3.3—Specific Event Probabilities—Continuous Release Autoignition Likely

Final Liquid State—Processed Above AIT						
Fluid	**Probability of Ignition**	**Probabilities of Outcome**				
		VCE	**Fireball**	**Flash Fire**	**Jet Fire**	**Pool Fire**
C_1-C_2						
C_3-C_4						
C_5						
C_6-C_8	1				1	
C_9-C_{12}	1				1	
C_{13}-C_{16}	1				0.5	0.5
C_{17}-C_{25}	1				0.5	0.5
C_{25+}	1					1
H_2						
H_2S						
Styrene	1				1	
Final Gas State—Processed Above AIT						
Fluid	**Probability of Ignition**	**Probabilities of Outcome**				
		VCE	**Fireball**	**Flash Fire**	**Jet Fire**	**Pool Fire**
C_1-C_2	0.7				0.7	
C_3-C_4	0.7				0.7	
C_5	0.7				0.7	
C_6-C_8	0.7				0.7	
C_9-C_{12}	0.7				0.7	
C_{13}-C_{16}						
C_{17}-C_{25}						
C_{25+}						
H_2	0.9				0.9	
H_2S	0.9				0.9	
Styrene	1				1	

NOTE 1   Shaded areas represent outcomes that are not possible.
NOTE 2   Must be processed at least 80 °F (27 °C) above AIT.

Table 3.A.3.4—Specific Event Probabilities—Instantaneous Release Autoignition Likely

Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
Final Liquid State—Processed Above AIT						
C_1-C_2	0.7		0.7			
C_3-C_4	0.7		0.7			
C_5	0.7		0.7			
C_6-C_8	0.7		0.7			
C_9-C_{12}	0.7		0.7			
C_{13}-C_{16}						
C_{17}-C_{25}						
C_{25+}						
H_2	0.9		0.9			
H_2S	0.9		0.9			
Styrene	1					1
Final Gas State—Processed Above AIT						
C_1-C_2	0.7		0.7			
C_3-C_4	0.7		0.7			
C_5	0.7		0.7			
C_6-C_8	0.7		0.7			
C_9-C_{12}	0.7		0.7			
C_{13}-C_{16}						
C_{17}-C_{25}						
C_{25+}						
H_2	0.9		0.9			
H_2S	0.9		0.9			
Styrene	1		1			

NOTE 1 Shaded areas represent outcomes that are not possible.

NOTE 2 Must be processed at least 80 °F (27 °C) above AIT.

Table 3.A.3.5—Specific Event Probabilities—Continuous Release Autoignition Not Likely

Final Liquid State—Processed Below AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1-C_2						
C_3-C_4						
C_5	0.1				0.02	0.08
C_6-C_8	0.1				0.02	0.08
C_9-C_{12}	0.05				0.01	0.04
C_{13}-C_{16}	0.05				0.01	0.04
C_{17}-C_{25}	0.020				0.005	0.015
C_{25+}	0.020				0.005	0.015
H_2						
H_2S						
DEE	1.0				0.18	0.72
Methanol	0.4				0.08	0.32
PO	0.4				0.08	0.32
Styrene	0.1				0.02	0.08
EEA	0.10				0.02	0.08
EE	0.10				0.02	0.08
EG	0.10				0.02	0.08
Final Gas State—Processed Below AIT						
Fluid	Probability of Ignition	Probabilities of Outcome				
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1-C_2	0.2	0.04		0.06	0.1	
C_3-C_4	0.1	0.03		0.02	0.05	
C_5	0.1	0.03		0.02	0.05	
C_6-C_8	0.1	0.03		0.02	0.05	
C_9-C_{12}	0.05	0.01		0.02	0.02	
C_{13}-C_{16}						
C_{17}-C_{25}						
C_{25+}						
H_2	0.9	0.4		0.4	0.1	
H_2S	0.9	0.4		0.4	0.1	
CO	0.899	0.4		0.4	0.099	
DEE	0.899	0.4		0.4	0.099	
Methanol	0.4	0.104		0.104	0.192	
PO	0.4	0.178		0.178	0.044	
Styrene	0.1	0.026		0.026	0.048	
EEA	0.1	0.026		0.026	0.048	
EE	0.1	0.026		0.026	0.048	
EG	0.1	0.026		0.026	0.048	
EO	0.9	0.4		0.4	0.1	

NOTE 1   Shaded areas represent outcomes that are not possible.
NOTE 2   Must be processed at least 80 °F (27 °C) below AIT.

Table 3.A.3.6—Specific Event Probabilities—Instantaneous Release Autoignition Not Likely

ParFluid	Probability of Ignition	Probabilities of Outcome				
Final Liquid State—Processed ~~Above~~ Below AIT						
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1-C_2						
C_3-C_4						
C_5	0.1					0.1
C_6-C_8	0.1					0.1
C_9-C_{12}	0.05					0.05
C_{13}-C_{16}	0.05					0.05
C_{17}-C_{25}	0.02					0.02
C_{25+}	0.02					0.02
H_2						
H_2S						
DEE	0.9					0.9
Methanol	0.4					0.4
PO	0.4					0.4
Styrene	0.1					0.1
EEA	0.1					0.1
EE	0.1					0.1
EG	0.1					0.1

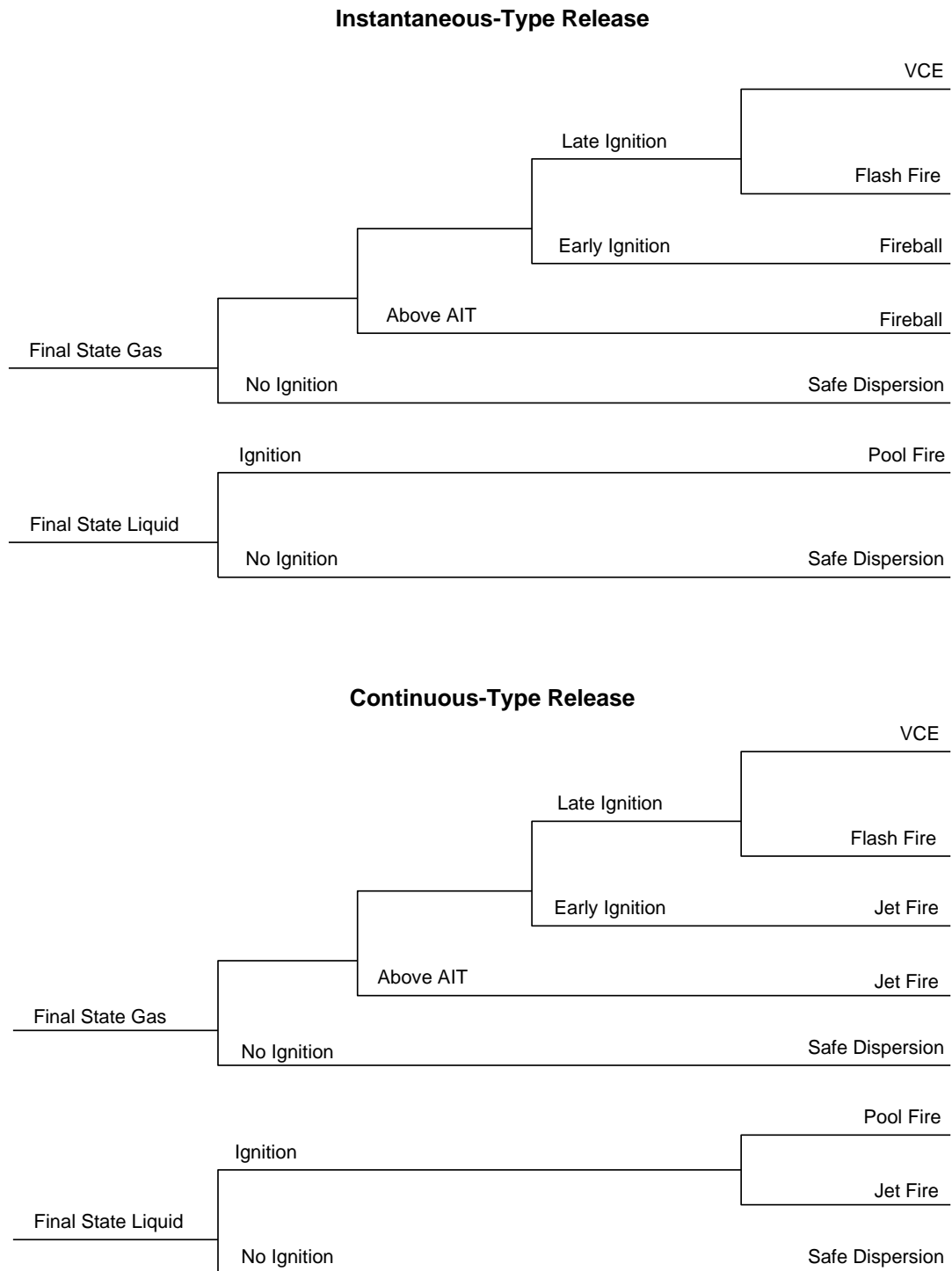| Fluid	Probability of Ignition	Probabilities of Outcome				
Final Gas State—Processed ~~Above~~ Below AIT						
		VCE	Fireball	Flash Fire	Jet Fire	Pool Fire
C_1-C_2	0.2	0.04	0.01	0.15		
C_3-C_4	0.1	0.02	0.01	0.07		
C_5	0.1	0.02	0.01	0.07		
C_6-C_8	0.1	0.02	0.01	0.07		
C_9-C_{12}	0.04	0.01	0.005	0.025		
C_{13}-C_{16}						
C_{17}-C_{25}						
C_{25+}						
H_2	0.9	0.4	0.1	0.4		
H_2S	0.9	0.4	0.1	0.4		
CO	0.899	0.4	0.099	0.4		
DEE	0.899	0.4	0.099	0.4		
Methanol	0.4	0.099	0.038	0.263		
PO	0.4	0.178	0.044	0.178		
Styrene	0.101	0.025	0.01	0.066		
EEA	0.101	0.01	0.066	0.025		
EE	0.101	0.01	0.066	0.025		
EG	0.101	0.01	0.066	0.025		
EO	0.9	0.4	0.1	0.4		
NOTE 1 Shaded areas represent outcomes that are not possible.						
NOTE 2 Must be processed at least 80 °F (27 °C) above AIT.						

3.A.3.9 Figures

Instantaneous-Type Release

				VCE
		Late Ignition		Flash Fire
		Early Ignition		Fireball
	Above AIT			Fireball
Final State Gas	No Ignition			Safe Dispersion
	Ignition			Pool Fire
Final State Liquid	No Ignition			Safe Dispersion

Continuous-Type Release

				VCE
		Late Ignition		Flash Fire
		Early Ignition		Jet Fire
	Above AIT			Jet Fire
Final State Gas	No Ignition			Safe Dispersion
	Ignition			Pool Fire
				Jet Fire
Final State Liquid	No Ignition			Safe Dispersion

Figure 3.A.3.1—Level 1 Consequence Methodology Event Tree

Point of
Release

2a

2b

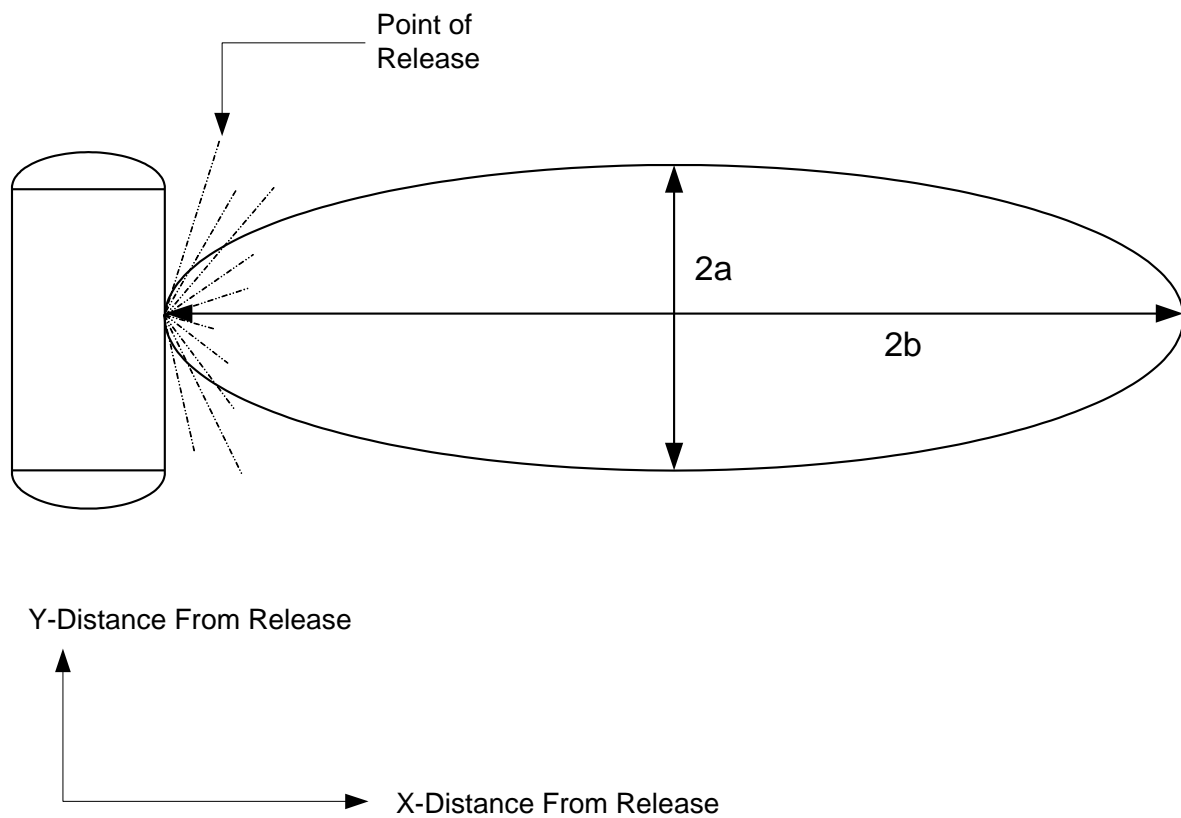Y-Distance From Release

X-Distance From Release

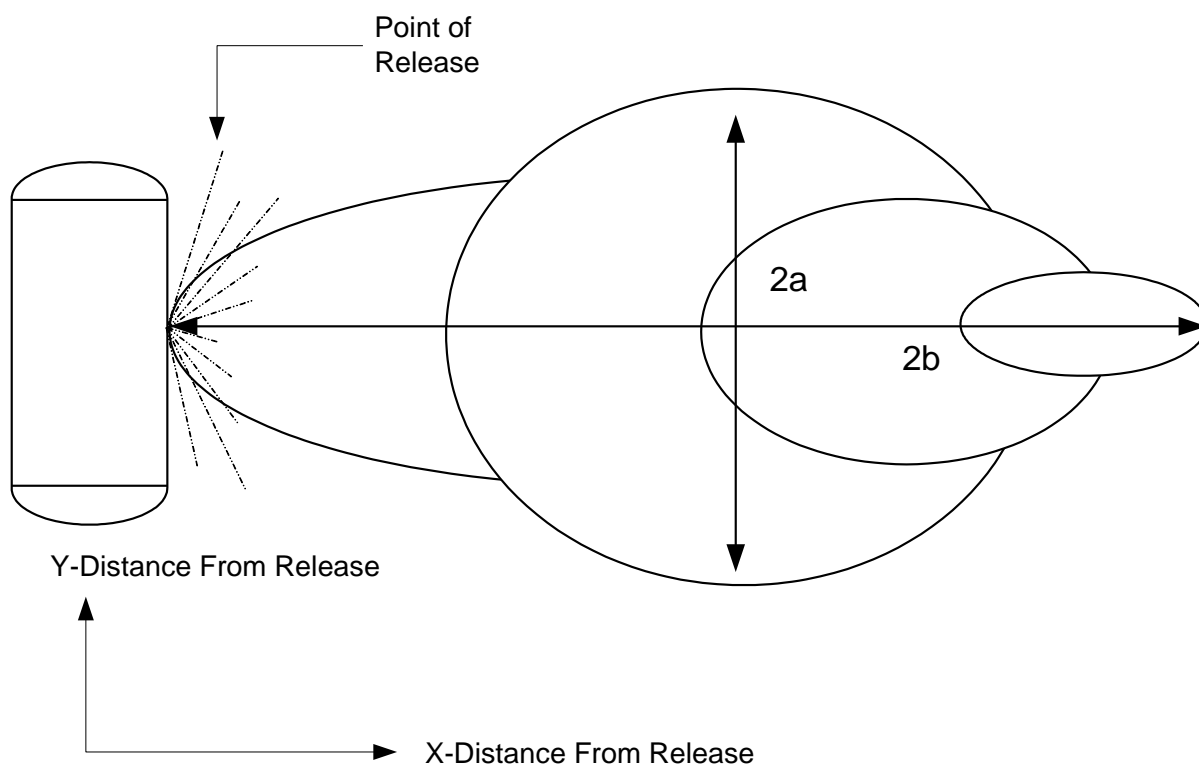**Figure 3.A.3.2—Approximated Cloud Shape for Toxic Plume from a Continuous Release**

Figure 3.A.3.3—Approximated Cloud Shape for Toxic Puff from an Instantaneous Release

3.A.4 Level 2 Consequence Methodology

3.A.4.1 General

The use of event trees and semi-quantitative effects analysis forms the basis for the Level 2 consequence methodology provided in Part 3, Section 5 with the details for calculating event tree probabilities and the effects of pool fires, jet fires, flash fires, fireballs, VCEs, and BLEVEs are provided. Part 3 provides the impact of most of these events with the closed-form equations.

3.A.4.2 Cloud Dispersion Analysis

Some events, such as VCEs and flash fires, require the use of sophisticated dispersion analysis software to model how the flammable or toxic releases mix and disperse with air as they are released to the atmosphere.

There are several commercially available software packages that enable the user to perform dense gas dispersion consequence modeling. Examples include, such as SLAB, DEGADIS and PHAST, some of which are available in the public domain, while others are commercially available. A study contracted by the U.S. Department of Energy provides a comparison of many different software packages, and recommendations are provided to help select the appropriate package for a particular application.

In general, packages that perform dense gas dispersion modeling should be chosen as opposed to neutrally buoyant models because hazardous releases typically will be materials with molecular weights heavier than air. Even light hydrocarbons can be modeled accurately using dense gas modeling since the temperature of the releases will result in releases with densities heavier than air.

Dispersion models will provide a cloud concentration profile. For flammables releases, the concentration profile is used to assess which portions of the cloud are in the flammable range. For flash fires, the impact area at grade is determined to be the area in the cloud that has flammable concentrations between the released fluid's LFL and UFL. For VCEs, a volumetric calculation is required since the total amount of flammable volume and mass is required to assess the magnitude of the explosion.

3.A.5 Consequence Methodology For Atmospheric Storage Tanks

3.A.5.1 Overview

The consequence model for atmospheric storage tanks (ASTs) is based on a modification of the Level 1 consequence analysis. Only a financial consequence analysis is provided for the AST bottom.

3.A.5.2 Representative Fluid and Associated Properties

A representative fluid that most closely matches the fluid contained in the AST system being evaluated is selected from the representative fluids shown in Part 3, Table 6.1. The required fluid properties for the consequence analysis are also contained in this table.

In addition to selecting a fluid, a soil type must also be specified because the consequence model depends on soil properties. Representative soil conditions and the associated soil properties required for the consequence analysis is provided in Part 3, Table 6.2.

3.A.5.3   Generic Failure Frequencies and Release Holes Sizes

3.A.5.3.1   Atmospheric Storage Tank Bottom

The base failure frequency for the leak of an AST bottom was derived primarily from an analysis of a portion of the API publication *A Survey of API Members' Aboveground Storage Tank Facilities*, published in July 1994. The survey covered refining, marketing, and transportation storage tanks, each compiled separately. The survey included the years 1983 to 1993, and summary failure data are shown in Table 3.A.5.1. The base failure frequencies obtained from this survey are shown in Part 2, Table 3.1. One of the most significant findings was that tank bottom leaks contributing to soil contamination had been cut in half in the last 5 years compared to the first 5 years covered by the survey. This was attributed to an increased awareness of the seriousness of the problem and to the issuance of the API 653 standard for aboveground storage tank inspection.

A bottom leak frequency of 7.2E-03 leaks per year was chosen as the base leak frequency for an AST bottom. Although the leak frequency data in Part 2, Table 3.1 indicate that ASTs less than 5 years old had a much lower leak frequency, it was decided to use the whole survey population in setting the base leak frequency. The age of the AST was accounted for elsewhere in the model since the percent of wall loss in the model is a function of the AST age, corrosion rate, and original wall thickness. The percent of wall loss was selected as the basis for the modifier on the base leak frequency; thus, a very young AST with minimal corrosion would have a frequency modifier of less than 1, which lowers the leak frequency accordingly.

It should be noted that the damage factor (DF) for AST bottoms in Part 2 was originally developed based on a GFF of equal to 7.2E-03, which equates to a range in DFs from less than 1 to 139. In order to be consistent with the other components in Part 2, the range of DFs was adjusted to a range of 1 to 1390. This adjustment in the DF required a corresponding change of the GFF to a value of 7.2E-04, and this is the value shown in Part 2, Table 3.1.

The survey did not report the size of leaks, but a survey of the sponsors for the AST RAP project indicated that leak sizes of less than or equal to $^1/_2$ in. in diameter would adequately describe the vast majority of tank bottom leaks. An $^1/_8$ in. release hole size is used if a RPB is present and a $^1/_2$ in. hole size is used for AST bottoms without a RPB. A GFF of 7.2E-04 is assigned to this hole size in the consequence analysis. In addition, the number of release holes in an AST bottom is determined as a function of the AST bottom area; see Part 3, Table 6.3.

3.A.5.3.2   Shell Courses

The generic failure rate for rapid shell failures was determined based on actual incidents. A review of literature produced reports of two rapid shell failures in the U.S. petroleum industry over the last 30 years.

a)   1971 (location unknown), brittle fracture caused loss of 66,000 bbl crude oil.

b)   1988 Ashland Oil, PA, brittle fracture caused loss of 96,000 bbl diesel.

The number of tanks that provided the basis for the two failures was estimated from the literature to be about 33,300 large storage tanks. This value was based on a 1989 study carried out for API by Entropy Ltd. In this case, large is defined as having a capacity greater than 10,000 bbl. The number of tanks represents the United States total for the refining, marketing, transportation, and production sectors; thus, the total number of tank years was found to be approximately 1,000,000. Dividing the number of failures by the number of tank years yields a rapid shell failure frequency of 2E-06 per tank year. API 653 requires tank evaluations for susceptibility to brittle fracture. A hydrostatic test or re-rating of the tank is required for continued service. As a result, API 653 provides protection against brittle fracture. Assuming that one-half of the tanks are not maintained to API 653, the base leak frequencies for rapid shell failures would be 4E-06 per tank year. Because the committee team members had no available documented cases of rapid shell failures for a tank that was operated, maintained, inspected, and altered in accordance with API 653, the failure frequency was believed to be significantly better than the calculated average result and the committee selected a frequency of 1E-07 per tank year.

The total GFF for leakage events in AST shell courses is set at 1E-04. The generic failure frequencies for the small, medium and large holes size is determined by allocating the total GFF for leakage on a 70 %, 25 %, and 5 % basis for these release hole sizes, respectively. The resulting generic failure requires are shown in Part 2, Table 3.1.

3.A.5.4 Estimating the Fluid Inventory Available for Release

The consequence calculation requires an upper limit for the amount of fluid or fluid inventory that is available for release from a component. The total amount of fluid available for release is taken as the amount of product located above the release hole size being evaluated. Flow into and out of the AST is not considered in the consequence methodology.

3.A.5.5 Determination of the Release Type (Instantaneous or Continuous)

The release type for the AST bottom is assumed to be continuous.

3.A.5.6 Determination of Flammable and Explosive Consequences

Flammable and explosive consequences are not included in the AST bottom consequence methodology.

3.A.5.7 Determination of Toxic Consequences

Toxic consequences are not included in the AST bottom consequence methodology.

3.A.5.8 Determination of Environmental Consequences

Environmental consequences for AST bottoms are driven by the volume and type of product spilled, the property impacted, and the cost associated with cleanup. The consequence methodology includes the potential environmental impact to the locations shown below; see Part 3, Figure 6.1.

a) Diked Area—A release of petroleum products is contained within a diked area or other secondary containment system such as a RPB, spill catch basin, or spill tank. The "diked area" impacted media assumes the spill is of a size and physical characteristics to be contained within a system that is sufficiently impermeable to prevent migration of the spill off-site, prevent contamination of groundwater and surface water, and minimize the volume of impacted on-site soil. Minimal on-site soil impact is defined as less than 1 ft (0.30 m) depth of soil contamination in a 72 hour period. An earthen secondary containment system that contains a release of petroleum may be considered a "diked area" if the soil permeability and stored material properties are sufficient to meet the above definition. For example, a secondary containment system constructed from a uniform sandy soil containing asphalt or other heavy petroleum products would be considered "diked" because a release into the containment is not expected to impact other media (e.g. limited on-site soil impact, no off-site soil, no groundwater or surface water impacts). Conversely, the same system containing gasoline may not meet this definition.

b) On-site Soil—A release of petroleum products is limited to contaminating on-site surficial soils. On-site refers to the area within the physical property boundary limits of the facility. Surface soils refer to the upper 0.61 m (2 ft) of soil that could be readily removed in the event of a spill. The volume spilled, location of spill, site grade, size of the property, soil permeability, and stored material properties are important in determining whether a spill will be contained on-site. For example, a flange leak on a section of aboveground piping may be limited to impacting a small section of on-site soils.

c) Off-site Soil—A release of petroleum products contaminates off-site surface soils. Off-site refers to the property outside of the physical property boundary limits of the facility. Surface soils refer to the upper 2 ft (0.61 m) of soil that could be readily removed in the event of a spill. The volume released location of spill, site grade, land use of the off-site impacted property, soil permeability, and stored material properties are important in determining the impacts to off-site property.

d) Subsurface Soil—A release of petroleum products contaminates subsurface soils. Subsurface impacts may or may not be contained within the physical property boundary limits of the facility. Subsurface soils refer to soils deeper than 2 ft (0.61 m) in depth or those soils that cannot be readily removed in the event of a spill, such as soils beneath a field erected tank or building slab. The soil permeability, stored material properties, and location of the spill are important in determining the extent of the environmental consequences associated with subsurface soil impacts. For example, a release of petroleum from an AST bottom that rests on native clay soils will have minor subsurface impacts relative to the same AST that is located on native sand soil.

e) Groundwater—A release of petroleum products contaminates groundwater. Groundwater refers to the first encountered phreatic water table that may exist subsurface at a facility. Groundwater elevation may fluctuate seasonally and different groundwater tables may exist at a site (e.g. possible shallow soil water table and a deep bedrock water table). The soil permeability, stored material properties, and location of the spill are important in determining the extent of the environmental consequences associated with groundwater impacts. The nature of the subsurface soils will dictate the time required for a spill to impact the groundwater and the severity of the impact.

f) Surface Water—A release of petroleum products contaminates off-site surface water. Conveyance of spilled product to surface waters is primarily by overland flow, but may also occur through subsurface soils. Surface water refers to non-intermittent surficial waters from canals, lakes, streams, ponds, creeks, rivers, seas, or oceans and includes both fresh and salt water. Surface waters may or may not be navigable. The stored material properties, type of surface water, and response capabilities are important in determining the extent of the environmental consequences associated with surface water impacts.

The cleanup costs associated with these environmental impacts are provided in Part 3, Table 6.6 as a function of environmental sensitivity. The environmental sensitivity is given as Low, Medium, or High and determines the expected cost factor per barrel of spilled fluid for environmental cleanup in a worst-case scenario.

3.A.5.9 Tables

Table 3.A.5.1—Summary of API Members' Aboveground Storage Tank Facilities Relative to Tank Bottom Leakage

Population Description	Number of Tanks	Percent with Bottom Leaks in Last 5 Years	Number with Bottom Leaks in Last 5 Years	Tank Years (see Note)	Bottom Leak Frequency (1988 to 1993)
Tanks < 5 years old	466	0.9%	4	2,330	1.7×10^{-3}
Tanks 6 to 15 years old	628	3.8%	24	3,140	7.6×10^{-3}
Tanks > 15 years old	9,204	3.8%	345	46,020	7.5×10^{-3}
All tanks in survey	10,298	3.6%	373	51,490	7.2×10^{-3}
NOTE Tank years = number of tanks × average number of years in service.					