THE CHLORINE INSTITUTE

Pamphlet 74

Guidance on Estimating the Area Affected by a Chlorine Release

Edition 7

A LEGACY OF SAFETY STEWARDSHIP since 1924

October 2019

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1. INTRODUCTION

1.1 SCOPE

The intent of this pamphlet is to provide a simplified document to assist chlorine producers/users, local emergency planning committees, fire departments, and municipalities in estimating the area affected by a chlorine release for emergency planning and hazard assessment purposes, and to provide a general understanding of the expectations of chlorine cloud release scenarios. As noted elsewhere herein, the worst-case scenarios modeled in this pamphlet are based upon numerous assumptions prescribed by the Environmental Protection Agency (EPA) in their Risk Management Program (RMP) guidance. The reader must bear in mind that these worst-case assumptions are, in most cases, highly unlikely to occur and should not be used for purposes other than to address the regulatory worst-case scenario requirements. This pamphlet also provides alternate cases with assumptions that provide more realistic results that can be considered for emergency response planning and risk management.

1.2 CHLORINE INSTITUTE STEWARDSHIP PROGRAM

The Chlorine Institute (CI) exists to support the chlor-alkali industry in advancing safe, secure, environmentally compatible, and sustainable production, distribution, and use of its mission chemicals.[1]

Chlorine Institute members are committed to adopting CI's safety and stewardship initiatives, including pamphlets, checklists, and incident sharing, that will assist members in achieving measurable improvement. For more information on the Institute's stewardship program, visit CI's website at www.chlorineinstitute.org.

1.3 DEPARTMENT OF HOMELAND SECURITY – CHEMICAL SECURITY ANALYSIS CENTER

The Department of Homeland Security (DHS) Chemical Security Analysis Center (CSAC), part of the Science and Technology Directorate (S&T), collaborated with the Chlorine Institute to develop updated guidance in this version of Pamphlet 74, based upon new experimental research into chlorine releases and the associated chemical and physical phenomena. The Hazard Prediction and Assessment Capability (HPAC) model, developed and widely used by the U.S. Government, was used to simulate the release scenarios in this pamphlet to provide new modeling results. New data and findings available from the chlorine release field trials performed in CSAC's Project Jack Rabbit II (JRII) in 2015 and 2016 have been applied to the modeling and guidance presented in this pamphlet, representing the most current knowledge of chlorine releases to date.

[1] CI's mission chemicals: chlorine, sodium and potassium hydroxides, sodium hypochlorite, the distribution of vinyl chloride monomer (VCM), and the distribution and use of hydrogen chloride.

1.4 DEFINITIONS AND ACRONYMS

Accidental Release	An unanticipated emission of a regulated substance or other highly hazardous substance into the environment.
ACGIH	American Conference of Governmental Industrial Hygienists
AEGL	Acute Exposure Guideline Levels – The threshold exposure limits for the general public as defined by the National Advisory Committee (NAC) for the Development of Acute Exposure Guideline Levels for Hazardous Substances.
AEGL-2	The airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
AEGL-3	The airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.
AIHA	American Industrial Hygiene Association
ALOHA®	Areal Locations of Hazardous Atmospheres
Atm	Atmospheric pressure
BTU	British Thermal Unit
CBRN	Chemical, Biological, Radiological, and Nuclear
CFR	Code of Federal Regulations (U.S.)
CI	The Chlorine Institute
CSAC	Chemical Security Analysis Center
Crosswind Distance(s)	A point or points that are in the 90° direction from the path of the wind. If the wind is blowing from the west, points in the north and south directions constitute crosswind distances. The concentration at a specific crosswind distance will vary as the downwind distance is changed. In this pamphlet, concentrations at crosswind distances are reported at ground level elevation. At different elevations, the concentration at a specific crosswind point will vary.
DHS	Department of Homeland Security (U.S.)
DOD	Department of Defense (U.S.)

Downwind Distance(s)	A point or points that are directly in the path of the wind direction. If the wind is blowing from the west, points directly east of and downwind from the release source constitute downwind distances. In this pamphlet, concentrations at downwind distances are reported at ground level elevation. For any release, the maximum concentration of the material being released will occur at some downwind distance. At different elevations, the concentration at a specific downwind point will vary.
DPG	Army Dugway Proving Ground (U.S.)
DTRA	Defense Threat Reduction Agency
EPA	Environmental Protection Agency (U.S)
EPRI	Electric Power Research Institute
ERPG	Emergency Response Planning Guidelines as defined by AIHA
ERPG-2	The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. For chlorine, this value is 3 ppm (as defined by AIHA).
ERPG-3	The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects. For chlorine, this value is 20 ppm (as defined by AIHA).
footprint	In this pamphlet, a release scenario plot that depicts the total impact zone resulting from the entire chemical release event, assuming no variation in wind speed or wind direction
ft	Foot
GUI	Graphical user interface
HSIN	Homeland Security Information Network
Institute	The Chlorine Institute (CI)
JRII	Jack Rabbit II
kg	Kilogram
kPa	Kilopascals
LEPC	Local Emergency Planning Committee

Maximum Crosswind Distance	The maximum distance in the crosswind direction that a specific concentration reaches. The maximum crosswind distance will occur at some point both downwind and crosswind from the release point.
MDS	Meteorological Data System
mg/m^3	Milligrams per cubic meter
m/s	Meters per second
NAC	National Advisory Committee
NWS	National Weather Service
OAQPS	Office of Air Quality Planning and Standards
ppm	Parts per million
psig	Pounds per square inch gauge
RMP	Risk Management Program (40 CFR Part 68)
SAFER/TRACE™	Systematic Approach for Emergency Response/Toxic Release Analysis of Chemical Emissions
SCICHEM	Second-order Integrated Puff Model with Chemistry
S&T	Science and Technology Directorate
SCIPUFF	Second-order Closure Integrated Puff
SWIFT	Stationary Wind Fit and Turbulence
TWA	Time-Weighted Average
Ullage	Unfilled space in a container
VCM	Vinyl Chloride Monomer
Worst-Case Scenario	As used in this pamphlet, the instantaneous release of the entire contents of chlorine from a container and the complete evaporation at a constant rate in a ten-minute period with no mitigating devices allowed. Under specific circumstances, passive mitigation devices, such as diking, may be utilized to mitigate the consequences of a release. However, the worst-case scenarios described in this pamphlet assume no mitigating devices are available

1.5 DISCLAIMER

The information in this pamphlet is drawn from sources believed to be reliable. The Institute, its members, and its partners jointly or severally, make no guarantee and assume no liability in connection with any of this information. Moreover, it should not be assumed that every acceptable safety procedure is included or that special circumstances may not warrant modified or additional procedures. The user should be aware that changing technology or regulations may require a change in the recommendations herein. Appropriate steps should be taken to assure that the information is current when used. These suggestions should not be confused with federal, state, provincial, municipal, or insurance requirements or with national safety codes.

1.6 APPROVAL

The Chlorine Institute's Health, Environment, Safety, and Security Issue Team approved Edition 7 of this pamphlet on October 21, 2019.

1.7 REVISIONS

Suggestions for revisions should be directed to the Secretary of the Chlorine Institute.

1.7.1 Significant Revisions in Current Edition

All of the scenarios in this pamphlet were modeled by DHS's Chemical Security Analysis Center. Four new sections were added:

- Section 4, Modeling Assumptions, Limitations, And Methodology
- Appendix C, Jack Rabbit History and Influence.
- Appendix D, SAFER/TRACE™ and ALOHA Flowrate Calculations
- Appendix E, Dry Deposition

Additionally, Appendices A and B were overhauled due to modeling software updates and the new data presentation in this edition. Clarifying statements were added throughout the pamphlet.

1.8 REPRODUCTION

1.9 ABSTRACT

Because of the toxicity of chlorine, the chlor-alkali industry has established strict safety measures for the handling of chlorine under normal circumstances, process upset, or disrupted conditions.

In planning for emergency response to a chlorine release, it is necessary to estimate the hazard area affected by the release. This pamphlet provides examples of scenarios that may help facilities and personnel better understand the characteristics, behavior, and potential impact area of a chlorine release cloud. These scenarios were conceptualized and selected based upon typical chlorine industry containers, equipment, and operations.

Results of model predictions are provided as graphical representations of the estimated downwind distances for specific chlorine concentrations and dosages that are estimated to be encountered during various release scenarios. Also graphs depicting Instantaneous Concentrations as a function of time and peak Instantaneous concentration as a function of distance and time are provided.

These results have been prepared using the Hazard Prediction and Assessment Capability (HPAC) model, developed by the U.S. Department of Defense (DOD) through the Defense Threat Reduction Agency (DTRA). Descriptions of this model and its application to the scenarios in Pamphlet 74 can be found in Appendix A. It is important to note that the HPAC software may be obtained only by persons at U.S. government agencies and their contractors. Although HPAC is not available to the general public, the dispersion model within HPAC is called SCIPUFF. SCIPUFF does have different versions for different applications with different capabilities, but they all use the same basic dispersion model. There is an older, public domain version of SCIPUFF available from Xator/Sage website (*6.1.23*), but it does not have dense gas capabilities. A current version is available from EPRI (Electric Power Research Institute) as SCICHEM (*6.1.17*), and that should be able to produce the same, or very similar, results to HPAC for the CI Pamphlet 74 calculations.

The modeling results included in this pamphlet represent the general range of expectations from chlorine release scenarios, and they are relevant to typical industrial facilities. However, it is important to note that every individual facility will have its own unique set of characteristics that will affect how a released chlorine cloud will behave. Where more precision or different scenarios are required, it is recommended that a person skilled in the modeling of dense gases or computational fluid dynamics be consulted to perform site-specific simulations.

2. CHARACTERISTICS OF CHLORINE RELEASES

2.1 Sources

Under process upset or other abnormal circumstances (for example: equipment failure, or natural disaster, transport accident, terrorist act), chlorine could be released from a number of sources. Common sources may include:

- Storage facilities (tanks or spheres)
- Piping or Pipelines
- Process vessels
- Vents

- Relief valves
- Railroad tank cars
- Highway cargo tanks
- Portable containers or Cylinders
- Chemical reactions (for example: if acid and sodium hypochlorite were accidently mixed together)

2.2 PHYSICAL FORM

Chlorine occurs as a greenish-yellow gas or an amber liquid depending on the pressure and temperature. Typically, chlorine is stored and transported as a liquid under pressure. However, at standard atmospheric pressure (1 atm) and temperatures well above its boiling point -29ºF (-34ºC), liquid chlorine boils extremely rapidly in a process known as “flashing”, and expands in volume by nearly 460 times to a vapor. Chlorine vapor is 2.5 times denser than air and as a result, chlorine clouds tend to flow into and accumulate in low-lying areas. During a release, chlorine can escape from a containment vessel as a vapor, a liquid, or both, depending upon where the breach occurs on the vessel and the release conditions.

2.3 CHARACTERISTICS OF CHLORINE RELEASES

2.3.1 Upward Releases

If there is a breach in containment in the headspace (or ullage) of a pressurized storage tank, the pressurized chlorine gas in the headspace will escape to the outside as a jet of vapor and/or liquid, depending on the size of the hole and pressure difference between the vessel and atmosphere. Once outside the tank, the liquid will quickly heat up and change phase to a vapor and the chlorine vapor will cool as it expands and slump to the ground as a dense gas. If the jet impinges against an object or the ground, frost may be observed forming from condensed humidity on surfaces impacted by the cold jet.

2.3.2 Auto-refrigeration

Inside the tank the dropping pressure will cause the liquid chlorine to boil, which sustains the escaping jet with additional chlorine, however the boiling causes the remaining liquid chlorine in the tank to rapidly cool in a process known as “auto-refrigeration”. As the liquid chlorine cools, the boiling will slow and eventually stop once the boiling point has been reached. At this stage, chlorine vapor will only be generated at a relatively slow rate. An upward, vertical release was included in the Jack Rabbit test regime to aid in modeling this. The remaining liquid chlorine in the tank will be maintained at -29ºF (-34ºC), and in some cases may remain for hours or days. For breached tanks that have reached an auto-refrigerated state, a frost line can be observed on the outside of the tank as an indication of the approximate amount and location of liquid chlorine that remains in the tank.

Releases Below the Liquid Level in the Vessel

If there is a breach in containment at or below the liquid level of a pressurized tank, in general when the hole is formed, the pressure inside the tank will force liquid chlorine out of the opening, which will immediately flash to a vapor at the exit. Because the liquid is nearly 460 times denser than the vapor, the rate at which chlorine leaves the tank in a liquid release is much greater than a vapor release for the same hole size and tank conditions. A liquid chlorine release can therefore generate a substantially larger and more concentrated cloud, at a much faster rate, and possibly impact a significantly greater area compared to an otherwise equivalent vapor release (*6.1.4*).

As the liquid chlorine exits the tank and approximately 80% of the mass flashes to a vapor jet, it will expand greatly and cool to temperatures near its boiling point. At these low temperatures, the vapor's density will be substantially greater than that of air, due both to the dense gas and to the imbedded aerosol drops, and the resulting cloud may sink toward the ground, tend to flow downhill with gravity following the terrain, and accumulate in low-lying areas near the release site, especially under low wind conditions. Chlorine is denser than air, but chlorine can behave like a passive gas for small release quantities or high wind speeds as quantified by a Richardson number (*6.1.15*).

Auto-refrigeration will not initially be a significant factor inside the tank during the release, because nearly all of the chlorine's vaporization, expansion, and cooling occur outside the tank. Also, internal tank pressure can remain fairly constant until the liquid level approaches the breach (hole). However, once the liquid level drains below the level of the hole, the process takes on the characteristics of a "chlorine vapor release", as described in Section 2.3. At this point the remaining liquid inside the tank will boil and rapidly cool to the point where the contents have been auto-refrigerated, and the vapor will only very slowly be released thereafter.

In some cases involving a chlorine liquid release, escaping liquid may collect in a pool or flow to the lowest level. Generally, liquid chlorine will boil and be rapidly vaporized upon contact with a heat source such as the air, the ground, or water. However, as the heat sources surrounding the chlorine pool are cooled, its vaporization rate will slow and liquid chlorine can accumulate outside the tank. Pooling is more likely to be observed in releases that involve large quantities, large holes, or when the escaping jet impinges against the ground or another object. Chlorine aerosols can also be formed in a release where there is not enough heat available in the surroundings to fully vaporize the escaping liquid chlorine. Favorable conditions for the formation of chlorine aerosols can develop during the release as the area is chilled rapidly by the expanding gas. Droplets of chlorine aerosol that are small enough to be suspended reduce the cloud's transparency and can significantly add to its density. Additionally, the aerosol can undergo evaporative cooling which can further drop the cloud temperature below even the boiling point. Chlorine clouds have been measured at temperatures of -100^{o}F (-73^{o}C) and lower due to this effect.

Since water in bulk provides a vast heat source for evaporation, water will rapidly vaporize liquid chlorine upon contact. This can quickly cause a chlorine vapor cloud to grow significantly larger and more concentrated. Water should therefore not be applied to liquid chlorine, and liquid chlorine should be prevented from flowing into areas with water such as puddles, drains, and streams, ponds, or natural sources of water. Humidity in the air may result in the formation of an ice layer [consisting primarily of chlorine hydrate (freezing point of 49.3°F (9.6°C)) at a liquid pool or the container. Such effects may reduce the evaporation or release rate, and in some cases the area affected by such an incident may be lessened. None of the scenarios depicted in this pamphlet assume the formation of any such ice layer, and this possible effect is not further discussed.

2.4 Mode of Release

For modeling purposes, chlorine releases can be classified into two categories based upon the duration of the release into the atmosphere:

- Immediate/Rapid
- Continuous

An immediate/rapid release is characterized by the release of chlorine to the atmosphere in a relatively short period of time (usually less than 10 minutes), resulting in a cloud which moves downwind while diffusing and mixing with the air. Diffusion spreads out the cloud which results in it growing in size but decreasing in concentration (see Figure 2.1). Thus, the concentration of chlorine monitored at any given point downwind will vary over time depending on the position of the chlorine cloud. As depicted in Figure 2.1, the footprint of the cloud at a given concentration initially increases as the cloud expands. As the cloud continues to expand and diffuse into the atmosphere, however, the footprint will decrease along with the overall chlorine cloud concentration. The catastrophic rupture of a chlorine container is an example of an immediate/rapid release.

A continuous release is characterized by the release of chlorine to the atmosphere over a longer period of time (usually more than 5-10 minutes), resulting in a continuous plume which reaches an equilibrium size and concentration gradient (see Figure 2.2). Thus, the concentration of chlorine monitored at any given point downwind from the source will be modeled as approximately constant for the duration that the equilibrium is established. It will ramp up and tail off at the beginning and the end of the release. The failure of a valve or fitting on a large container is an example of a continuous release.

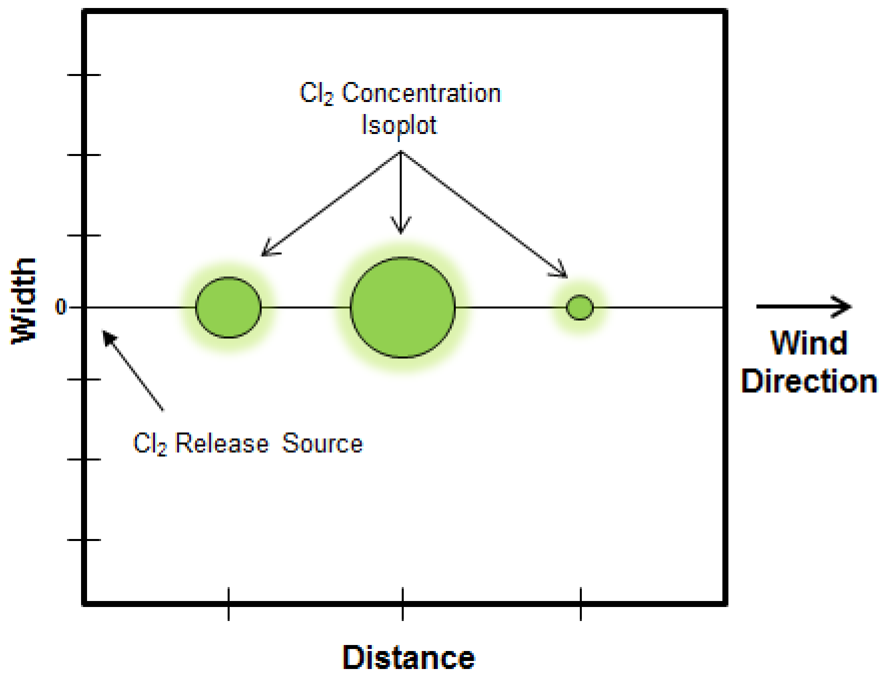

Figure 2.1 - Immediate/Rapid Release Footprint
The size and shape of any contour with constant concentration varies as the cloud goes downwind due to a variety of factors such as details of transport and dispersion and assumptions regarding deposition.

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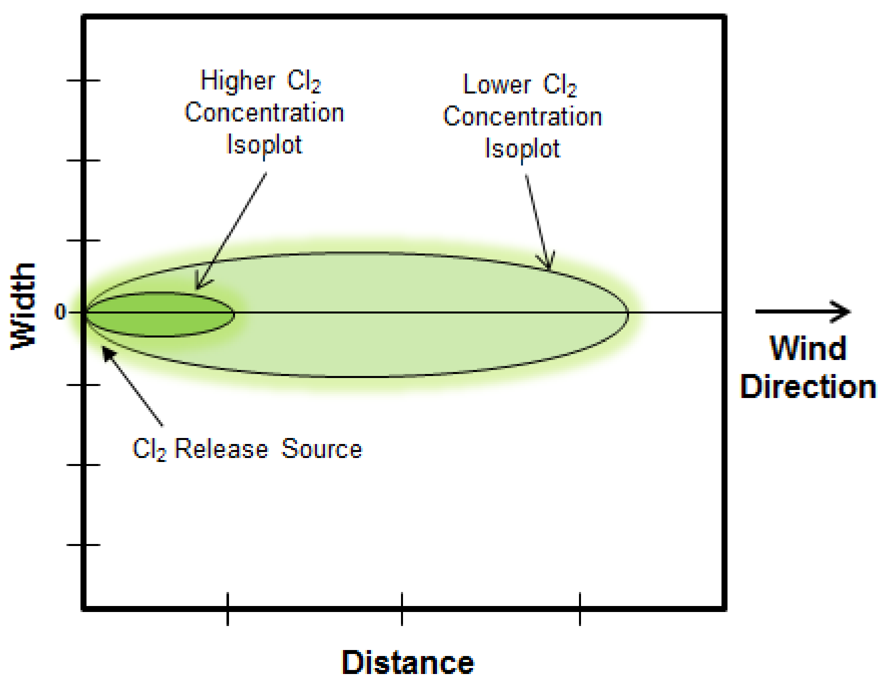


Figure 2.2 - Continuous Release Footprint
A continuous release, the concentration contours approach an equilibrium, on average. This is shown in the patterns of concentration contours in the figure. In reality, the concentrations within the cloud can exhibit significant variability and even intermittency.

3. RELEASE AND DISPERSION PHENOMENOLOGY

When chlorine is released to the atmosphere, its behavior and subsequent transport and dispersion in the atmosphere can be considered in three stages:

- Release stage
- Transition stage
- Transport and Dispersion stage

3.1 THE RELEASE STAGE

In this stage, as chlorine is released, it enters the atmosphere and begins to disperse. Initially, the release is influenced by the source conditions and by the physical properties of chlorine itself. Therefore, the factors characterizing this stage of the release include:

- The type of release (vapor, liquid, or both)
- Geometry of the source
- Location and orientation of the source
- Conditions at the source (temperature, pressure)
- Atmospheric conditions existing during the release (wind speed, temperature, solar radiation and humidity)

If vapor chlorine is released, it will start mixing with air immediately. If liquid chlorine is released under pressure, a portion of the escaping liquid is flashed off to a vapor. The remaining chlorine will either aerosolize or fall to the ground as a liquid. Figure 3.1 depicts some of these conditions.

3.2 THE TRANSITION STAGE

In this stage, the released chlorine transitions from the influence of its initial source conditions to the increasing influence of gravity and of the atmosphere. The released chlorine continues to mix with air and with moisture in the air. The cooling effect of the evaporating chlorine may cause sufficient cooling to enable the formation of an aerosol. Aerosols will contribute to the excess density of the cloud and may cool the cloud even further through evaporative cooling. Eddy currents may also form, which can enhance the turbulence and the mixing of the plume.

As the heavier-than-air chlorine plume moves downwind, the chlorine concentration at a given downwind distance will typically be higher at lower elevations than at raised elevations. However, due to internal turbulence (eddies) and atmospheric motion, the mixture is further diluted by atmospheric air as it is being transported by the wind (Figure 3.2). Eventually, the plume is diluted to the point that its density approaches that of the surrounding air and it no longer behaves as a heavy gas, ending the transition stage.

The energy and mass transfer processes taking place between the chlorine, the ground and the atmosphere (Figure 3.3), again, are approximated by complex mathematical equations.

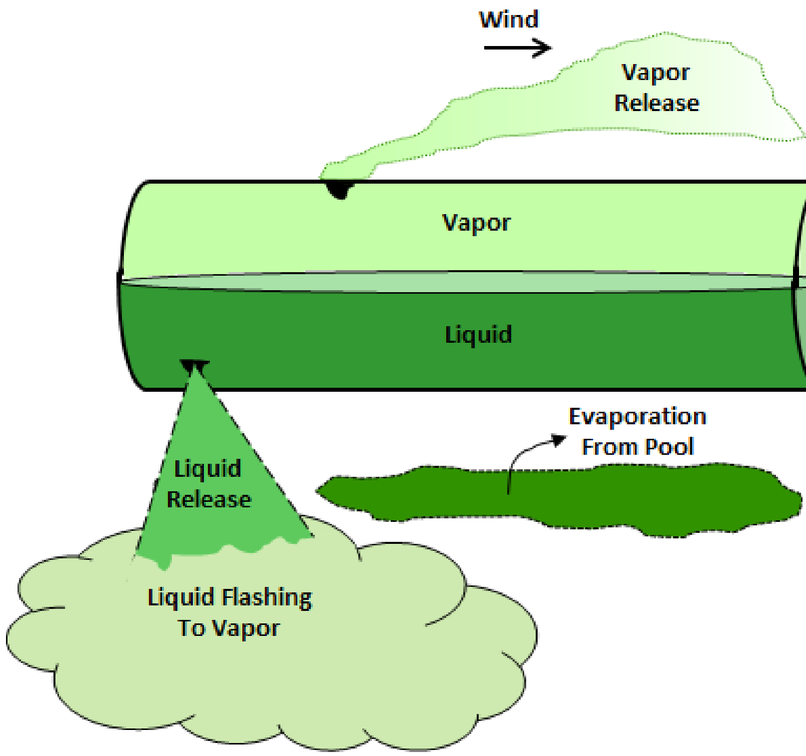


Figure 3.1 - Chlorine Vessel Leak Scenarios

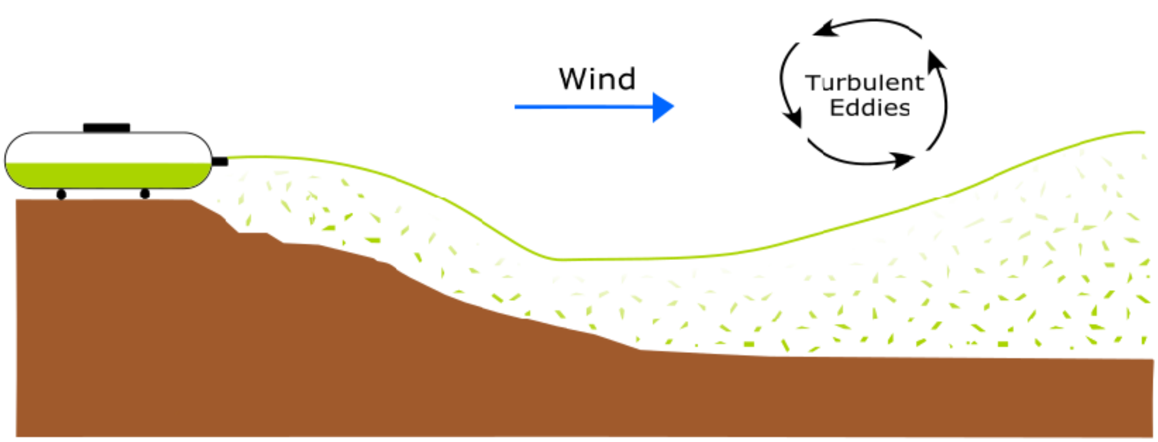


Figure 3.2 - Dense Gas Behavior

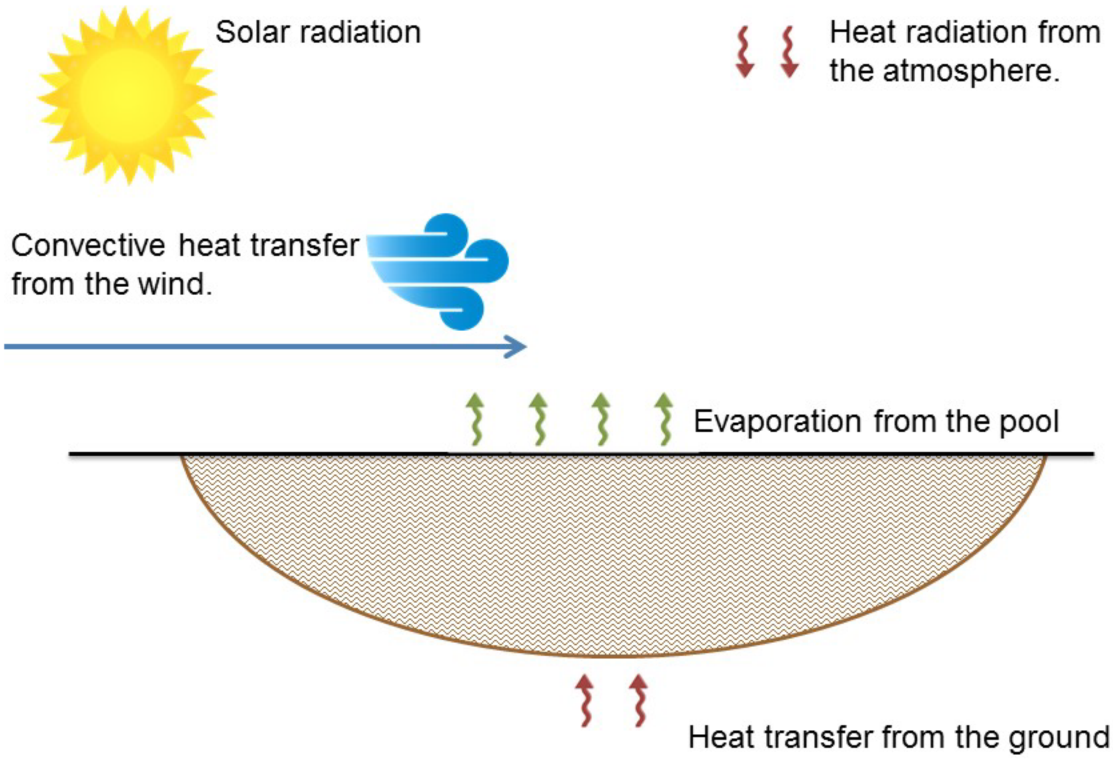


Figure 3.3 - Heat Sources Affecting Evaporation Rate

3.3 THE TRANSPORT AND DISPERSION STAGE

In the final stage, the plume is almost completely dominated by the dynamics of the atmosphere. The dynamics of the atmosphere, on the other hand, are controlled by the level of incoming solar radiation and the wind speed. This radiation causes the heating of the earth's surface, which then generates the vertical and horizontal movement of the atmosphere (wind).

Normally, the earth's surface absorbs the incoming heat and in turn heats the air layer directly above it. As a result, the ambient air temperature decreases as the altitude increases. During daytime, since the warmer air on the earth's surface has lower density, it tends to rise inducing a vertical atmospheric movement and consequently, vertical instability of the atmosphere. In this situation the atmosphere is referred to as being unstable. In the pre-dawn hours, after the earth's surface has cooled down during the evening, the reverse is true. In that case, the atmosphere is called stable. To characterize the vertical and horizontal movements (turbulence or stability) of the atmosphere, stability classes are used. Most commonly, the atmosphere is classified from Stability Class A (very unstable) to Stability Class F (very stable) (Table 3.1).

The horizontal and vertical movements of the atmosphere (turbulence) have great influence on the dispersion of the chlorine plume. In fact, in mathematical equations describing the dispersion of the plume, its spread is directly related to the stability classes. If the release lasts for an extended period of time, the change in wind direction also needs to be considered due to the possible new direction the plume might travel (Figure 3.4). Wind direction generally varies in space and time and becomes less predictable at low wind speeds.

Table 3.1: Pasquill-Turner Approach for Determining Atmospheric Stability in Rural Terrain.

Atmospheric Stability Categories

Surface Wind Speed (elevation of 10 meters) (33 ft.)		**Day**			**Night**	
		Incoming Solar Radiation			**Thinly Overcast or**	
		Strong	**Moderate**	**Slight**	**> ½ Cloud Cover**	**< ½ Cloud Cover**
m/s	ft/s					
<2	<6.6	A	A – B	B		
2 – 3	6.6 – 9.8	A-B	B	C	E	F
3 – 5	9.8 – 16.4	B	B – C	C	D	E
5 – 6	16.4 – 19.7	C	C – D	D	D	D
>6	>19.7	C	D	D	D	D

Note:

“Strong” incoming solar radiation corresponds to a solar altitude of > 60°F (>15.56°C) with clear skies.

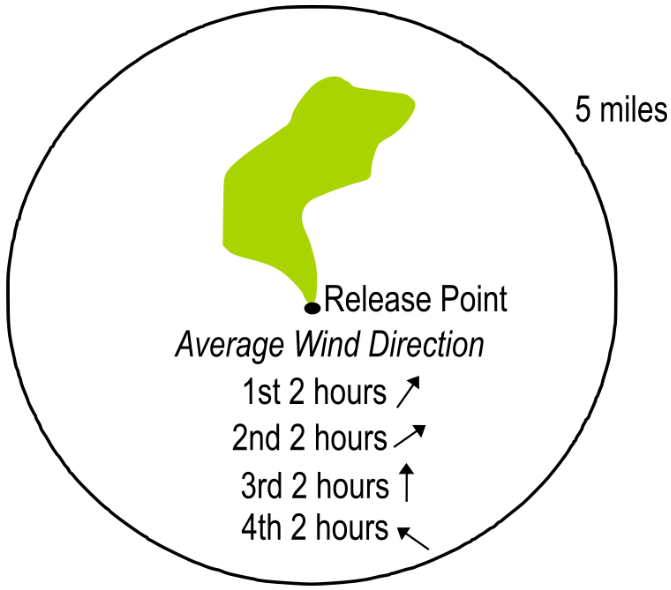
“Slight” incoming solar radiation corresponds to a solar altitude of 15°F to 35°F (-9.44°C to 1.66°C) with clear skies.

The degree of cloudiness strongly influences the incoming solar radiation and the long-wave radiation.

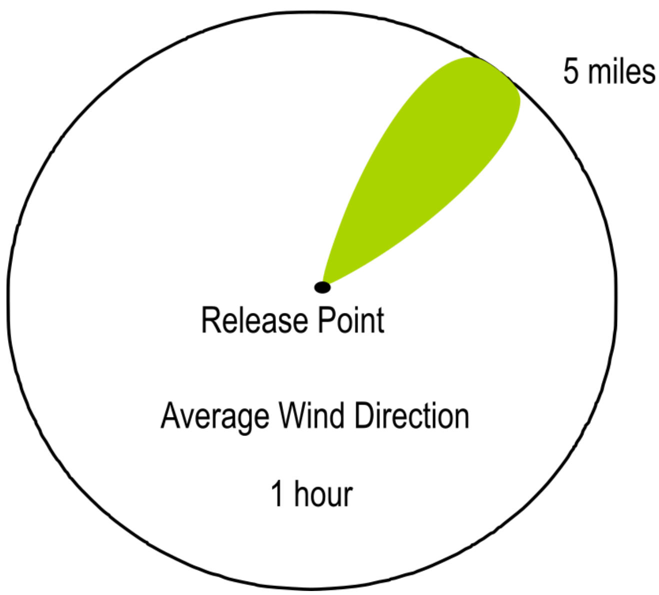
Neutral category D can be assumed for overcast conditions day or night, regardless of wind speed. “Night” refers to a period from 1 hour before sunset to 1 hour after sunrise.

*This categorization scheme applies only to rural areas (i.e., areas consisting of flat, vegetated terrain). Stability categories for urban areas are generally one or two categories more unstable than stability categories estimated for a rural area using the Pasquill-Turner approach.

Source: *Reference 6.1.15*



(a) Vapor Cloud Movement During an 8-Hour Period with a Constant Wind Speed and Direction of 8 Hours. This example has a very light wind speed of 5/8 mile per hour for continuous release over an extended period of time**.**



(b) Vapor Cloud Movement During an 8-Hour Period with a Constant Wind Speed and Direction. This example has a very light wind speed of 5/8 mile per hour for continuous release over an extended period of time.

Figure 3.4
Example of Atmospheric Dispersion of Vapor Clouds with Different Constant Wind Speed and Direction

4. MODELING ASSUMPTIONS, LIMITATIONS, AND METHODOLOGY

4.1 General

The Department of Homeland Security (DHS) Chemical Security Analysis Center (CSAC), part of the Science & Technology (S&T) Directorate, collaborated with the Chlorine Institute to develop updated guidance in this version of Pamphlet 74, based upon new experimental research into chlorine releases and the associated chemical and physical phenomena. The Hazard Prediction and Assessment Capability (HPAC) model, developed and widely used by the U.S. Government, was used to simulate the release scenarios in this pamphlet to provide new modeling results.

The HPAC software is available only to U.S. government agencies and their contractors. It cannot be acquired by private companies. Although HPAC is not available to the general public, the dispersion model within HPAC is called SCIPUFF. SCIPUFF does have different versions for different applications with different capabilities, but they all use the same basic dispersion model. There is an older, public domain version of SCIPUFF available from Xator/Sage website (*6.1.23*), but it does not have dense gas capabilities. A current version is available from EPRI (Electric Power Research Institute) as SCICHEM (*6.1.17*), and that should be able to produce the same, or very similar, results to HPAC for the Pamphlet 74 calculations.

4.2 Limitations of Modeling

The real-world transport and dispersion of a chemical release through the atmosphere is a very complex phenomenon. Every chemical will move and interact with its surroundings differently due to its own unique physical and chemical characteristics. The chemical's dispersion and the area impacted is also highly dependent upon the specifics of the release source (known as the "source term"), which includes the amount, rate, and direction of release, and the chemical's phase upon release (i.e. vapor, liquid, aerosol). Additionally, dispersion is affected by a great number of environmental variables such as temperature, wind direction and velocity, moisture (humidity, precipitation, bodies of water), the surface roughness near the release, vegetation, and many other components. With this inherent complexity, all models must make simplifying assumptions. It follows that all attempts to exactly model a chemical release via a mathematical algorithm must, by the limitations of the technology, be only an approximation. The accuracy of the model's estimation of cloud transport and dispersion is determined by both the assumptions and approximations contained within the model, by the assumptions made by the user, and by the accuracy of the input data and parameters used in the simulations.

Data sets from real-world chemical releases are very limited, and for many chemicals, the extensive experimentation and research needed to generate reliable data for atmospheric dispersion is also limited or nonexistent. Using available data, many mathematical models have been compared to real world releases. It is generally accepted that a model that predicts the atmospheric concentration of a chemical release within a factor of 2 (model prediction falls between one half and twice the actual concentration) if operating within the limits of current modeling technology. Such uncertainty factors are particularly relevant when looking at the low concentrations that are discussed in this pamphlet.

Even with the limits of the technology, dispersion modeling still provides the best working estimate of the potential impact of a chemical release. Such modeling is a useful tool that contributes to the continuous improvement process for chemical operations. As a screening tool, dispersion modeling can help establish priorities for detailed analysis, and as a portion of the detailed analysis, modeling can help guide, plan, and evaluate mitigation opportunities. Additionally, it is through the understanding of the potential impact of an incident that appropriate emergency response plans and procedures are developed to minimize the impact on the community and the environment should a chemical release occur.

Several chlorine release scenarios are described within this pamphlet. Each scenario has been modeled under a range of meteorological conditions and other variables. The information developed as a result of this modeling exercise is intended to allow the reader to appreciate the magnitude of a potential chlorine release and its expected hazard extent. However, it is impossible to represent here every possible combination of meteorological conditions, release configurations, and environmental variables. The reader should consider additional detailed modeling studies, beyond the scope of this pamphlet, as required to understand and mitigate the specific risk associated with the storage and/or use of chlorine for other unique and relevant scenarios.

For a variety of reasons there may be a need to evaluate scenarios beyond those presented in this pamphlet. Because of model variability in predictions of alternate models and source terms, it is highly desirable that outputs from the same computer model and methodology be compared whenever possible. This pamphlet provides all the release and meteorological conditions used to model each scenario. If a model other than HPAC is used, it is recommended that this model be used to simulate each of the worst-case and alternate scenarios from this pamphlet. Side-by-side comparisons of the relative impact from various release scenarios will be more meaningful using this approach.

To use the same modeling input and setup conditions in CI Pamphlet 74 in another model, please refer to that model's technical documentation. The services of an experienced modeling professional should be sought if needed. The U.S. Environmental Protection Agency provides several reference sources for modeling and other information pertaining to consequence analysis methods.

4.2.1 Scalability of Results

In many aspects, the behavior of chlorine (gas and/or aerosol) in the atmosphere is a standard fluid dynamics problem that can be described by non-dimensional numbers such as Reynolds number and Froude number. Therefore, for many important scenarios it is possible to carry out a dense gas transport and dispersion experiment in a wind tunnel and consider that the results apply to a full-scale dense gas release. For example, Snyder (*6.1.5*) and Briggs et al. (*6.1.3*) analyze results of dense gas dispersion studies in three wind tunnels. The release was CO_2 gas from a square area source at ground level. Roughness obstacles were an array of flat “billboards” set up perpendicular to the flow. The scenario was intended to simulate the release of a dense gas in a chemical processing plant. Yet the reader should note that the two references address mainly the vertical entrainment of ambient air into the plume, since wind tunnels are not so good at simulating the lateral meandering motions in the real atmosphere. Also, CO_2 gas was used and released at small velocity.

Problems such as momentum jets, effects of aerosols, and real topography were not addressed.

The Jack Rabbit I (chlorine and anhydrous ammonia) and Jack Rabbit II (chlorine) experiments took place in a real field situation with substantial masses of chlorine released (1 to 20 tons). The chlorine was stored as a pressurized liquefied gas, and the releases involved a powerful two-phase momentum jet. The flashed liquid had a median drop size of about 50 to 100 microns, which means that there was limited rainout and the aerosol is carried downwind by the jet and subsequent cloud. The small aerosol drops quickly evaporate, within about one minute. The aerosol drop size and the evaporation phenomenon are major aspects that are not scalable.

Another phenomenon that is not scalable is the modification of the ambient airflow and stability over a large chlorine release. The airflow is modified by the presence of a shallow dense cloud at -29.2°F (-34°C). The ambient air will flow over the dense cloud, and will be cooled where it meets the top of the chlorine cloud, generating a very stable boundary layer just over the chlorine cloud.

4.3 WORST-CASE SCENARIO ASSUMPTIONS AND PARAMETERS

Section 5 of this pamphlet contains release scenarios involving standard chlorine containers utilizing the methods prescribed by EPA in its RMP Offsite Consequence Analysis Guidance (*6.1.6*) and as outlined by regulation in 40 CFR 68 for worst-case and alternate scenarios. The scenarios, accompanying assumptions, and chosen modeling parameters are designed to conform to the EPA's RMP regulation and guidance document (*6.1.10), Chapter 4: Offsite Consequence Analysis*. It should be noted that in that document, the EPA states (bold emphasis added):

> Bear in mind that the results you obtain from modeling your worst-case or alternative scenarios should not be considered to predict the likely results of an accidental release. The worst-case assumptions are very conservative, and, regardless of the model used, you can expect very conservative results. Results from modeling alternative scenarios will be less conservative; however, you still must use conservative endpoints.
>
> In addition, results of an actual release will depend on many site-specific conditions (e.g., wind speed and other weather conditions) and factors related to the release (e.g., when and how the release occurs, how long it takes to stop it). You should make reasonable assumptions regarding such factors in developing your alternative scenarios, but the circumstances surrounding an actual release may be different. Different models likely will provide different results, even with the same assumptions, and most models have not been verified with experimental data; **therefore, results of even sophisticated modeling have a high degree of uncertainty and should be viewed as providing a basis for discussion among the regulated community, emergency planners and responders, and the public, rather than predictions.** Modeling results should be considered particularly uncertain over long distances (i.e., 6.21 miles (10 kilometers) or more).

All of the worst-case scenarios depicted in this pamphlet involve transportation containers. These have been selected because they represent various size containers in common use. Facilities must individually determine whether the use of any of these scenarios satisfies the requirements of EPA's Risk Management Rule (*6.1.1*). Inputs common to these worst-case scenarios are as follows:

Parameters Required by RMP Regulation:

- The ambient relative humidity is 50%
- The ambient temperature is 77°F (25°C)
- Liquid chlorine is at 77°F (25°C) and 100 psig (690 kPa) before the release
- Wind speed of 3.36 miles per hour (1.5 meter/second)
- The atmospheric stability is class F
- The release occurs at ground level
- The entire contents of the container are released rapidly as a 100% vapor at a constant rate over a ten-minute period
- No liquid pooling
- Use of ERPG-2 concentration value (3 ppm) for the toxic endpoint

Common Parameters Chosen for this Pamphlet:

- Concentration averaging time is 10 minutes
- Surface roughness is 0.001 meters. Such a surface roughness corresponds to a relatively flat, grassy, rural setting. This is based on assuming a desert/bare ground surface. Source for this is table 10-1 from Sykes et al, SCIPUFF Version 3.0 Technical Documentation, Sage Management, 2016 *(6.1.16, 6.1.19)* An urban environment or over water may have significantly different surface roughness and slightly different toxic endpoints.
- Solar radiation is assumed at 0 Btu/hr/ft2 (i.e., the sun is not shining at all)
- Receptor height of 0 feet
- Chlorine reactivity/soil deposition of 0.04 cm/s (0.0157 inches)

Background on Select Parameters

Some of the modeling parameters are not stipulated in 40 CFR 68.22. This section will provide background on why some of the parameters were chosen.

Averaging Time

Averaging time is the length of time in atmospheric dispersion modeling or field experiments over which concentration data are averaged. During the sensitivity tests to determine which averaging time produced the most conservative modeling results for this pamphlet, the same scenario was run using 10, 30, and 60 minute averaging times. Ten minutes consistently produced a more conservative result, that is the largest downwind extent, and was thus used for the worst-case scenarios. We note that for other scenarios, it is possible that a different averaging time will produce the more conservative result.

Surface Roughness

40 CFR 68.22(e) states, “The owner or operator shall use either urban or rural topography, as appropriate. Urban means that there are many obstacles in the immediate area; obstacles include buildings or trees. Rural means there are no buildings in the immediate area and the terrain is generally flat and unobstructed.”

The surface roughness chosen, 0.001 meters, is based on assuming a desert/bare ground surface, since the Jack Rabbit tests (*Appendix C*) were done in the desert. The source for this is table 10-1 from Sykes et al, SCIPUFF Version 3.0 Technical Documentation, Sage Management, 2016 *(6.1.16, 6.1.19).* An urban environment or over water may have significantly different surface roughness and slightly different toxic endpoints.

Solar Radiation

Solar radiation has two effects: 1) It can modify the stability of the ambient atmosphere, and 2) it can add energy to the chlorine cloud, possibly enhancing dispersion. To present the more conservative results, zero solar radiation was used.

Receptor Height

The EPA’s General Risk Management Program Guidance, Introduction Section, defines a “public receptor” as “any place where people live, work, or gather, with the exception of roads. Buildings, such as houses, shops, office buildings, industrial facilities, the areas surrounding buildings where people are likely to be present, such as yards and parking lots, and recreational areas, such as parks, sports arenas, rivers, lakes, and beaches, are considered public receptors.” The same document defines an environmental receptor as “a limited number of natural areas that are officially designated by the state or federal government” (*6.1.9*). The release is assumed to be at ground level. Since chlorine is heavier than air, it will tend to sink to the ground in any case. For this reason, in a given chlorine cloud the concentration will be highest near the ground and decrease with height. To present more conservative results, a receptor height of zero feet was used.

Soil Deposition/Chlorine Reactivity

Chlorine is a highly reactive chemical that will readily react with many substances found in outdoor environments, including organic matter like vegetation and soil, and many metals. With these reactions, the size of the cloud may be reduced as the chlorine is used up as a reactant in various chemical reactions at the surface. In these scenarios, the limiting reagent is the *other* reactant (for example, vegetation). Consistent with inferences from the Jack Rabbit II testing at a bare salt playa at Dugway Proving Ground, Utah, a low chemical reactivity and deposition velocity was observed. Based on knowledge of reactivity of chlorine over salt playas, a deposition velocity value of 0.04 cm/s (0.0157 inches) was used here to represent that. This is a conservative assumption, as it results in a minimal removal of chlorine from the cloud. More deposition and hence lower concentrations of chlorine gas in the cloud may occur in locations with more abundant vegetation or soil with organic content (*6.1.16, 6.1.19*).

4.4 Alternate Scenario Assumptions and Parameters

Section 5 describes alternative release scenarios involving transportation containers and equipment in use at chlorine production and/or use facilities. Facilities must individually determine whether the use of any of these scenarios satisfies the EPA regulatory requirements for worst case and alternate scenarios (*6.1.1*).

Parameters Required by RMP Regulation:

- Use of ERPG-2 concentration value (3 ppm) is used for the toxic endpoint

Common Parameters for Alternative Case Scenarios Chosen for this Pamphlet:

- The ambient relative humidity is 50%
- The ambient temperature is 77°F (25°C)
- The initial substrate temperature is 77°F (25°C)
- Liquid or gaseous chlorine is at 77°F (25°C) and 100 psig (690 kPa) before the release
- Surface roughness is 0.001 meters (0.0393 inches). Such a surface roughness corresponds to a relatively flat, grassy, rural setting. This is based on assuming a desert/bare ground surface. Source for this is table 10.1 from Sykes et al, SCIPUFF Version 3.0 Technical Documentation, Sage Management, 2016 (*6.1.14, 6.1.18).* An urban environment or over water may have significantly different surface roughness and slightly different toxic endpoints.
- Minimum pool depth is 0.394 inches (1 centimeter)
- The pool temperature is allowed to drop

- Averaging time used is as follows: If the release duration is greater than 10 minutes, one hour averaging time is used. Otherwise, a 10-minute averaging time is used.
- Receptor height is 0 feet (ground level)
- The model determines whether there is aerosol formation
- If aerosol has formed, it is assumed to evaporate at the source
- Chlorine reactivity/soil deposition velocity of 0.04 cm/s (0.0157 inches)
- For liquid releases, a vapor fraction of 80%; 80% of the release is vapor, 20% is liquid

Changes in the assumptions about the temperature and pressure of the chlorine prior to the release could significantly affect the dispersion. As stated in Section 1.9, the user of this pamphlet should consult with a person skilled in the modeling of heavy gases if different assumptions are used.

4.4.1 Background on Select Parameters

Some of the modeling parameters are not stipulated in 40 CFR 68.28. This section will provide background on why some of the parameters were chosen.

Averaging Time

Averaging time is the length of time in atmospheric dispersion modeling or field experiments over which concentration data are averaged.

Surface Roughness

40 CFR 68.22(e) states "The owner or operator shall use either urban or rural topography, as appropriate. Urban means that there are many obstacles in the immediate area; obstacles include buildings or trees. Rural means there are no buildings in the immediate area and the terrain is generally flat and unobstructed."

The surface roughness chosen, 0.001 meters (0.0393 inches), is based on assuming a desert/bare ground surface, since the Jack Rabbit tests (*Appendix C*) were done in the desert. Source for this is table 10.1 from Sykes et al, SCIPUFF Version 3.0 Technical Documentation, Sage Management, 2016 (*6.1.16, 6.1.19*). An urban environment or over water may have significantly different surface roughness and slightly different toxic endpoints.

Solar Radiation

As discussed in Section 3.2, solar radiation adds energy to the cloud, facilitating quicker dispersion. To present the more conservative results, zero solar radiation was used. All modeling runs used a release time of midnight on the 0,0 latitude and longitudinal coordinates, therefore solar radiation is not a factor in the results presented in this pamphlet.

Receptor Height

The EPA's General Risk Management Program Guidance, Introduction Section, defines a "public receptor" as "any place where people live, work, or gather, with the exception of roads. Buildings, such as houses, shops, office buildings, industrial facilities, the areas surrounding buildings where people are likely to be present, such as yards and parking lots, and recreational areas, such as parks, sports arenas, rivers, lakes, and beaches, are considered public receptors." The same document defines an environmental receptor as "a limited number of natural areas that are officially designated by the state or federal government" (*6.1.9*). Chlorine is heavier than air, which means it will sink to the ground. For this reason, without another strong force to cause the chlorine to rise, such as wind, in a given chlorine cloud the concentration will be highest near the ground and decrease with height. A height of zero was used in the modeling methodology.

Soil Deposition/Chlorine Reactivity

Chlorine is a highly reactive chemical that will readily react with many substances found in outdoor environments, including organic matter including vegetation and many metals. With these reactions, the size of the cloud is reduced as the chlorine is used up as a reactant in various chemical reactions. In these scenarios, the limiting reagent is the other reactant (for example, vegetation). To account for this finite ability for the cloud to reduce size due to reactions, a soil deposition value of 0.04 cm/s (0.0157 inches) was used.

Release Rates

The release rate for the alternative scenarios were originally calculated in prior versions of Pamphlet 74 using the Systemic Approach for Emergency Response/Toxic Release Analysis of Chemical Emissions (SAFER/TRACE™) (*Appendix D).* For this edition, these flow rates were recalculated using EPA's Areal Locations of Hazardous Materials (ALOHA®) tool (*6.1.3*). Since most of the flow rates calculated using ALOHA were within approximately 5% or less of the original SAFER/TRACE™ calculations, the original flow rates were used. There were three scenarios (1-inch liquid piping failure, 150-lb (68.04 kg) valve failure, and ton liquid valve failure) in which the SAFER/TRACE™ and ALOHA calculations were very different. In these incidents, ALOHA calculations were used and compared to the experience of CI members. Appendix D details the SAFER/TRACE™ flow rate calculations.

4.5 DRY DEPOSITION

There are two types of deposition – wet and dry deposition. Wet deposition occurs when ambient rain drops or snowflakes pass through the chlorine cloud. Dry deposition occurs in the absence of rain or snow, when the base of the chlorine cloud reacts with the material covering the ground. Dry deposition is commonly parameterized by the dry deposition velocity v_d (units of cm/s):

Deposition to the surface in g/cm^2 = v_d C, where C is the chlorine gas concentration at the surface (in g/m^3). For reactive chemicals like chlorine, the dry deposition velocity depends on the underlying surface.

As mentioned previously chlorine readily reacts with many types of materials and vegetation commonly found in the environment. However, chlorine gas is not very reactive when flowing over water or a dry desert. Because of the pamphlet's conservative approach, a very low dry deposition velocity of 0.04 cm/s is being assumed. See references *6.1.2, 6.1.8, 6.1.11, and 6.1.20*. Appendix E elaborates on this concept.

4.6 TOPOGRAPHY

Chlorine gas is over two times heavier than air, thus it has a tendency to sink and settle in low places. This density effect is important, though, only for large quantities of released chlorine and for slow wind speed. A small leak of chlorine gas will not exhibit dense gas behavior because it quickly mixes with ambient air and is diluted to very small concentrations. However, the density affect is important for accidents where more than about 100 kg (220.46 lbs) is released in less than about a minute. In such cases, changes in topography can dramatically affect chlorine transport and dispersion, as discussed in Section 2.2 and 3.2.

4.7 SOURCES OF ATMOSPHERIC DATA

For modeling purposes, historic weather data can be taken from an on-site weather station or from the closest station of the National Weather Service (NWS). Prior to preparing an agency-mandated study using data from an on-site station, it would be prudent to verify whether the reviewing regulatory agency has adopted any instrument and testing standards. This data can be entered into a model manually or imported as an electronic file. Electronic weather data are available from the EPA Office of Air Quality Planning and Standards (OAQPS) and from the National Weather Service. Electronic data often require preprocessing before they are in a form usable by a given model. Weather data may also be available from commercial sources.

A common problem in accidental release of chlorine is that the accident involves a railcar or truck, which can be anyplace, and is unlikely to be right next to a wind measuring station. The nearest NWS station might be several miles away and in different topography. Wind direction can easily be 180° degrees off.

4.8 UNDERSTANDING THE OUTPUTS

The results presented in this pamphlet are for the scenarios as shown, with the assumptions detailed here. Care should be taken when interpolating results as concentration is not linear with distance. Any change in the scenario or source term could result in different model predictions in a non-linear fashion. It cannot be assumed, for example, that if the release amount were doubled that the size of the cloud would be doubled. Detailed modeling by skilled modeling specialists is needed to determine modeling results for scenarios not listed here.

Appendix B provides a detailed explanation of how to interpret each of the outputs.

5. CHLORINE RELEASE SCENARIOS

Each of the following examples gives an estimate for the hazard area affected by a chlorine release under a given scenario. The scenarios were selected to give a wide range of potential release quantities and conditions. Also included are four (4) examples developed to demonstrate worst-case conditions as defined by the Environmental Protection Agency (*6.1.1.* and *6.1.6*). Appendix A gives additional information explaining the computer model utilized to make the estimates. The footprints depict downstream and crosswind distances at which chlorine sustains a concentration of at least 3 ppm and 20 ppm for at least 10-minutes. This depiction is different from the American Industrial Hygiene Association (AIHA) Emergency Response Planning Guidelines' definition of ERPG-3 and ERPG-2, which is a *1-hour* dosage at or above 3 ppm and 20 ppm, respectively (*6.1.7*). In addition to the footprint type of outputs, three additional outputs are included. There are two graphs that display instantaneous chlorine concentration versus time. This output provides information on the time a sensor placed directly downwind from the release will read a particular instantaneous concentration of chlorine. Each line represents a different downwind distance; two graphs were provided for ease of use. The final output shows the maximum or peak concentration of chlorine at a specific distance and downwind from the source. While the footprint output is both common and useful, it does not allow for a determination of how high the concentration of chlorine might be within the overall cloud. This output will allow the reader to determine the maximum distance that a cloud will travel at chlorine concentrations other than 3 or 20 ppm.

Appendix B provides additional information concerning how to interpret the output graphs.

5.1 CYLINDER SCENARIO MODELING RESULTS

5.1.1 Worst-Case 150-lb. (68.04 kg) Chlorine Cylinder Scenario – F Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	150 lb.	68.04 kg
Total Mass Released	150 lb.	68.04 kg
Release Duration	10 minutes	
Release Rate	15 lb./min	6.804 kg/min
Gaussian Spread[1]	0.44 ft	0.133 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

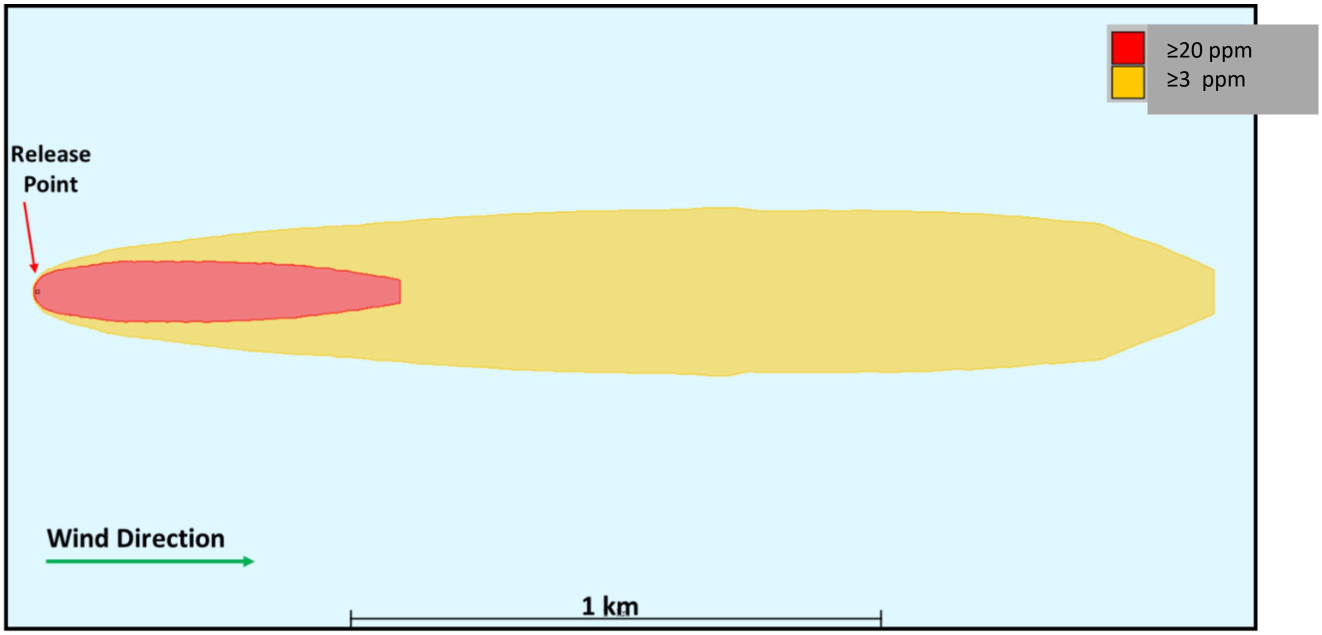
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

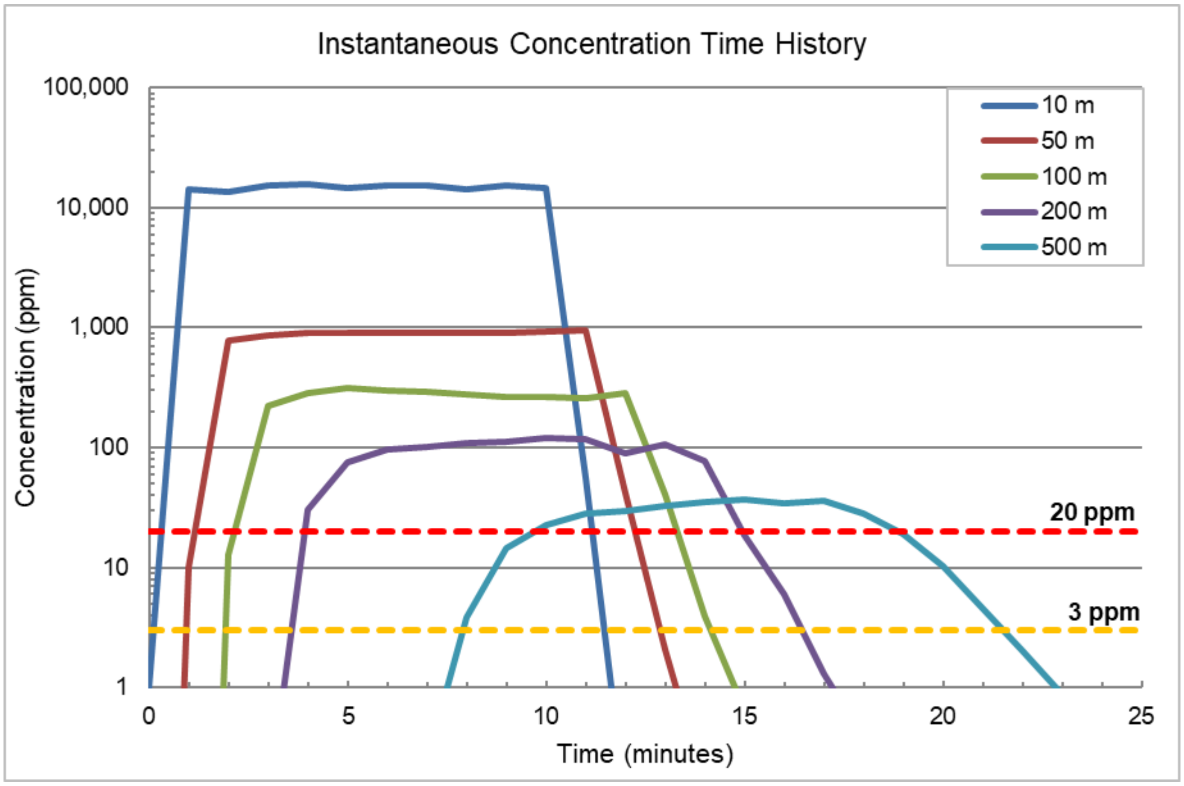
150 lb. (68.04 kg) Chlorine Cylinder

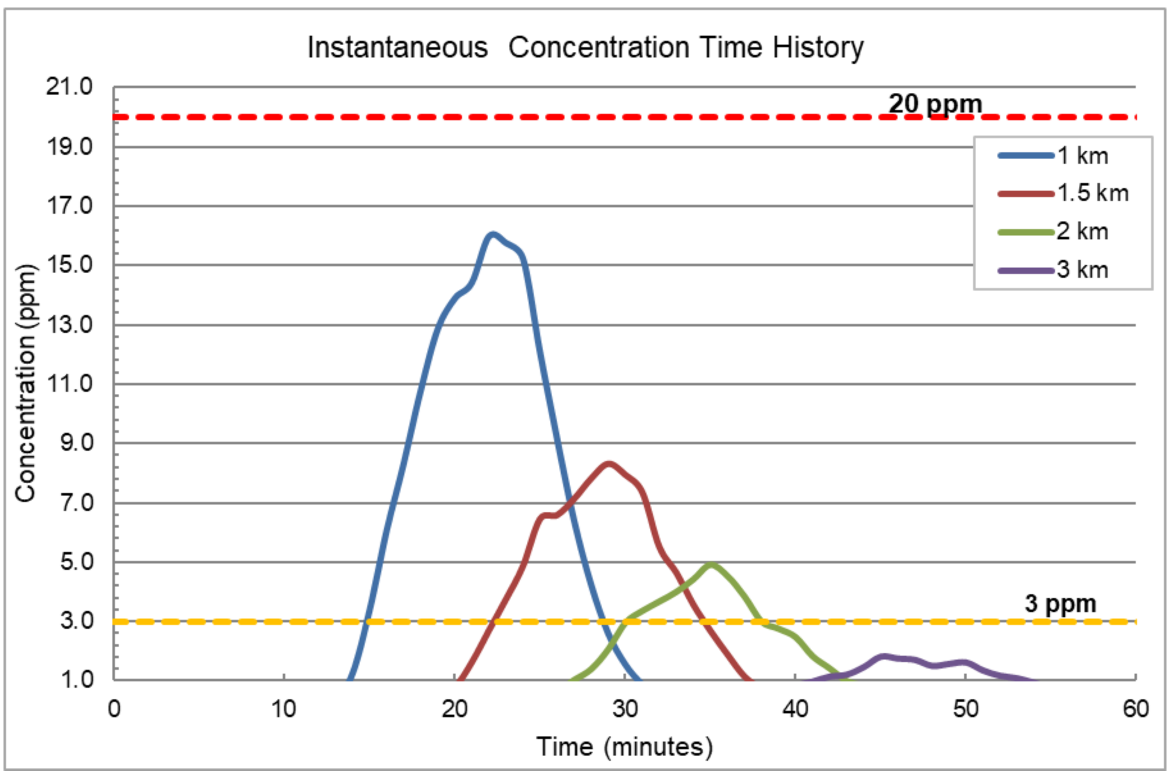


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.39	0.43
Kilometers	2.23	0.69
Maximum Crosswind Width		
Miles	0.18	0.07
Kilometers	0.29	0.11
Area Coverage		
Sq. Miles	0.20	0.02
Sq. Kilometers	0.52	0.06

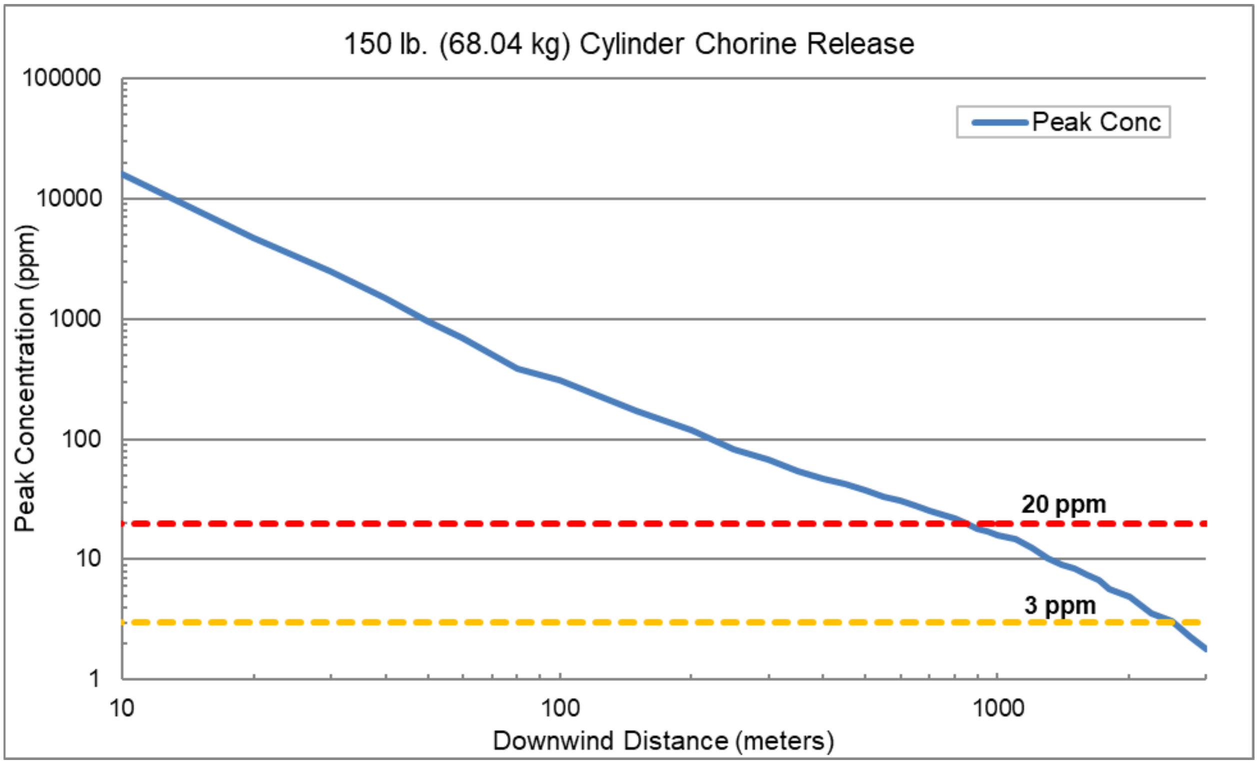
*Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.1.2 Worst-Case 150-lb. (68.04 kg) Chlorine Cylinder Scenario – D Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	150 lb.	68.04 kg
Total Mass Released	150 lb.	68.04 kg
Release Duration	10 minutes	
Release Rate	15 lb./min	6.804 kg/min
Gaussian Spread[1]	0.44 ft	0.133 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

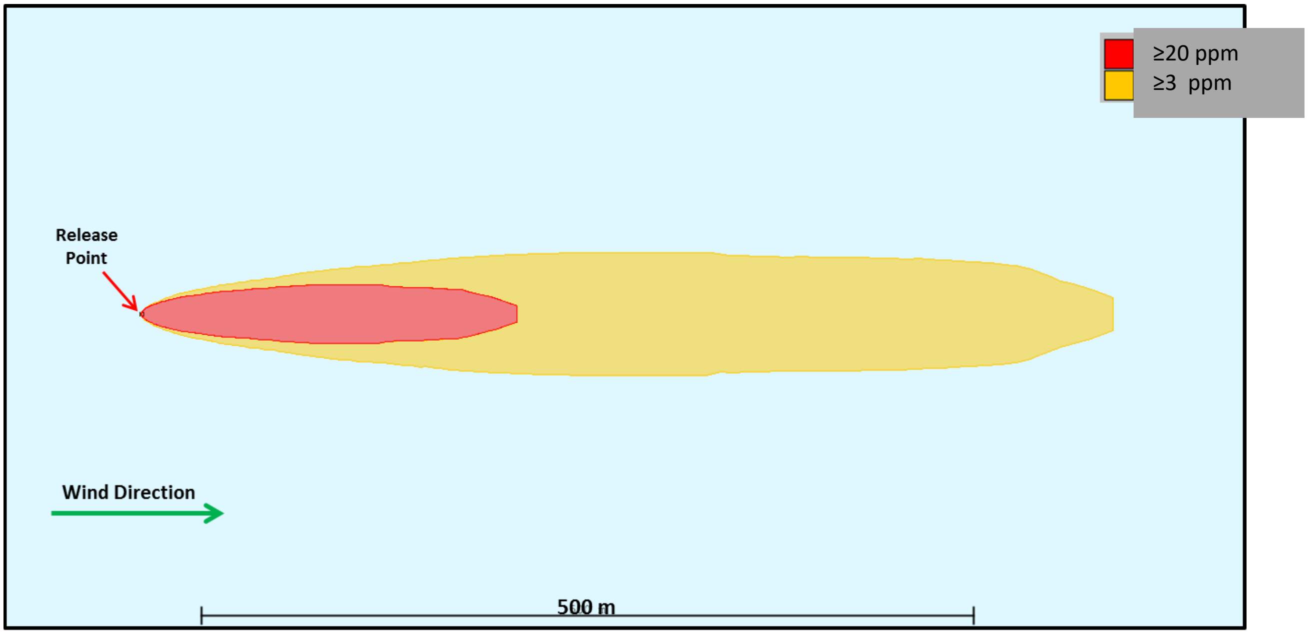
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction / Plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

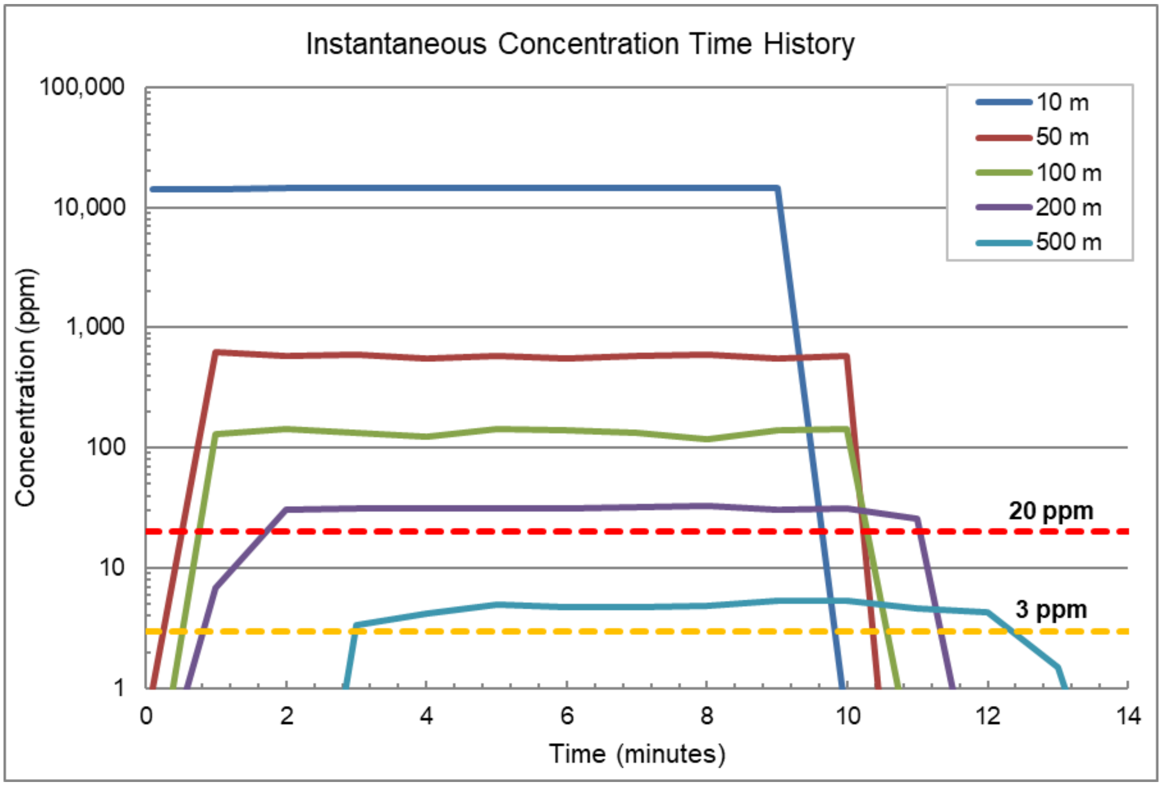
150 lb. (68.04 kg) Chlorine Cylinder

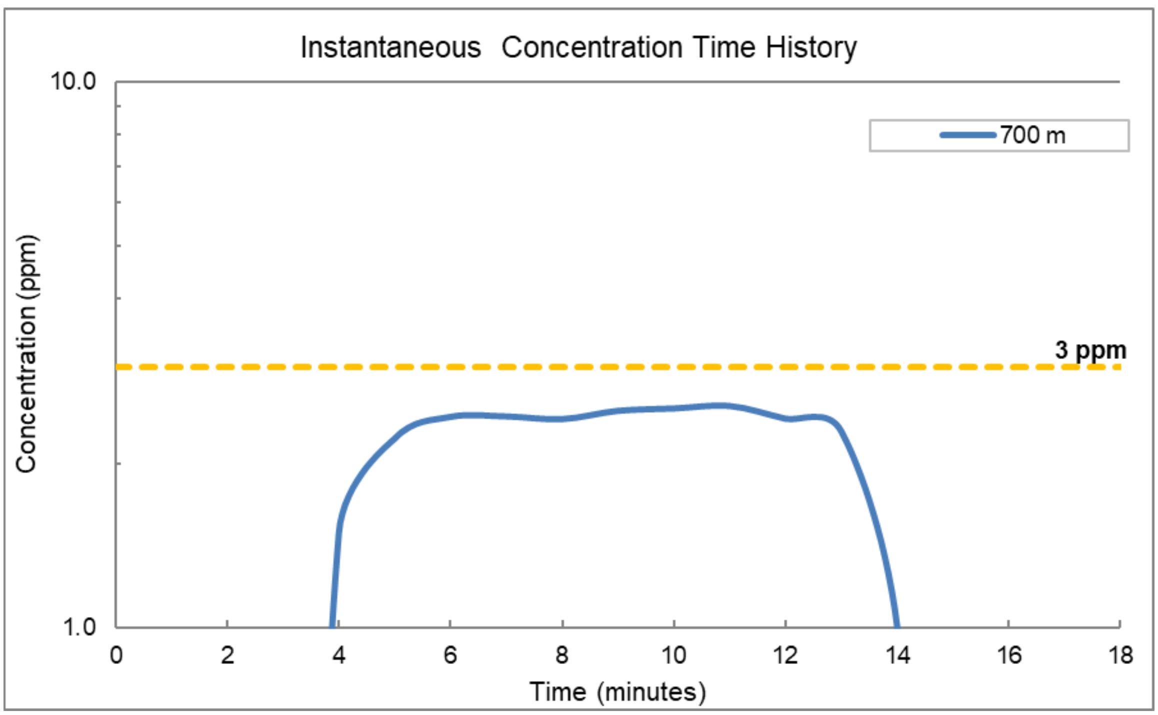


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.39	0.15
Kilometers	0.63	0.24
Maximum Crosswind Width		
Miles	0.047	0.022
Kilometers	0.075	0.035
Area Coverage		
Sq. Miles	0.0142	0.0026
Sq. Kilometers	0.0368	0.0067

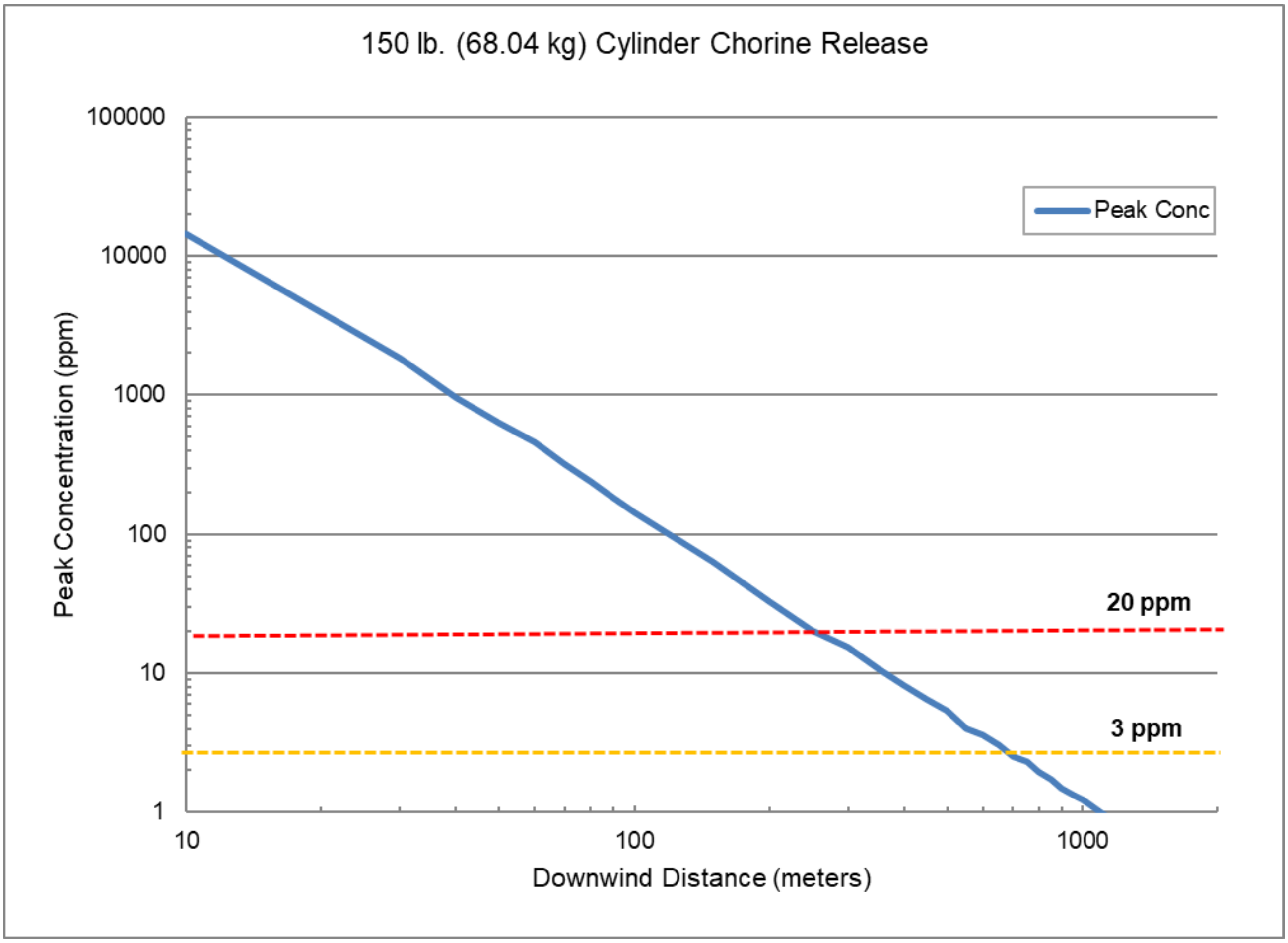
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.1.3 Alternative-Case 150 lb. (68.04 kg) Valve Failure Scenario – F Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	150 lbs. Cylinder	
Release Mechanism	Valve Failure	
Hole Elevation	0 ft.	0 m
Opening Diameter	3/16 inch	0.48 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	150 lbs.	68.04 kg
Release Rate	26 lbs./min	11.8 kg/min
Release Duration	5.8 minutes	
Total Mass Released	150 lbs.	68.04 kg
Gaussian Spread[1]	0.078 inch	0.79 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

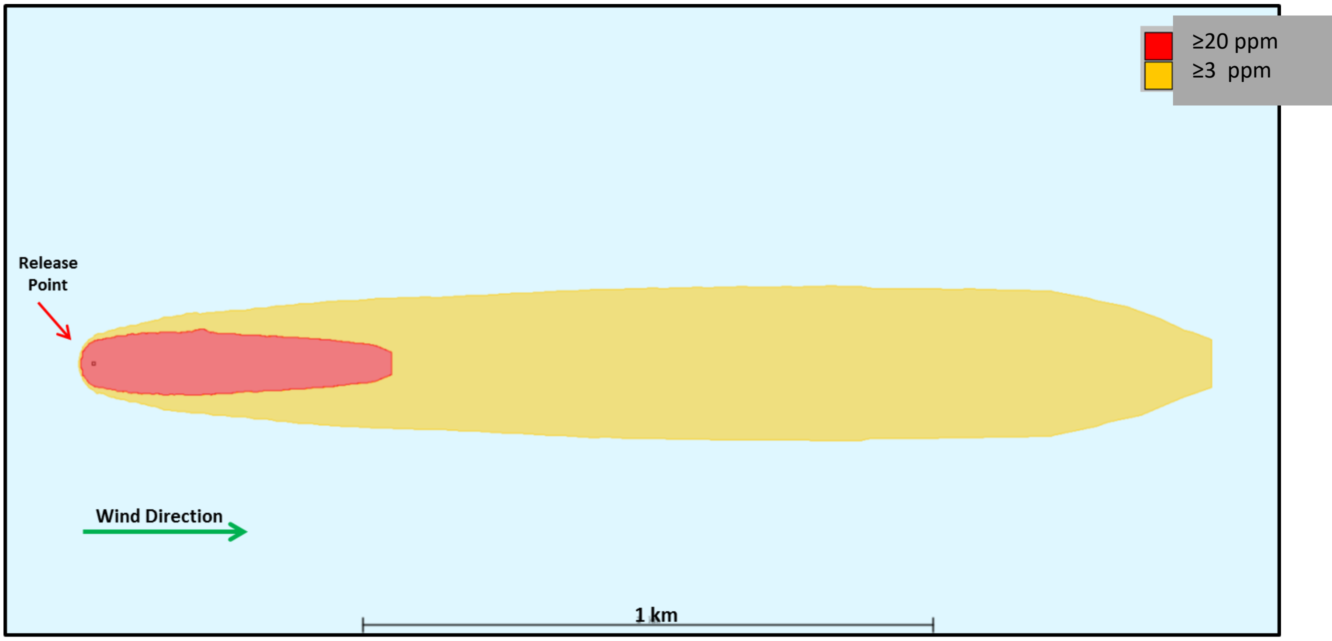
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

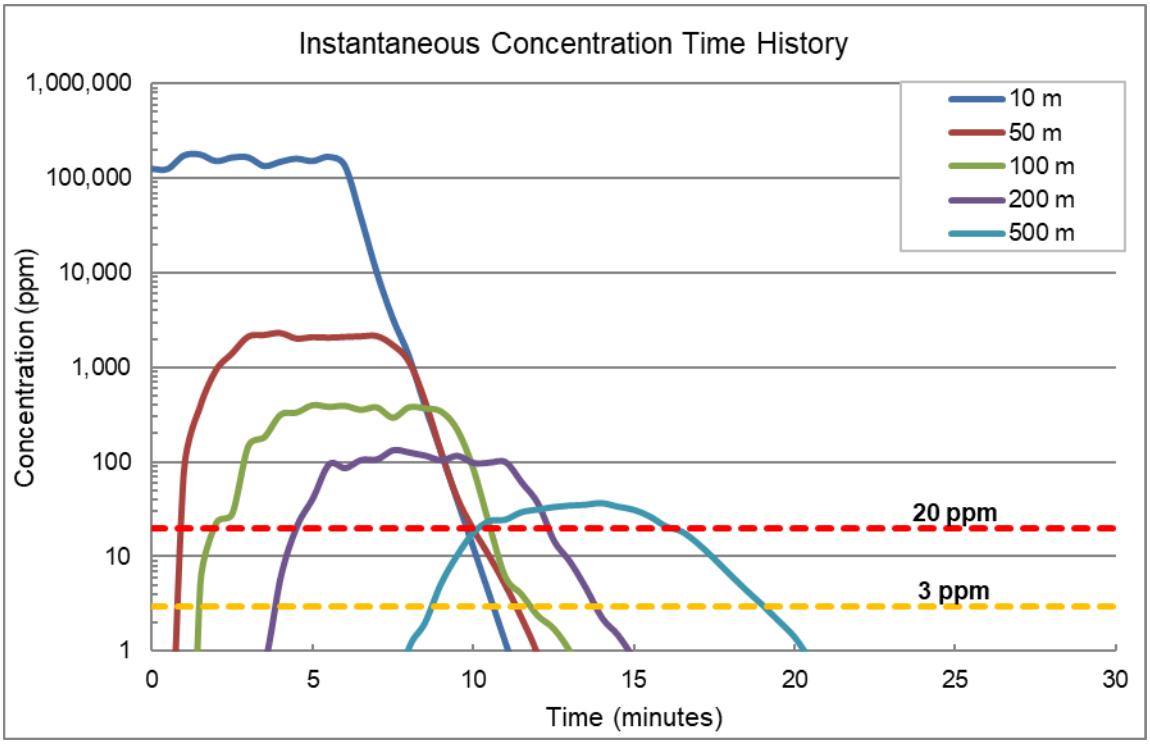
150 lb. (68.04 kg) Valve Failure

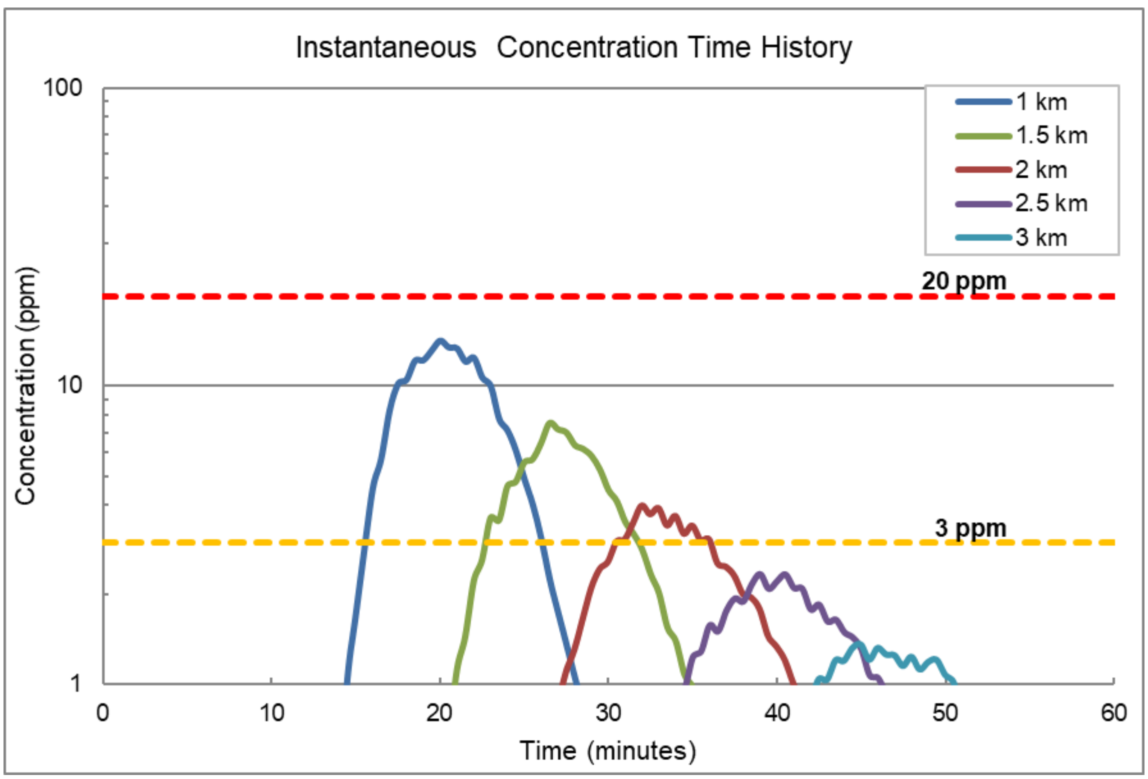


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.22	0.326
Kilometers	1.97	0.524
Maximum Crosswind Width		
Miles	0.155	0.065
Kilometers	0.250	0.104
Area Coverage		
Sq. Miles	0.159	0.018
Sq. Kilometers	0.412	0.046

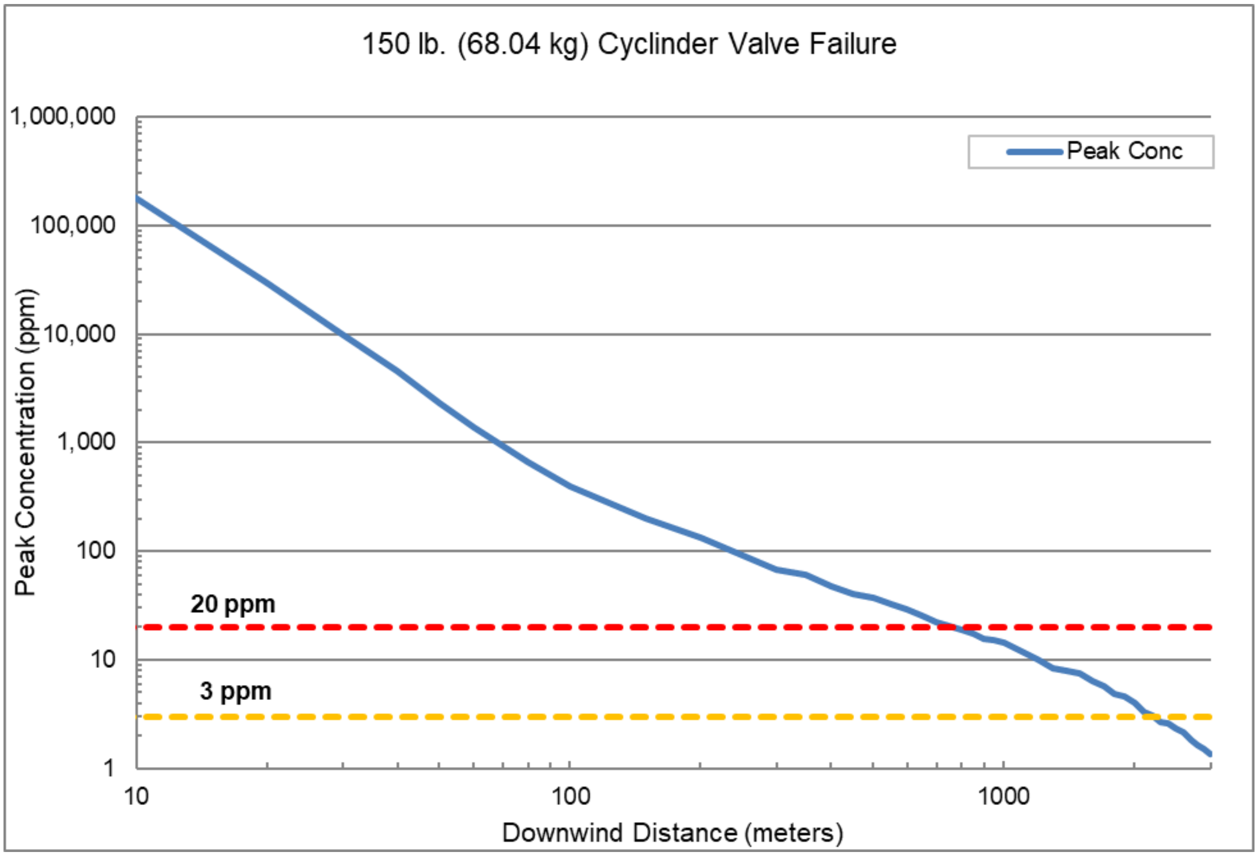
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.1.4 Alternative-Case 150 lb. (68.04 kg) Valve Failure Scenario – D Stability

Release from a 150-lbs. (68.04 kg) cylinder valve failure. Full release of contents in approximately two minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	150 lbs. (68.04 kg) Cylinder	
Release Mechanism	Valve Failure	
Hole Elevation	0 ft.	0 m
Opening Diameter	3/16 inch	0.48 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	150 lbs.	68.04 kg
Release Rate	26 lbs./min	31.0 kg/min
Release Duration	5.8 minutes	
Total Mass Released	150 lbs.	68.04 kg
Gaussian Spread[1]	0.31 inch	0.79 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

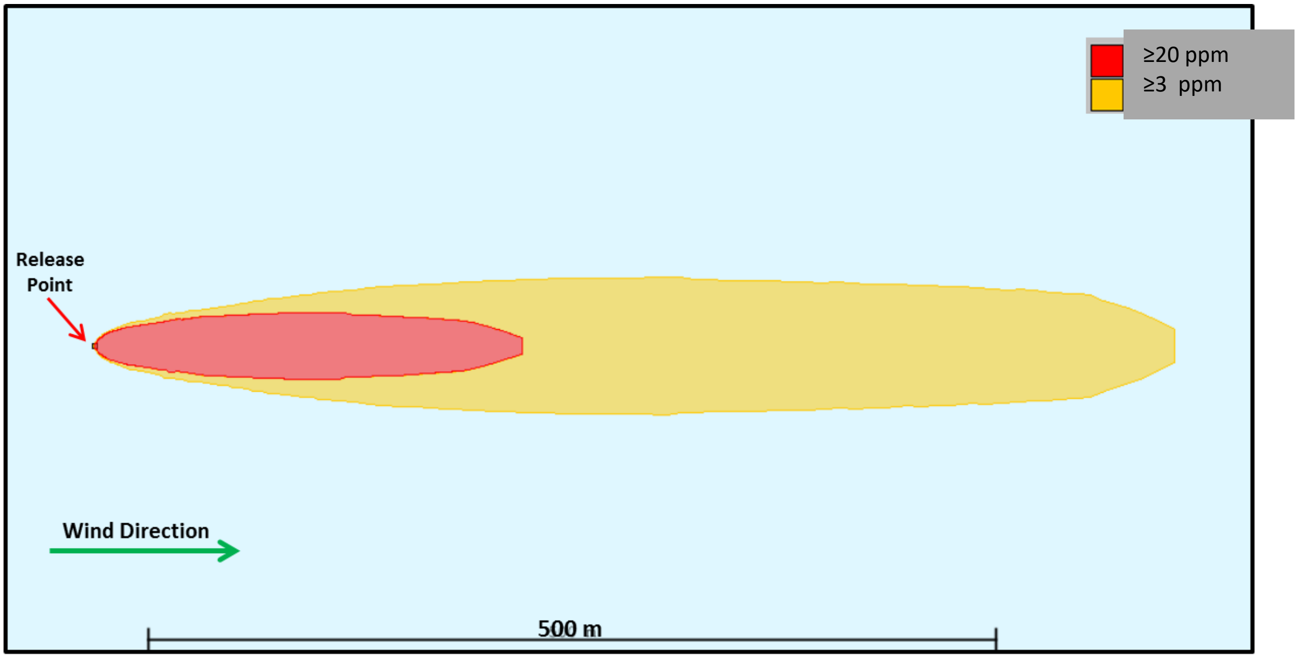
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

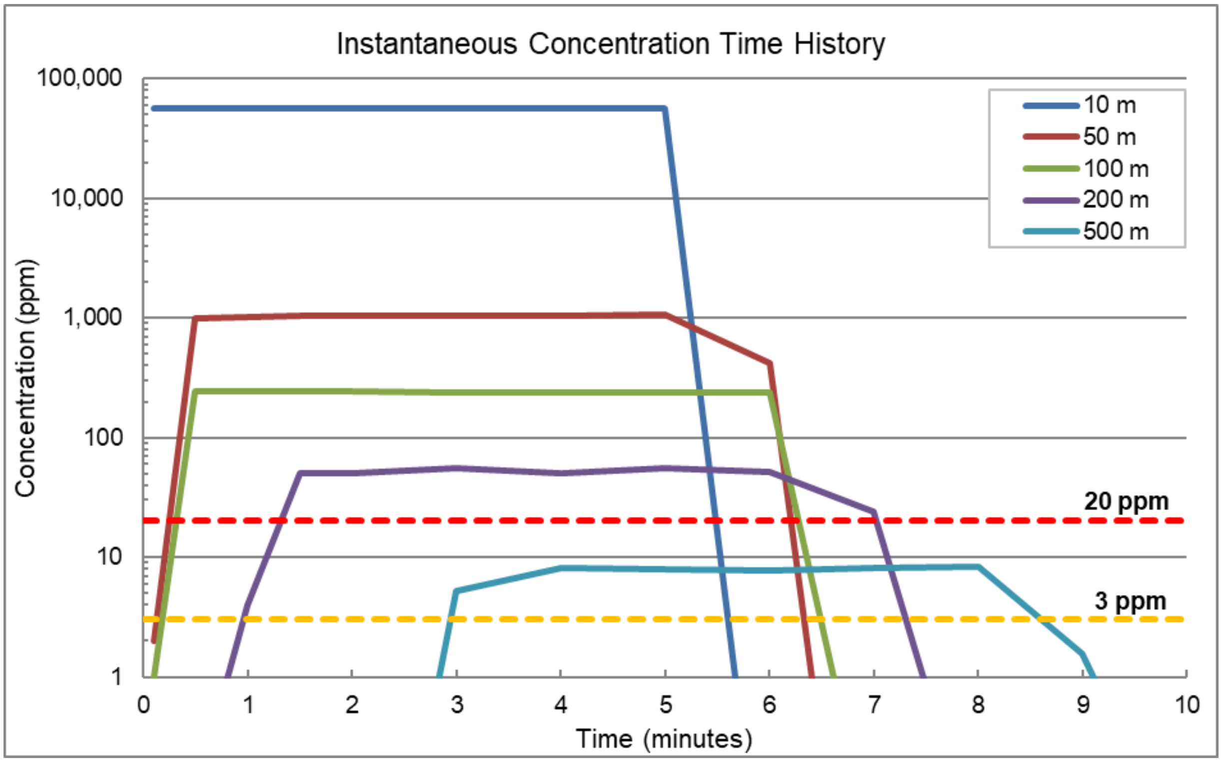
150 lb. (68.04 kg) Valve Failure

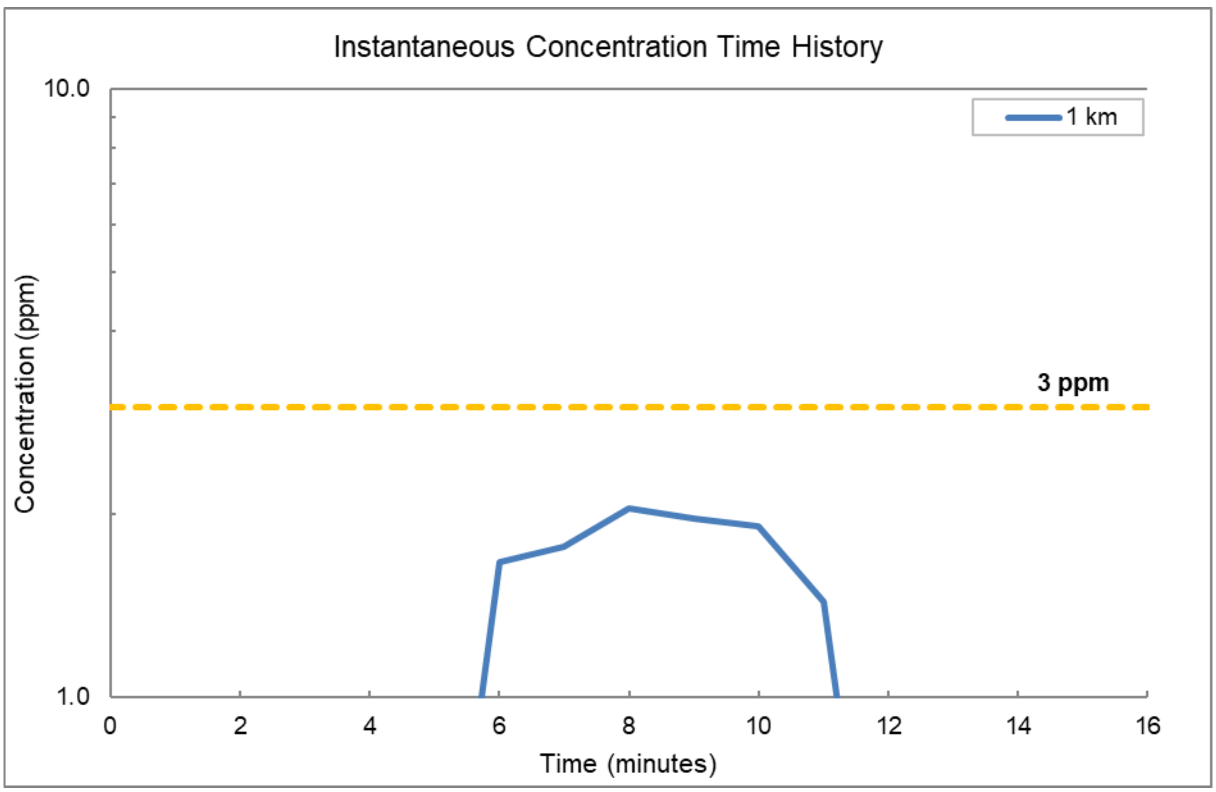


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.398	0.159
Kilometers	0.640	0.253
Maximum Crosswind Width		
Miles	0.047	0.022
Kilometers	0.075	0.036
Area Coverage		
Sq. Miles	0.0146	0.0028
Sq. Kilometers	0.0379	0.0072

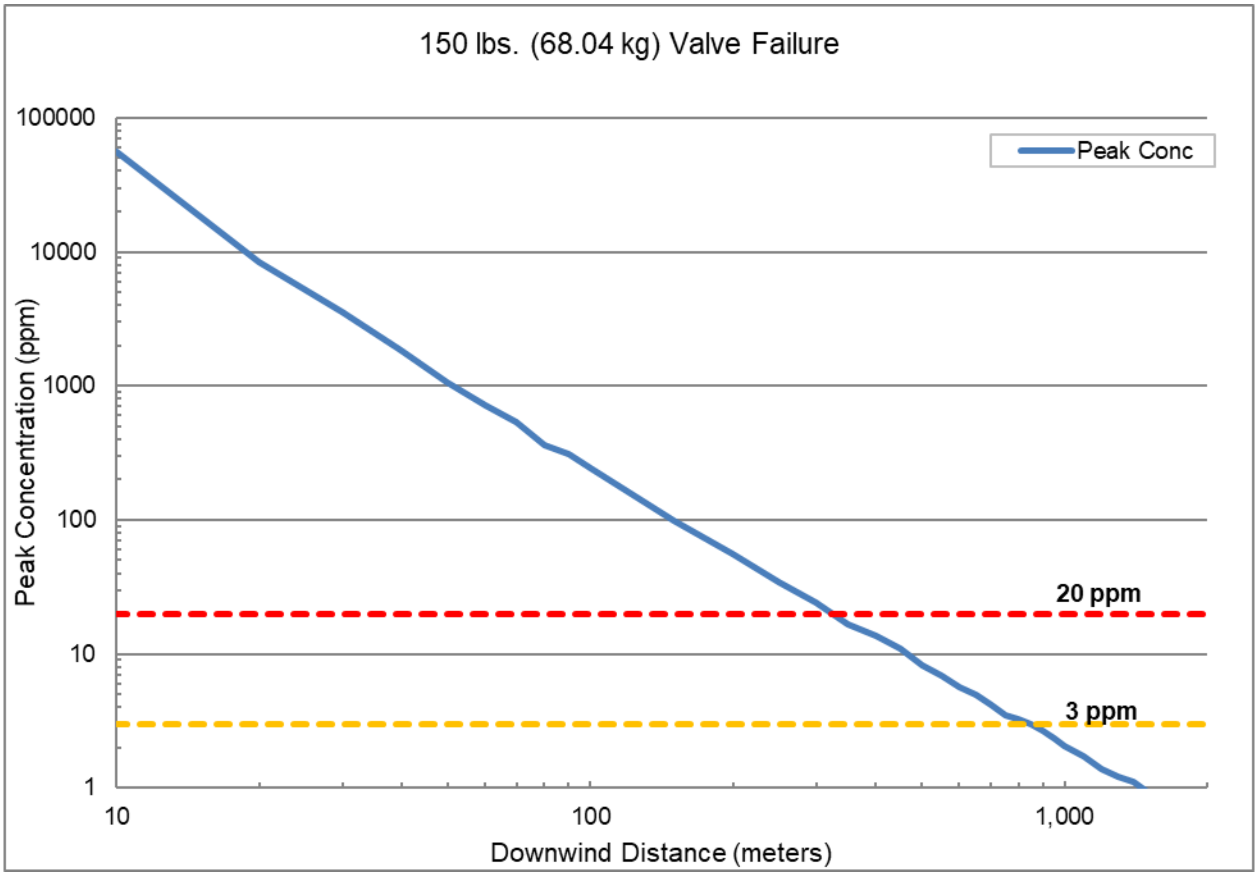
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2 TON CONTAINER SCENARIO MODELING RESULTS

5.2.1 Worst-Case 1-Ton Chlorine Container Scenario – F Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	2,000 lb.	907.2 kg
Total Mass Released	2,000 lb.	907.2 kg
Release Duration	10 minutes	
Release Rate	200 lb./min	90.72 kg/min
Gaussian Spread[1]	1.59 ft	0.485 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

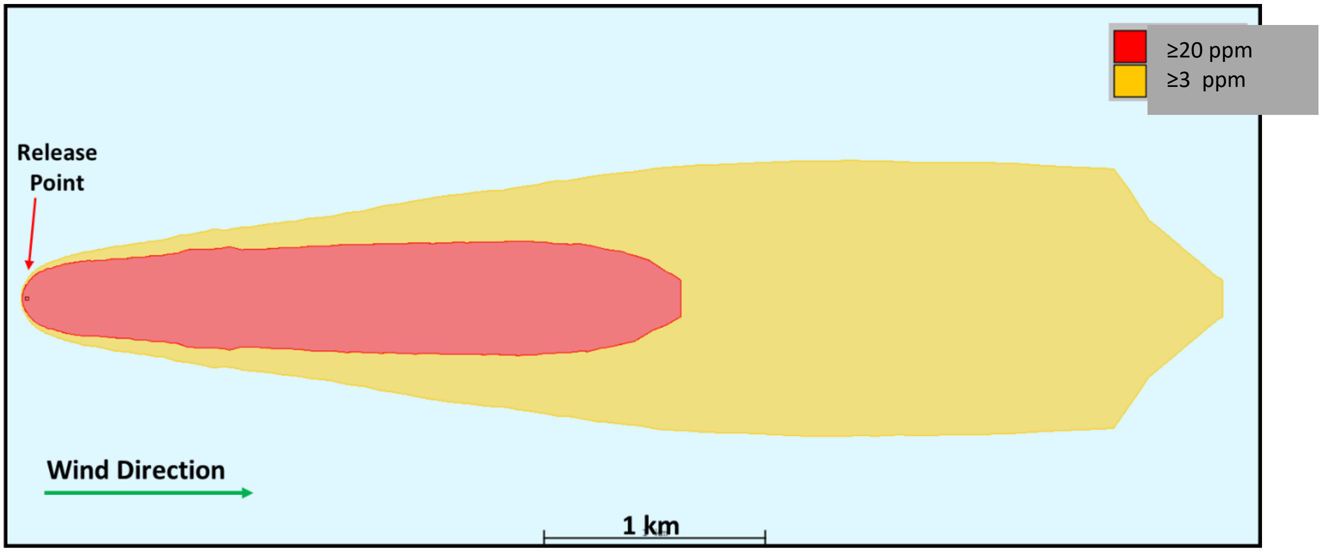
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

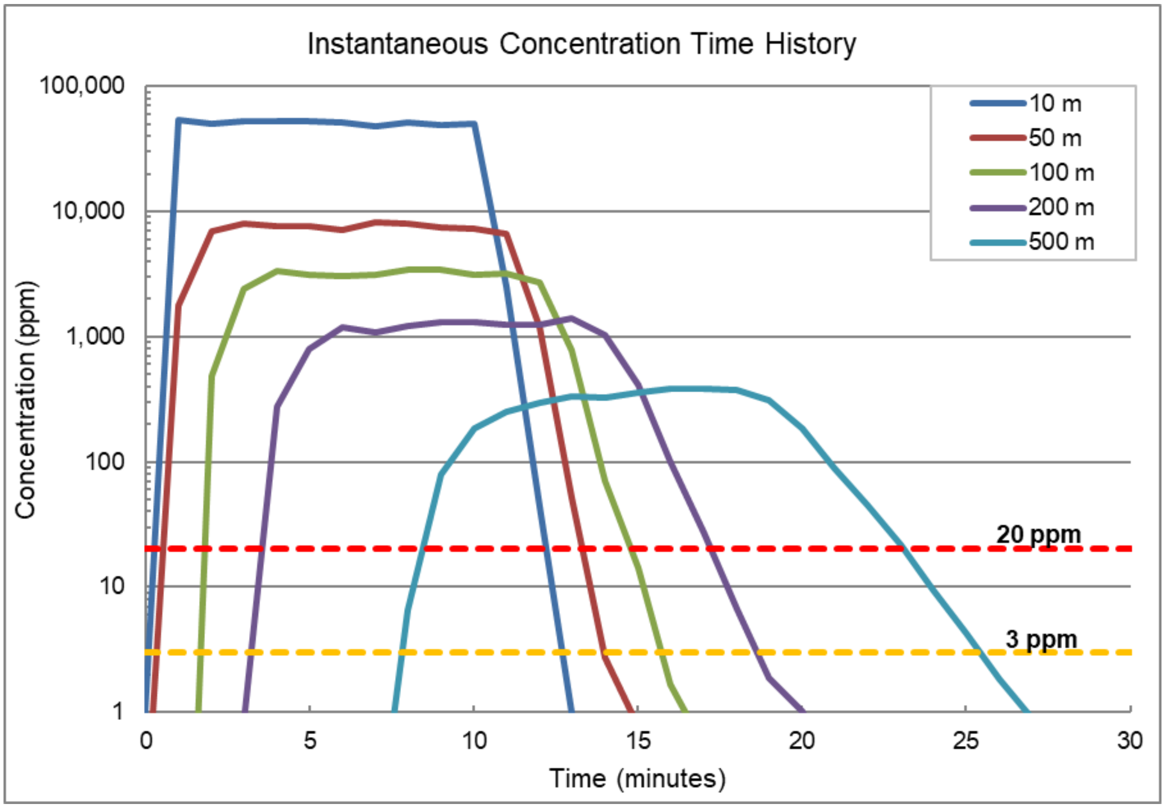
1-Ton Chlorine Container

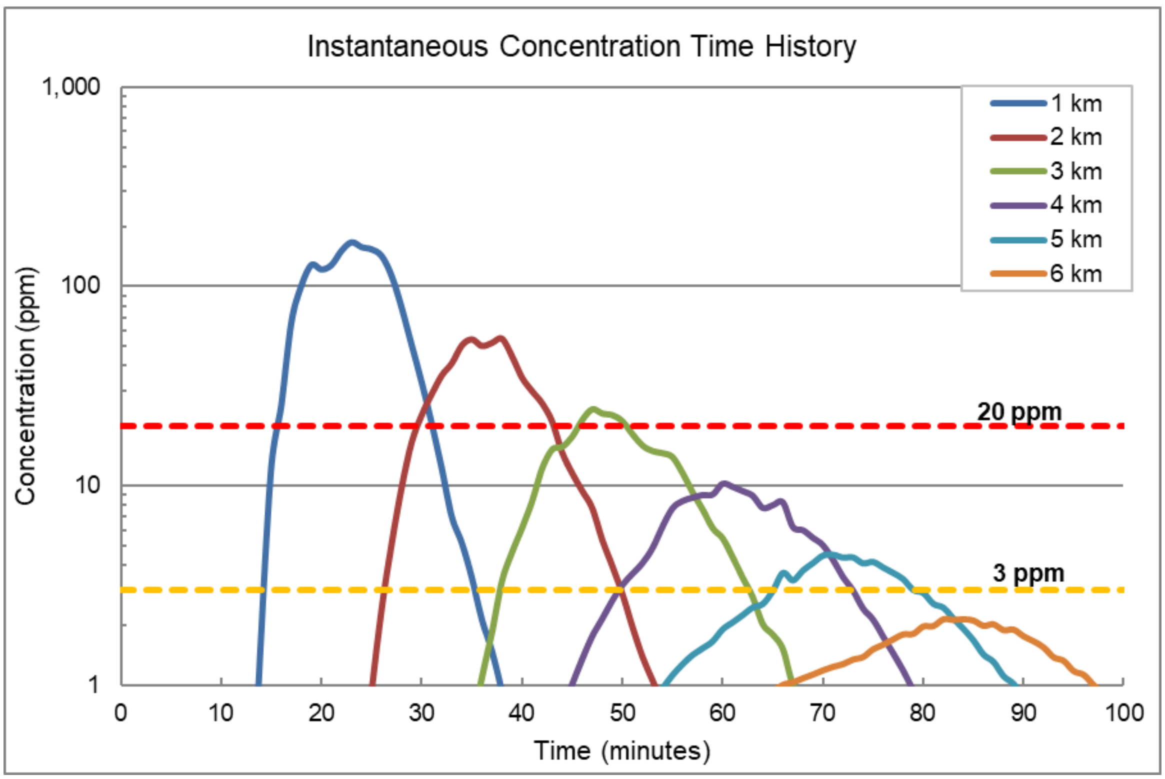


Hazard Footprint	≥3 PPM[2]	≥20 PPM[2]
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	3.39	1.85
Kilometers	5.45	2.98
Maximum Crosswind Width		
Miles	0.72	0.29
Kilometers	1.16	0.46
Area Coverage		
Sq. Miles	1.79	0.46
Sq. Kilometers	4.64	1.18

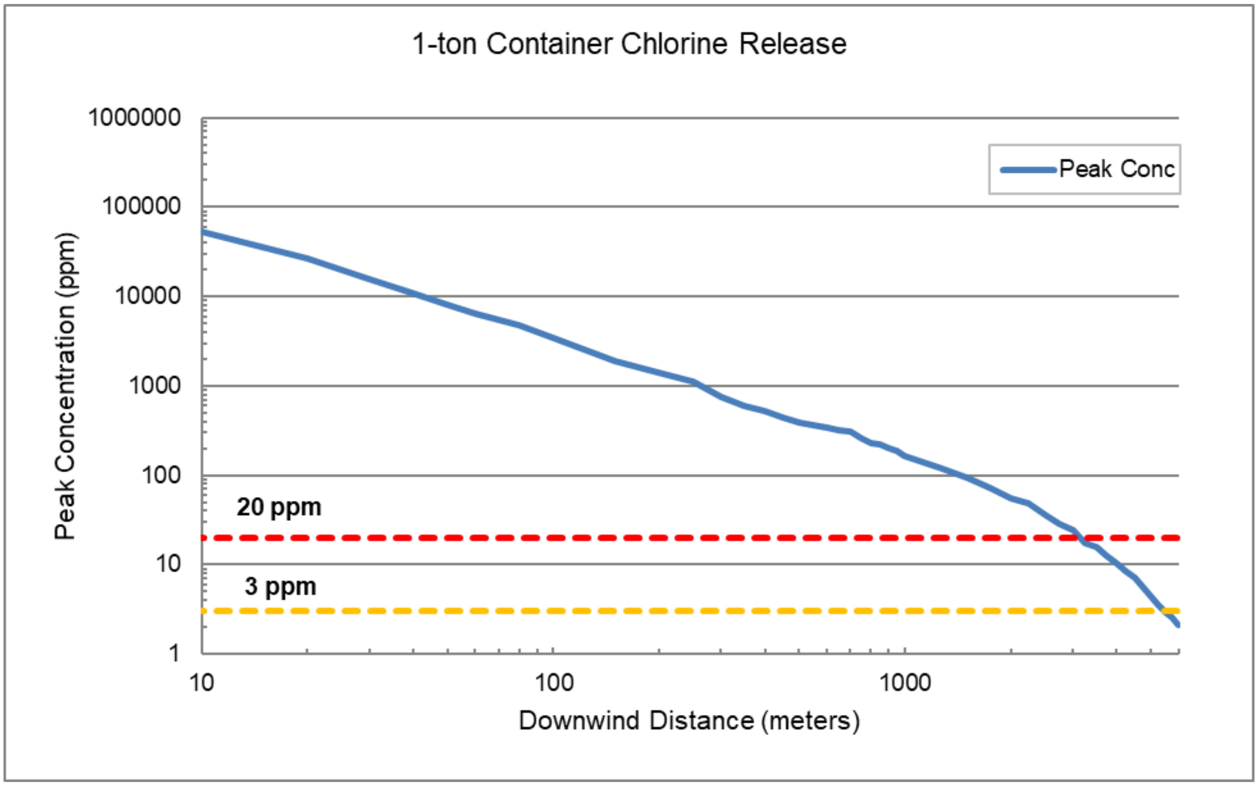
2 – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.2 Worst-Case 1-Ton Chlorine Container Scenario – D Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	2,000 lb.	907.2 kg
Total Mass Released	2,000 lb.	907.2 kg
Release Duration	10 minutes	
Release Rate	200 lb./min	90.72 kg/min
Gaussian Spread[1]	1.59 ft	0.485 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 °F	-34.04 °C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 °F	25 °C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

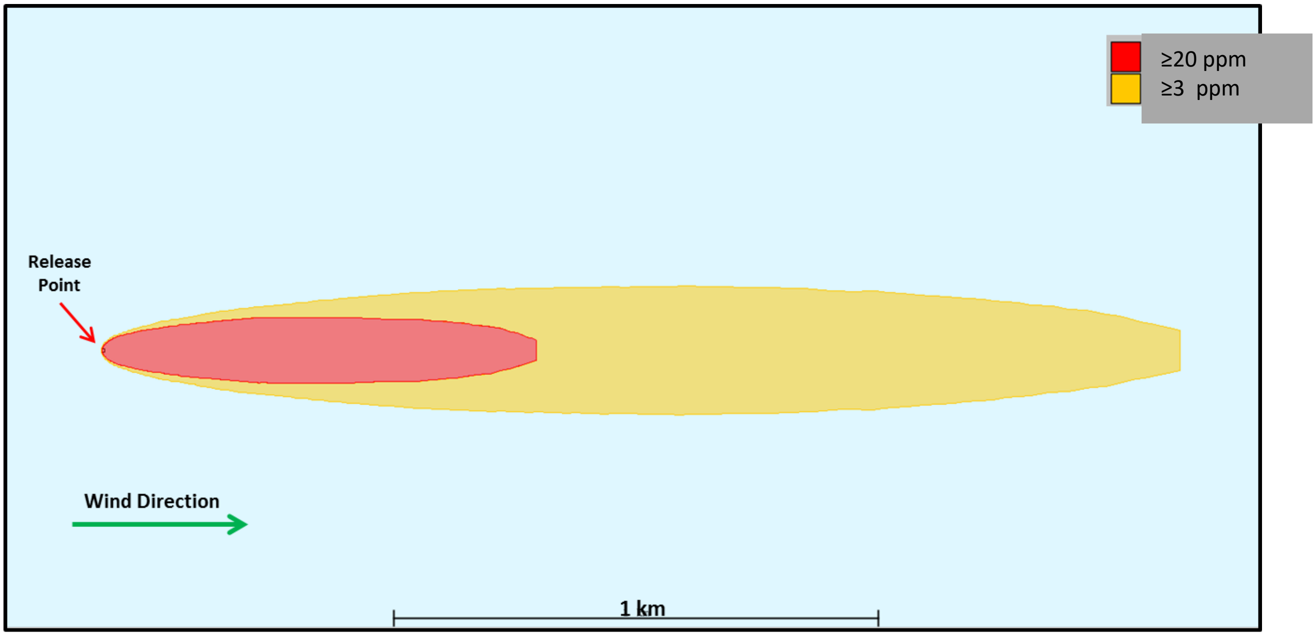
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

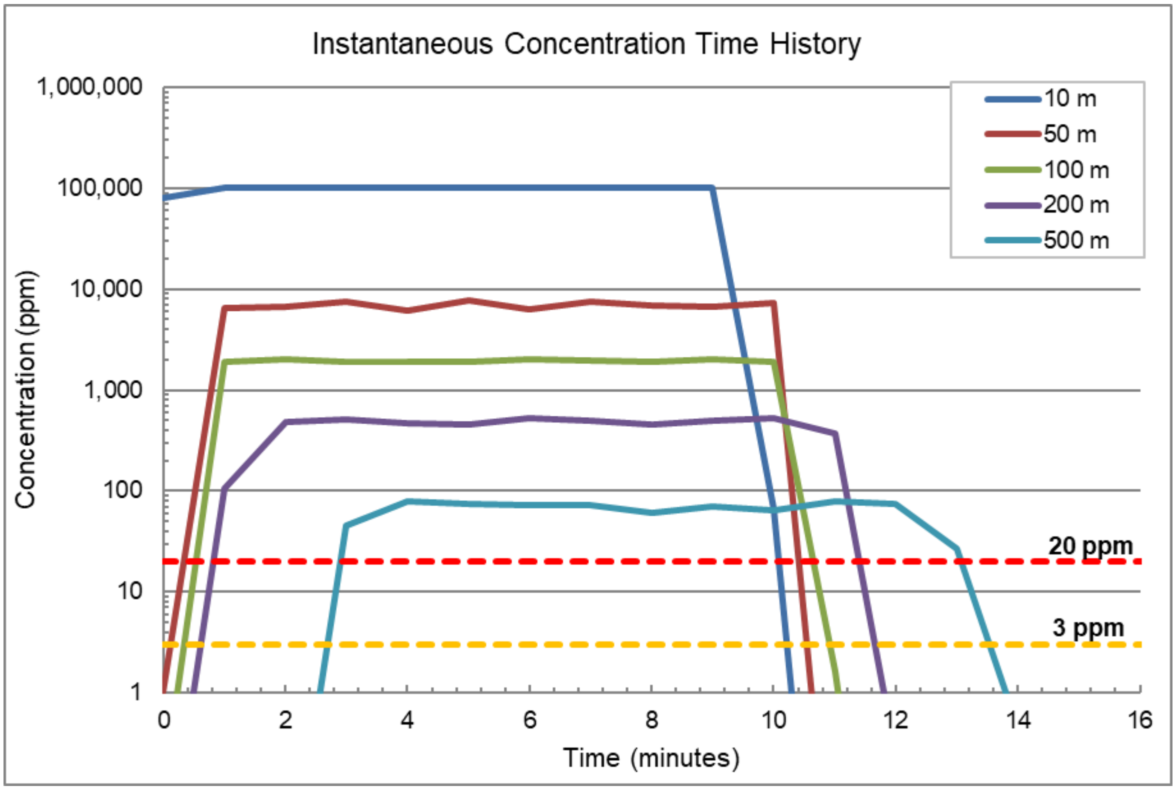
1-Ton Chlorine Container

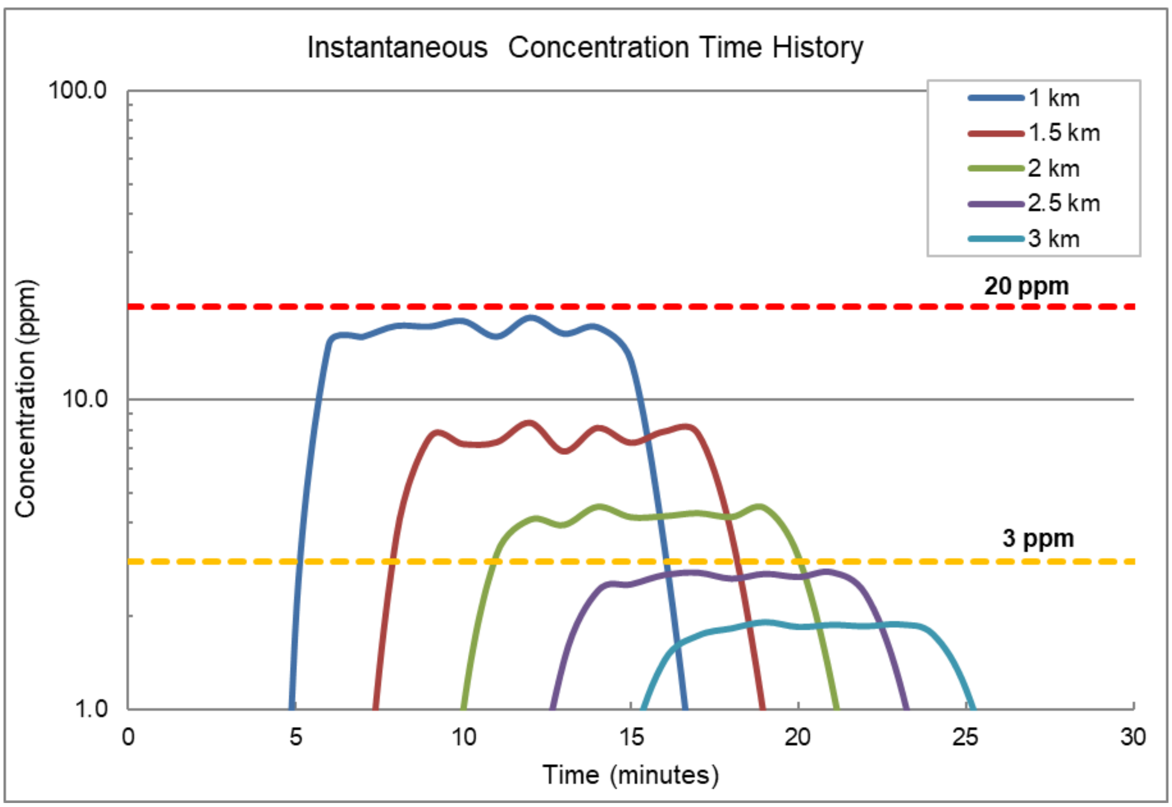


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.39	0.56
Kilometers	2.23	0.90
Maximum Crosswind Width		
Miles	0.15	0.078
Kilometers	0.24	0.126
Area Coverage		
Sq. Miles	0.17	0.035
Sq. Kilometers	0.43	0.091

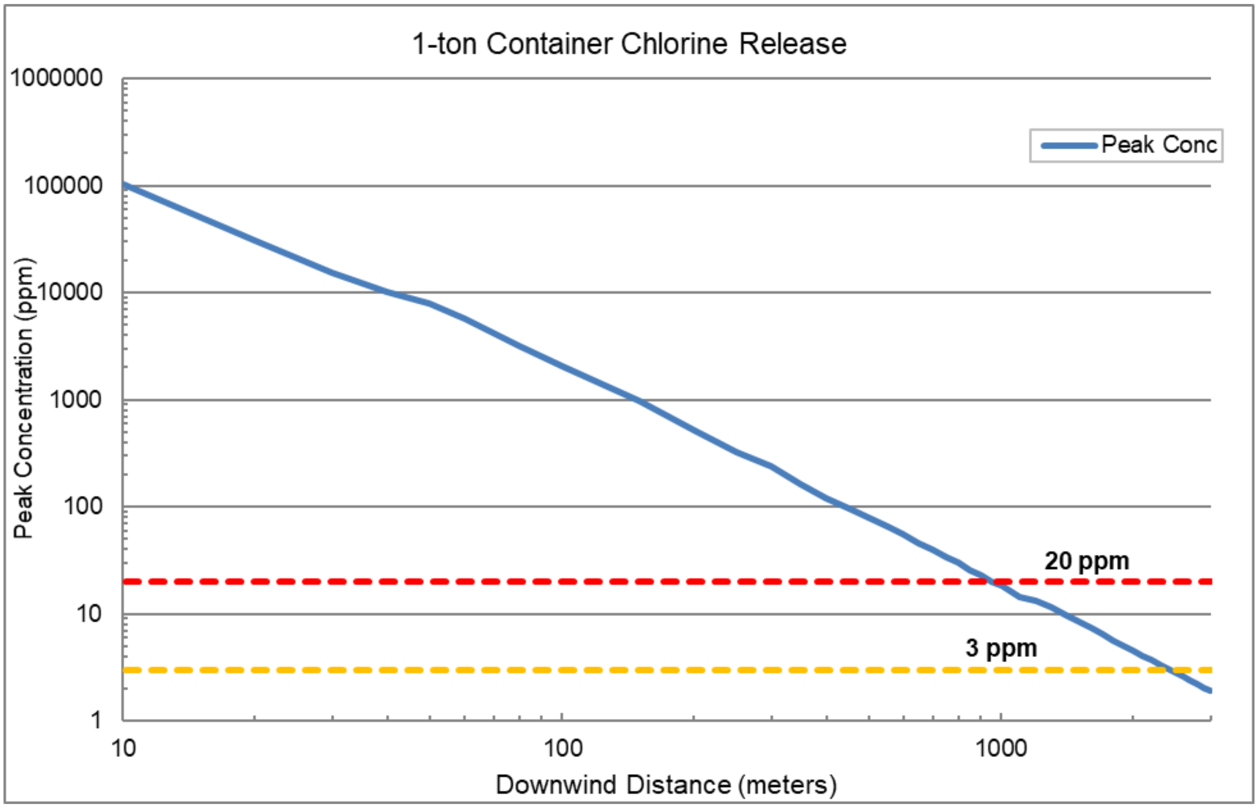
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.3 Alternative-Case 1-Ton Manifold (Four 1-ton Containers) Scenario – F Stability

Four 1-ton containers are connected to a 1-inch (2.54 cm) schedule 80 pipe manifold, and the manifold is sheared off. The release source is assumed to be stopped within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Line	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter[1]	5/16 inch	0.79 cm
Release State	Gas	
Contents Mass	8000 lbs.	3628.7 kg
Release Rate	120 lbs./min	54.4 kg/min
Release Duration	30 minutes	
Total Mass Released	3600 lbs.	1633 kg
Gaussian Spread[2]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

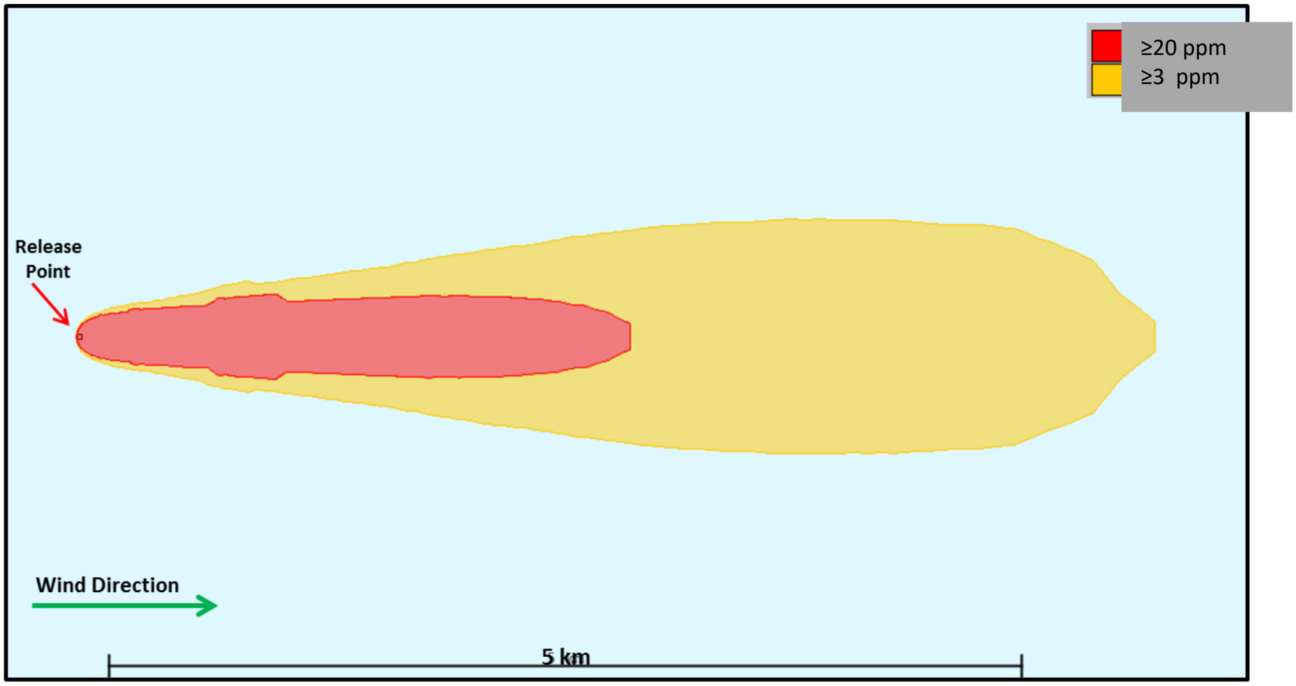
1 – For the opening diameter, the inside pipe diameter is 1 inch (2.54 cm), however, the 5/16 inch (0.79 cm) diameter valve opening on each cylinder is the limiting condition.

2 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

3 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

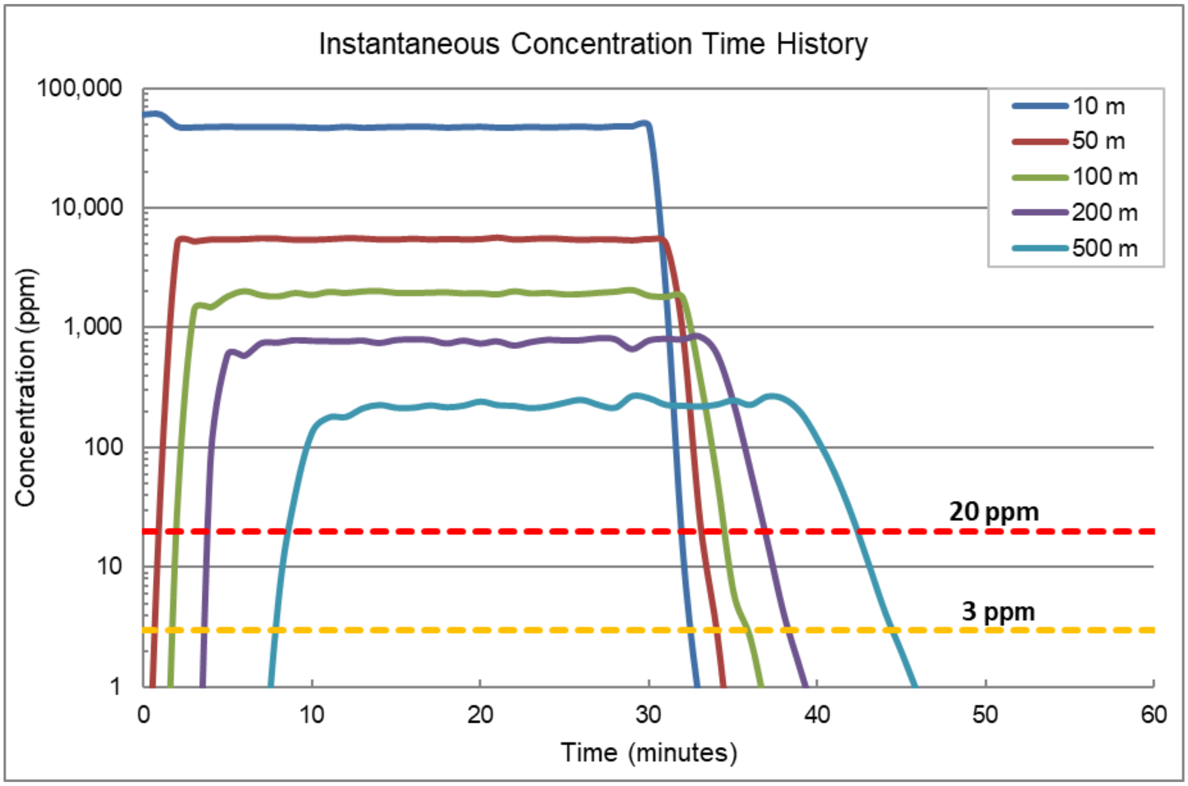
1-Ton Manifold (Four 1-ton Containers)

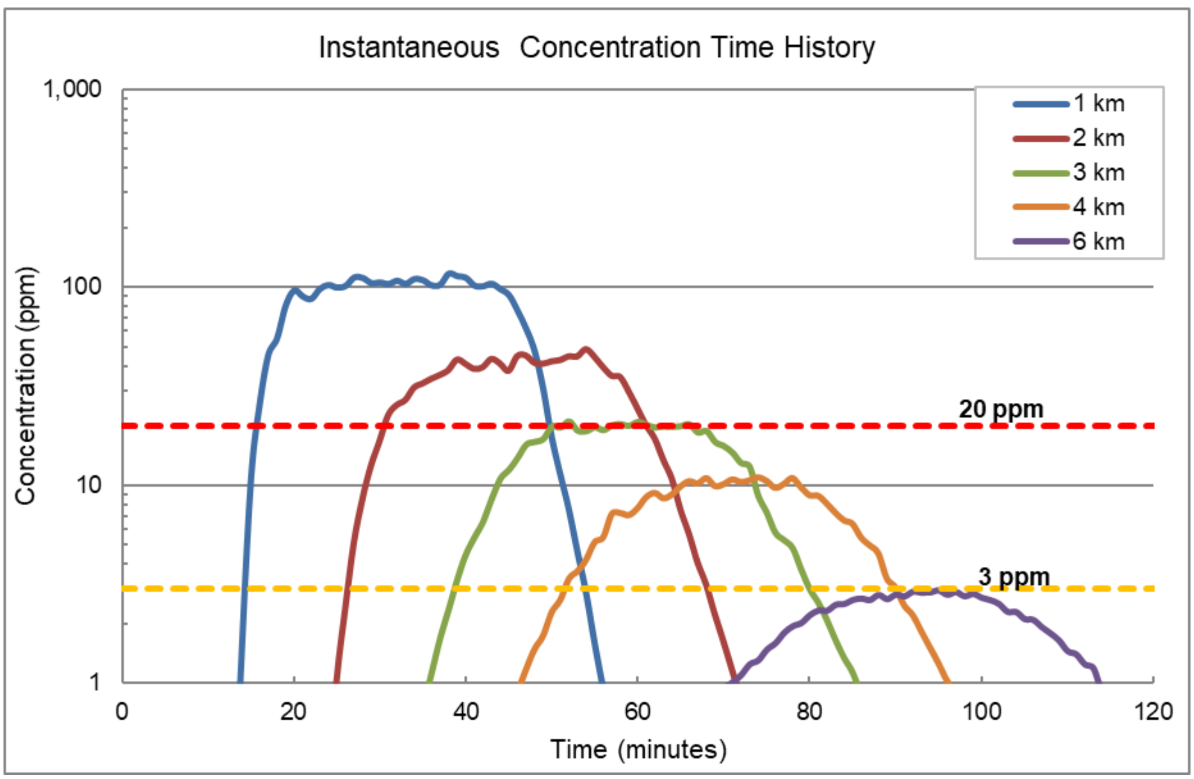


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	3.67	1.88
Kilometers	5.90	3.03
Maximum Crosswind Width		
Miles	0.74	0.26
Kilometers	1.19	0.43
Area Coverage		
Sq. Miles	1.93	0.40
Sq. Kilometers	4.99	1.04

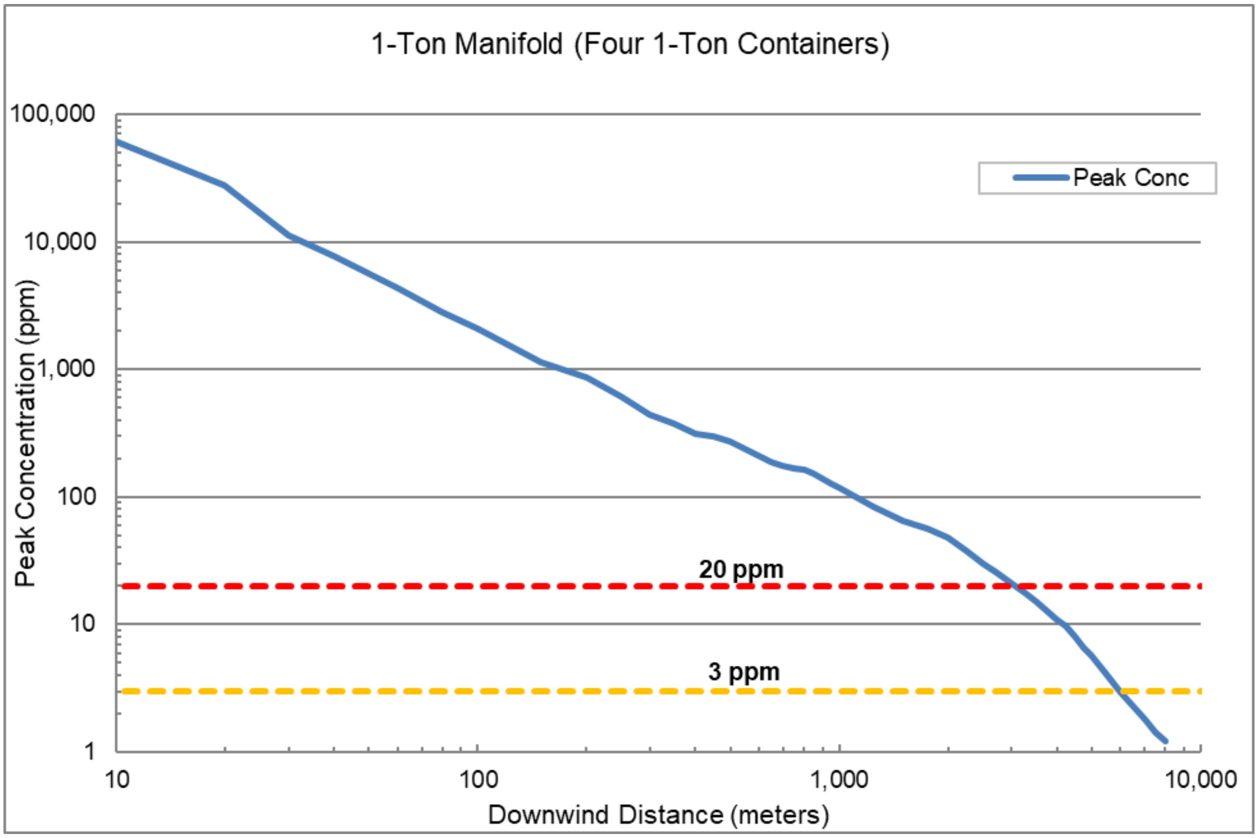
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.4 Alternative-Case 1-Ton Manifold (Four 1-ton Containers) Scenario – D Stability

Four 1-ton containers are connected to a 1-inch (2.54 cm) schedule 80 pipe manifold, and the manifold is sheared off. The release source is assumed to be stopped within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Line	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter[1]	5/16 inch	0.79 cm
Release State	Gas	
Contents Mass	8000 lbs.	3628.7 kg
Release Rate	120 lbs./min	54.4 kg/min
Release Duration	30 minutes	
Total Mass Released	3600 lbs.	1633 kg
Gaussian Spread[2]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

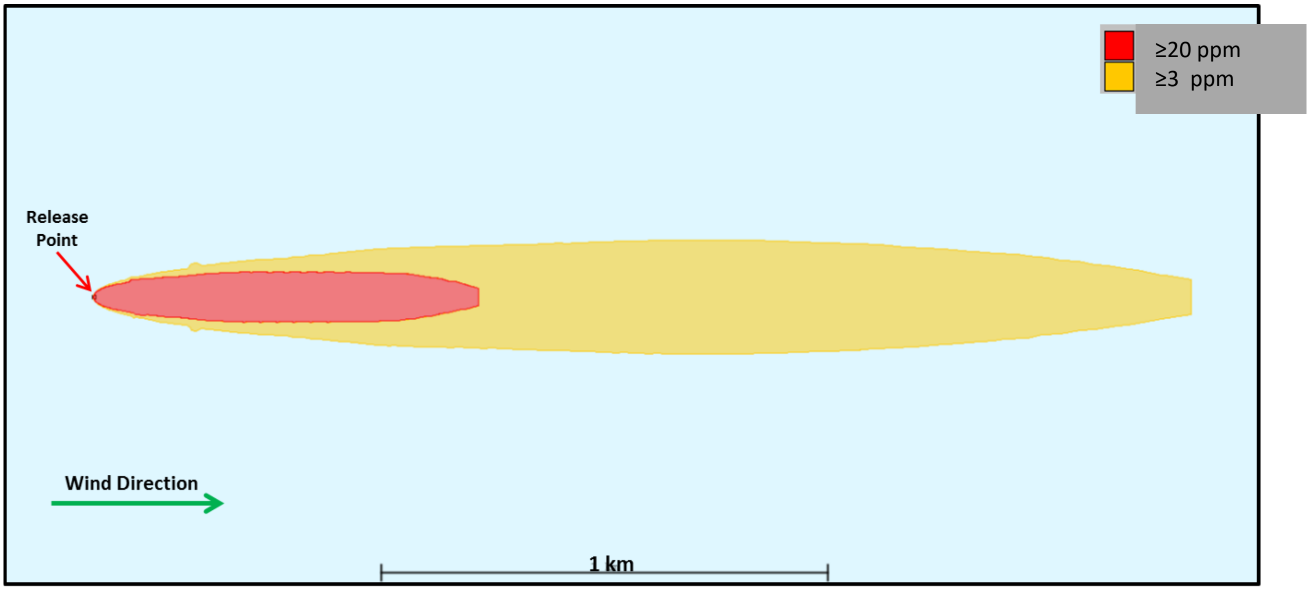
1 – For the opening diameter, the inside pipe diameter is 1-inch (2.54 cm), however, the 5/16 inch (0.79 cm) diameter valve opening on each cylinder is the limiting condition.

2 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

3 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

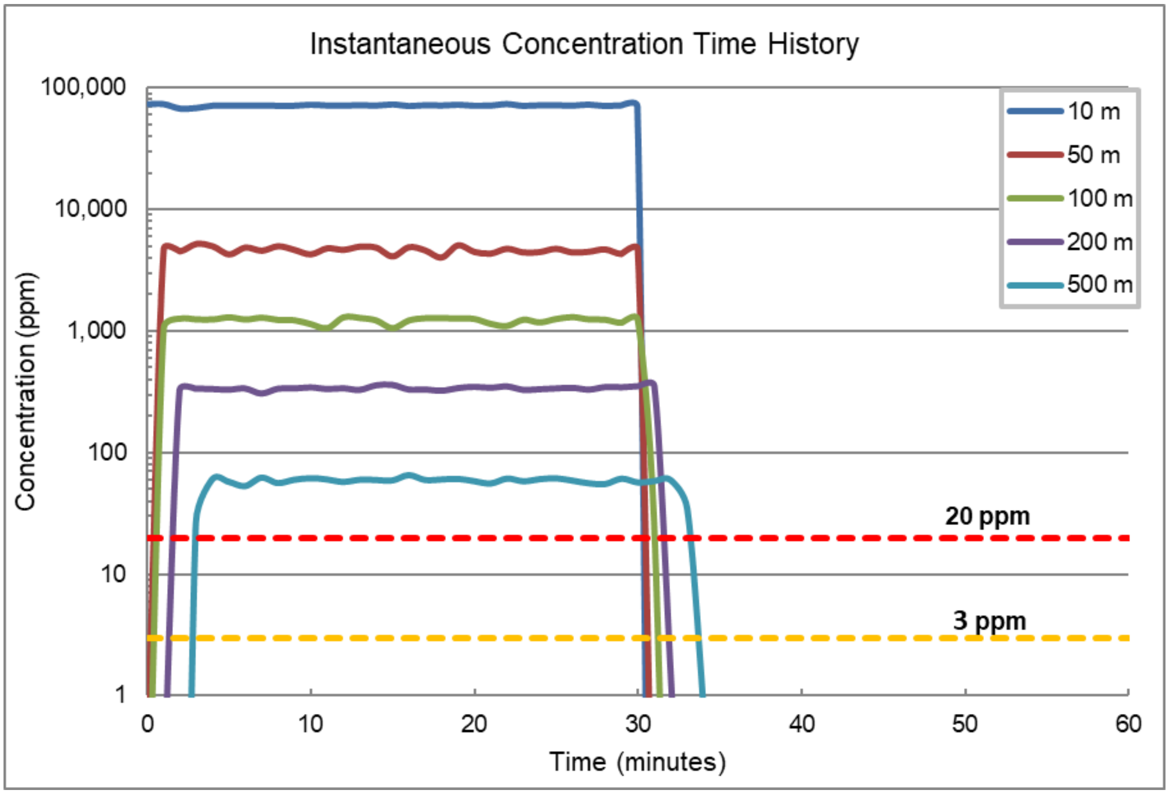
1-Ton Manifold (Four 1-ton Containers)

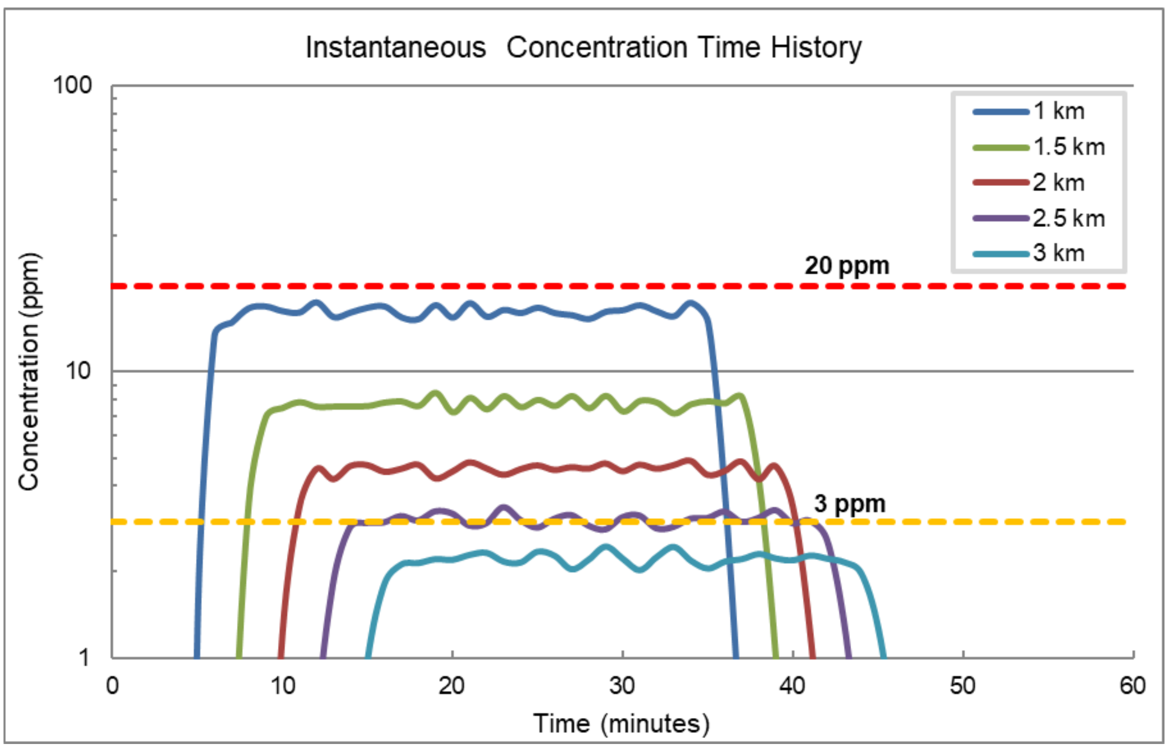


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.53	0.54
Kilometers	2.46	0.88
Maximum Crosswind Width		
Miles	0.14	0.063
Kilometers	0.23	0.102
Area Coverage		
Sq. Miles	0.170	0.030
Sq. Kilometers	0.441	0.077

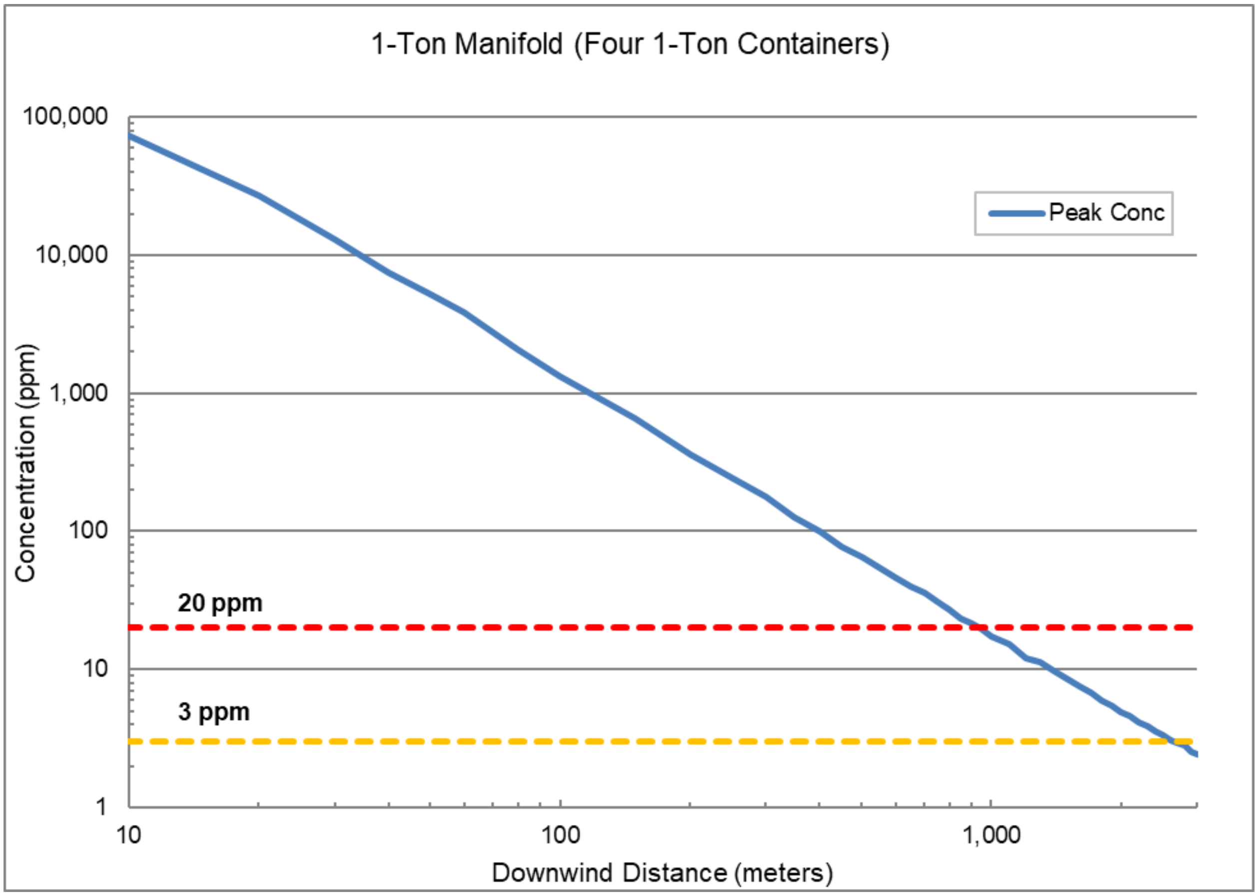
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.5 Alternative-Case 1-Ton Valve Failure (gas) Scenario – F Stability

1-ton container gas valve remains open. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Valve	
Release Mechanism	Failure	
Hole Elevation	1.5 ft.	0.46 m
Opening Diameter	5/16 inch	0.79 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	12.7 lbs./min	5.76 kg/min
Release Duration	30 minutes	
Total Mass Released	381 lbs.	172.8 kg
Gaussian Spread[1]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

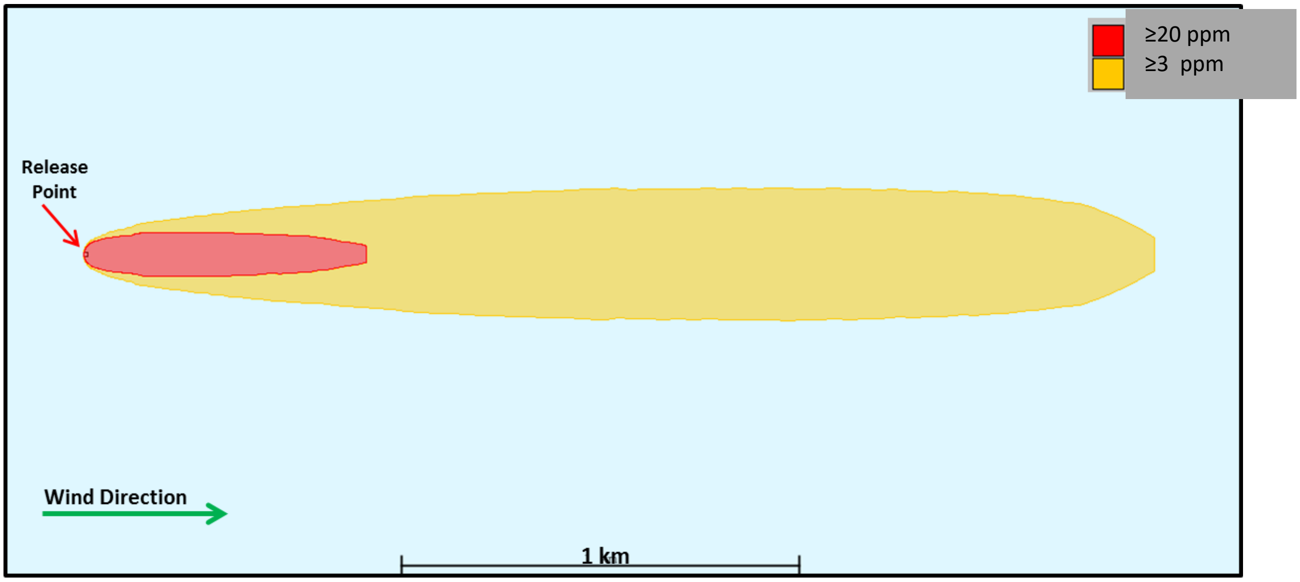
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

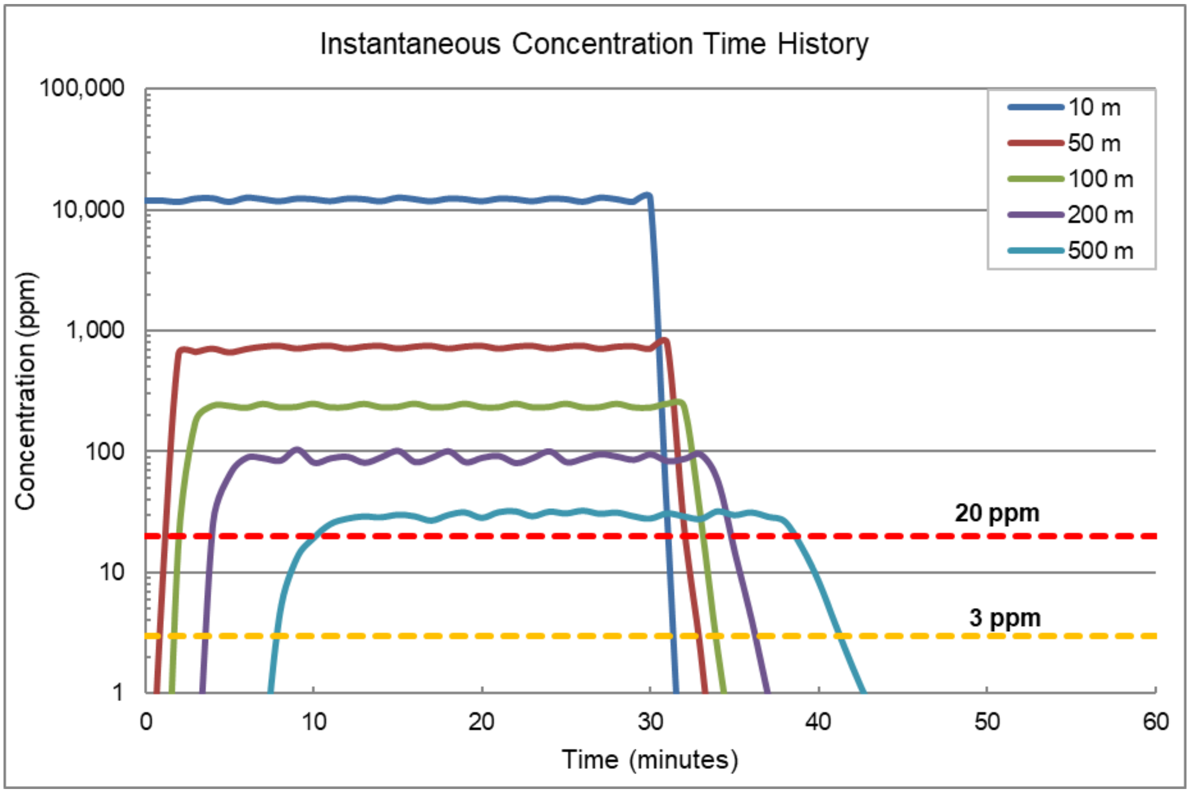
1-Ton Valve Failure (Gas)

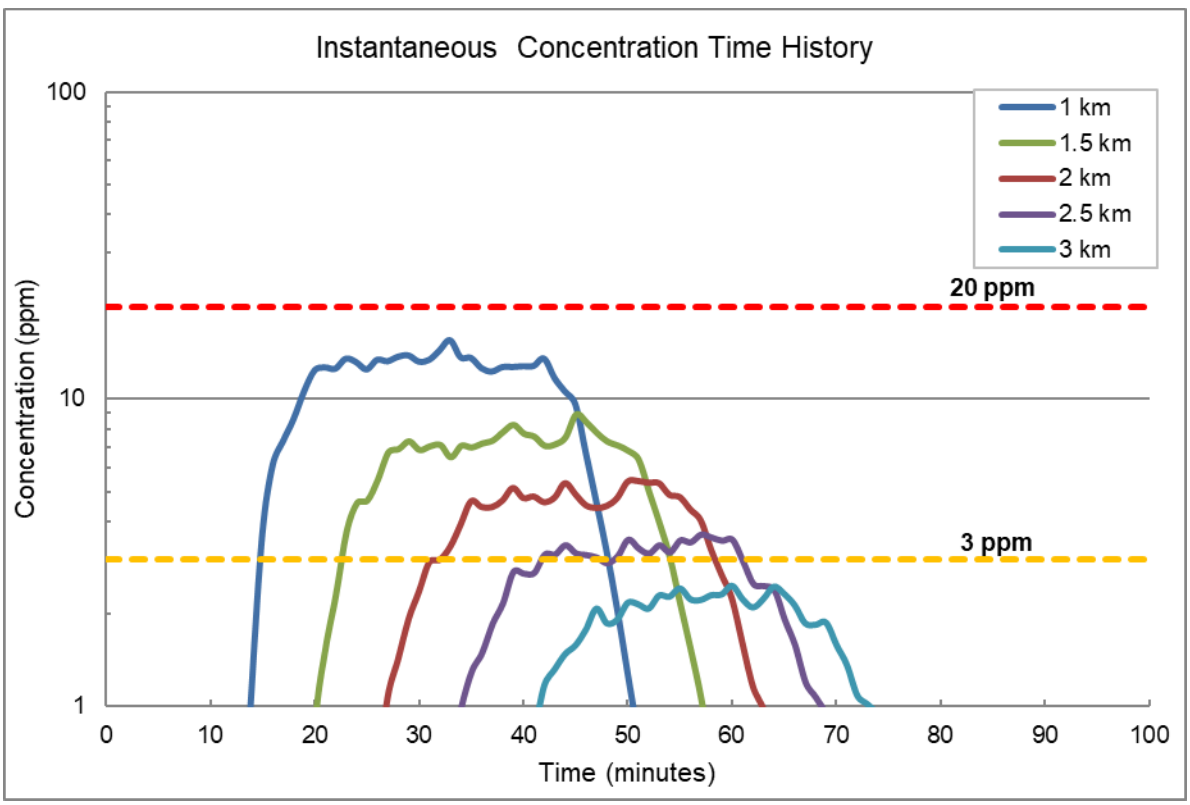


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.67	0.44
Kilometers	2.69	0.71
Maximum Crosswind Width		
Miles	0.19	0.064
Kilometers	0.30	0.103
Area Coverage		
Sq. Miles	0.26	0.023
Sq. Kilometers	0.67	0.060

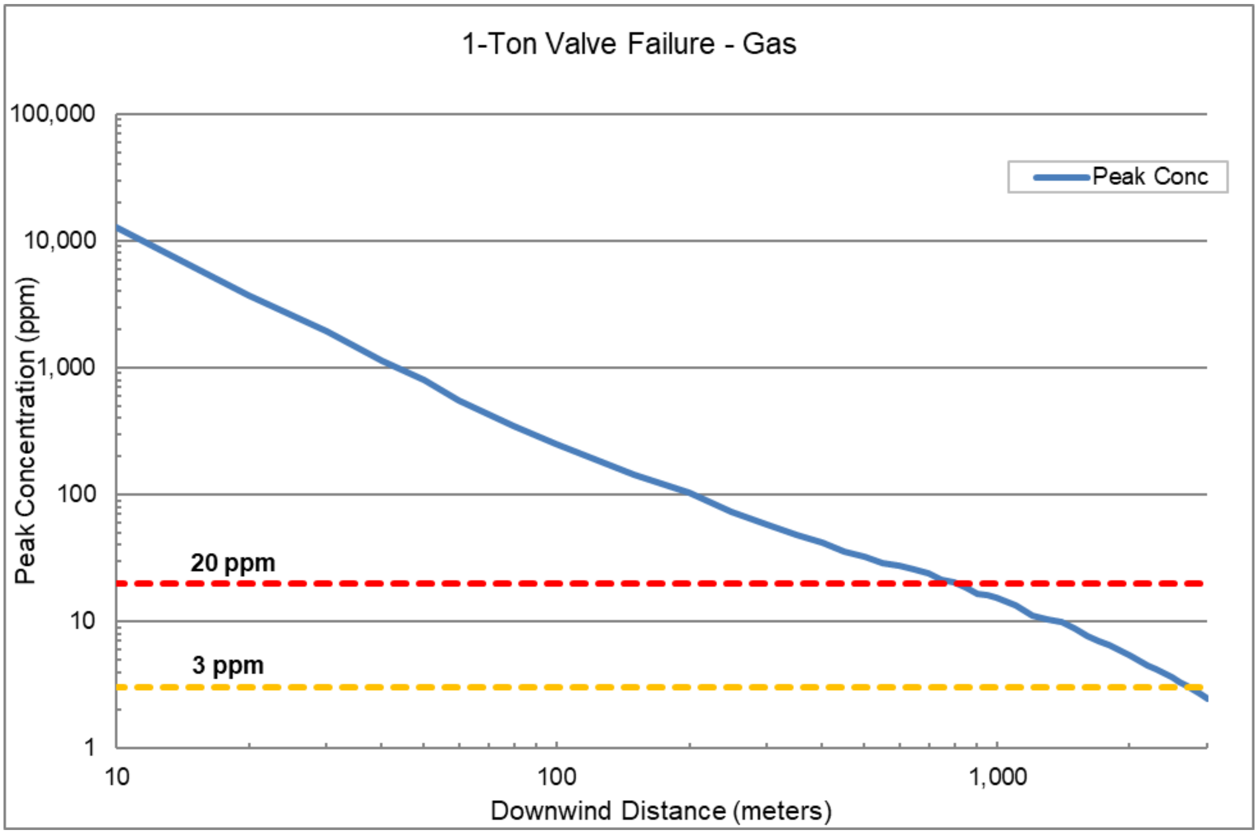
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.6 Alternative-Case 1-Ton Valve Failure (gas) Scenario – D Stability

1-ton container gas valve remains open. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Valve	
Release Mechanism	Failure	
Hole Elevation	1.5 ft.	0.46 m
Opening Diameter	5/16 inch	0.79 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	12.7 lbs./min	5.76 kg/min
Release Duration	30 minutes	
Total Mass Released	381 lbs.	172.8 kg
Gaussian Spread[1]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

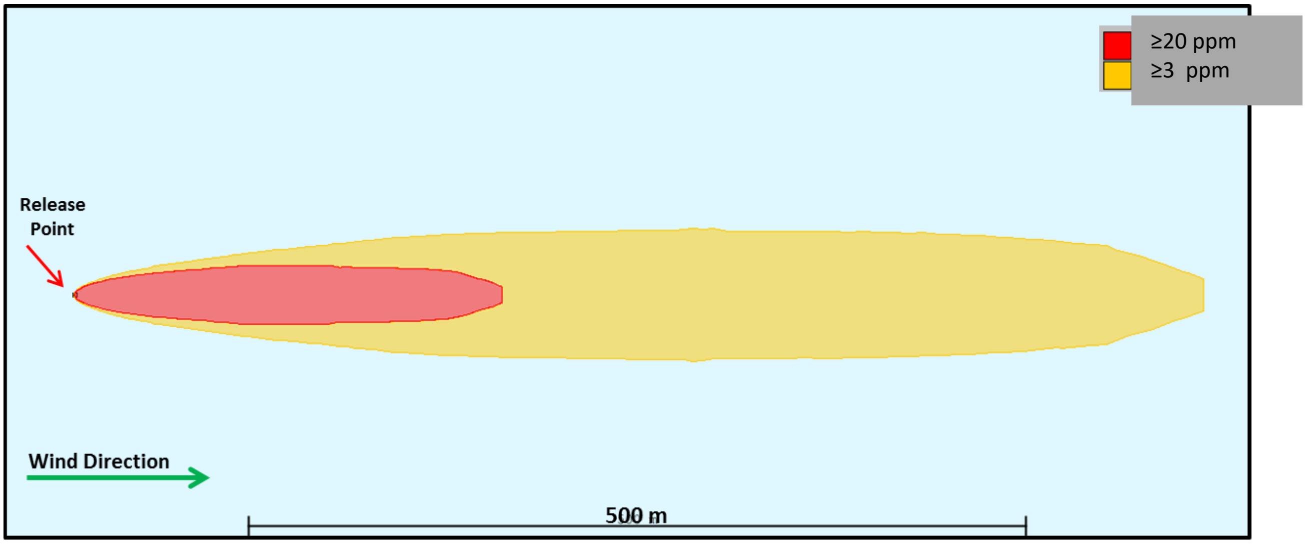
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

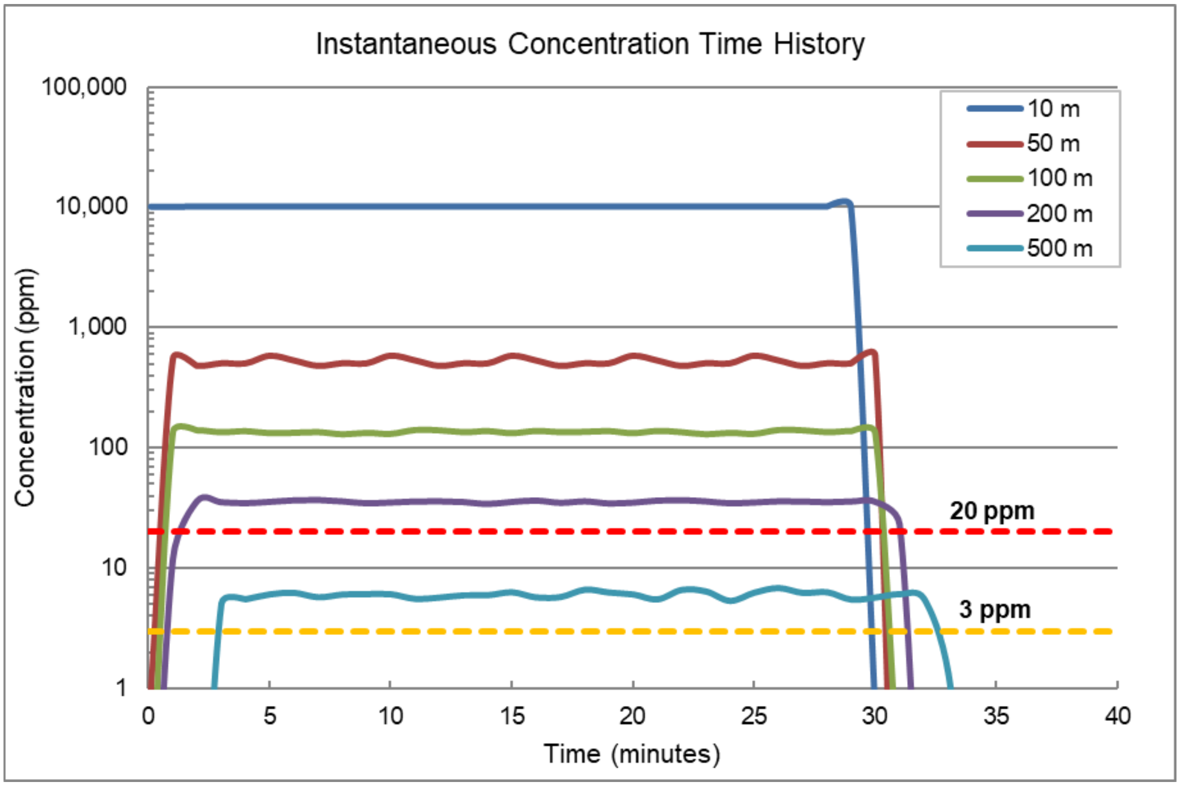
1-Ton Valve Failure (Gas)

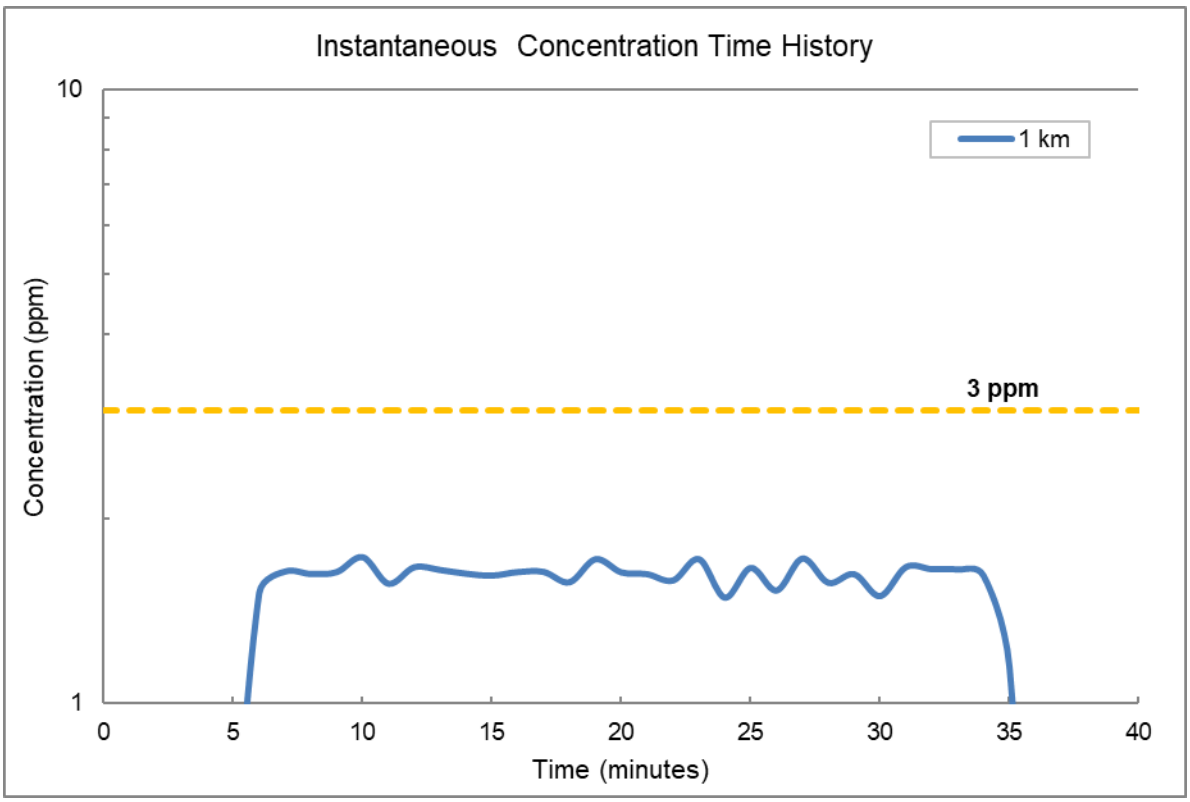


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.45	0.17
Kilometers	0.73	0.28
Maximum Crosswind Width		
Miles	0.049	0.022
Kilometers	0.079	0.035
Area Coverage		
Sq. Miles	0.017	0.003
Sq. Kilometers	0.045	0.008

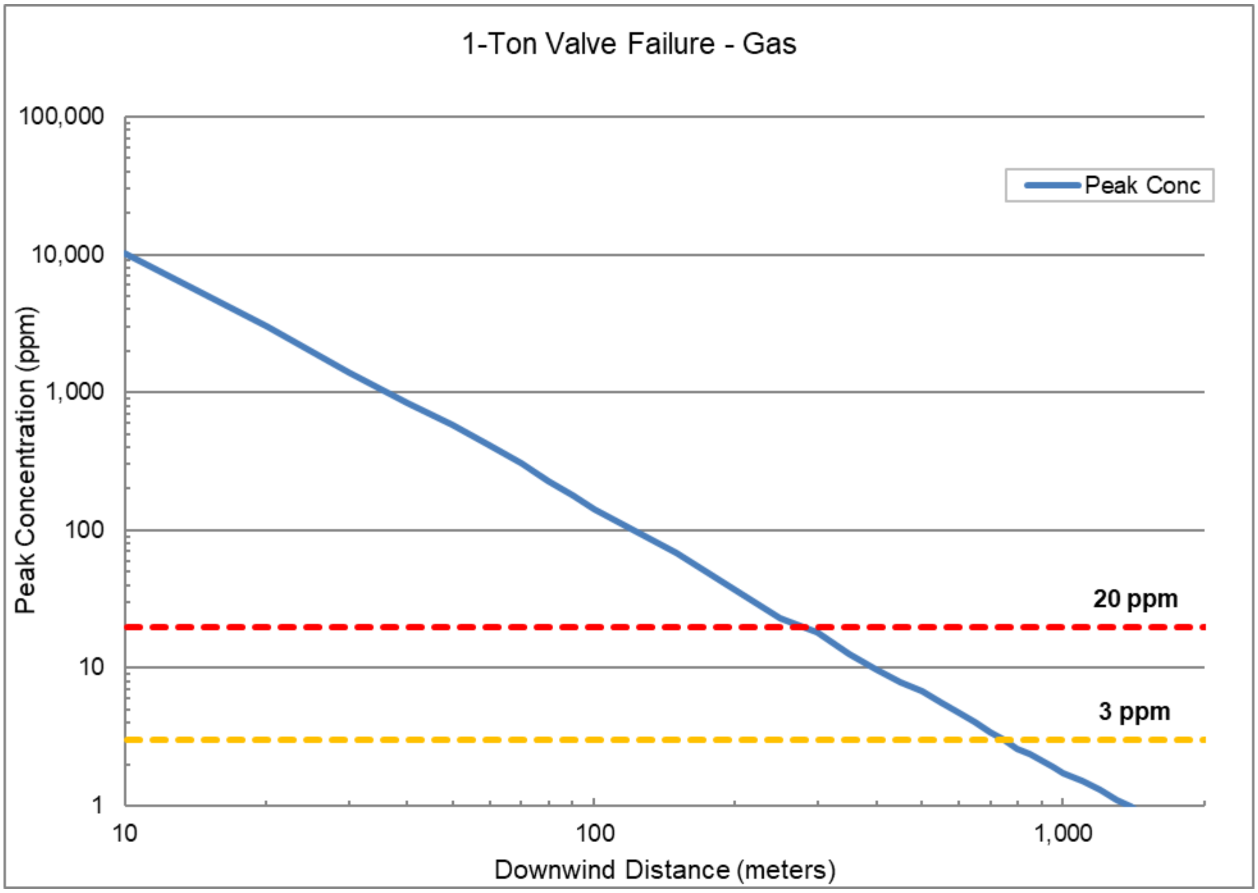
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.7 Alternative-Case 1-Ton Valve Failure (liquid) Scenario – F Stability

1-ton container liquid valve remains open. Full release of contents in approximately 28 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Valve	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	5/16 inch	0.79 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	72 lbs./min	32.7 kg/min
Release Duration	27.8 minutes	
Total Mass Released	2000 lbs.	907.2 kg
Gaussian Spread[1]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

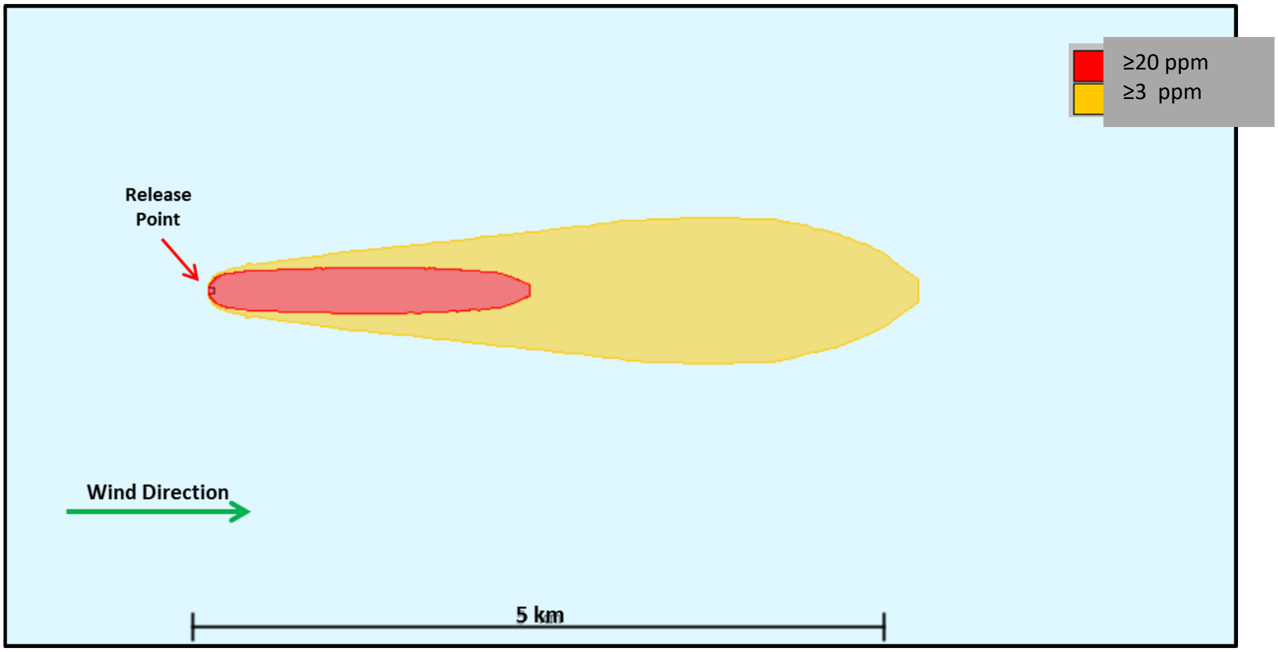
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

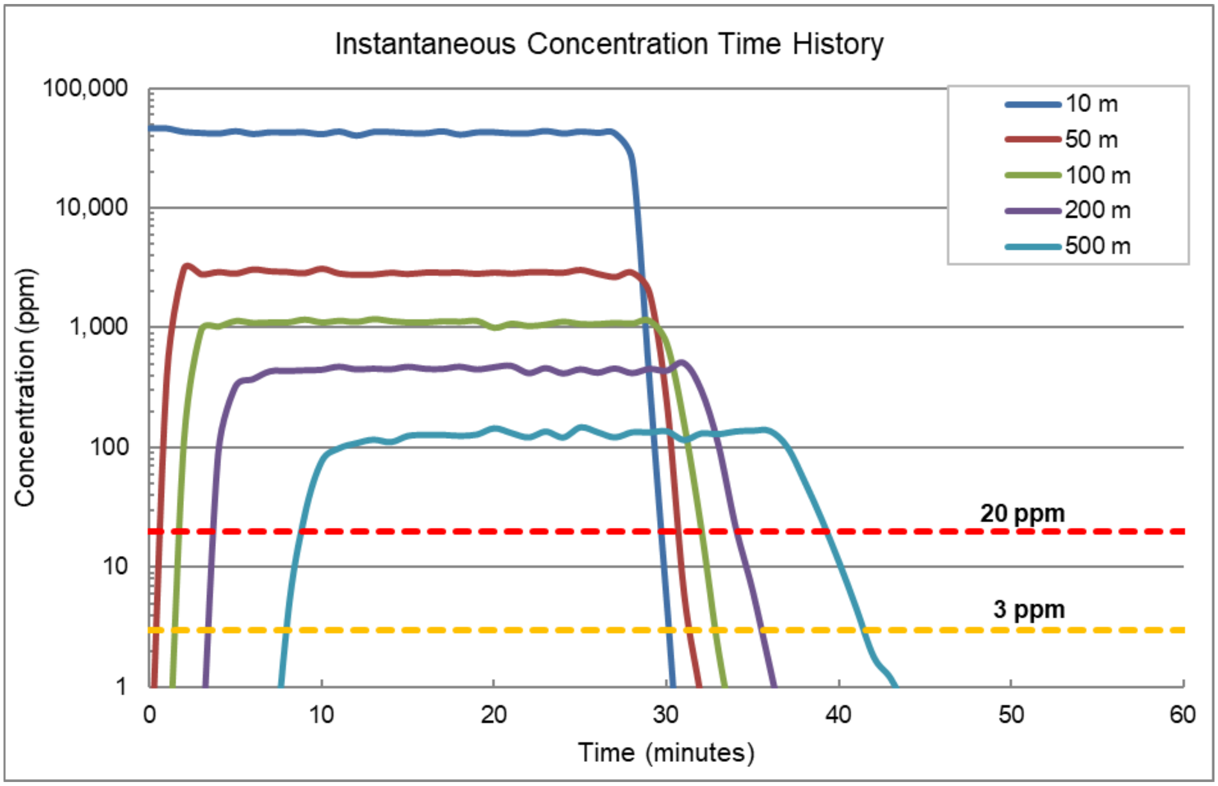
1-Ton Valve Failure (Liquid)

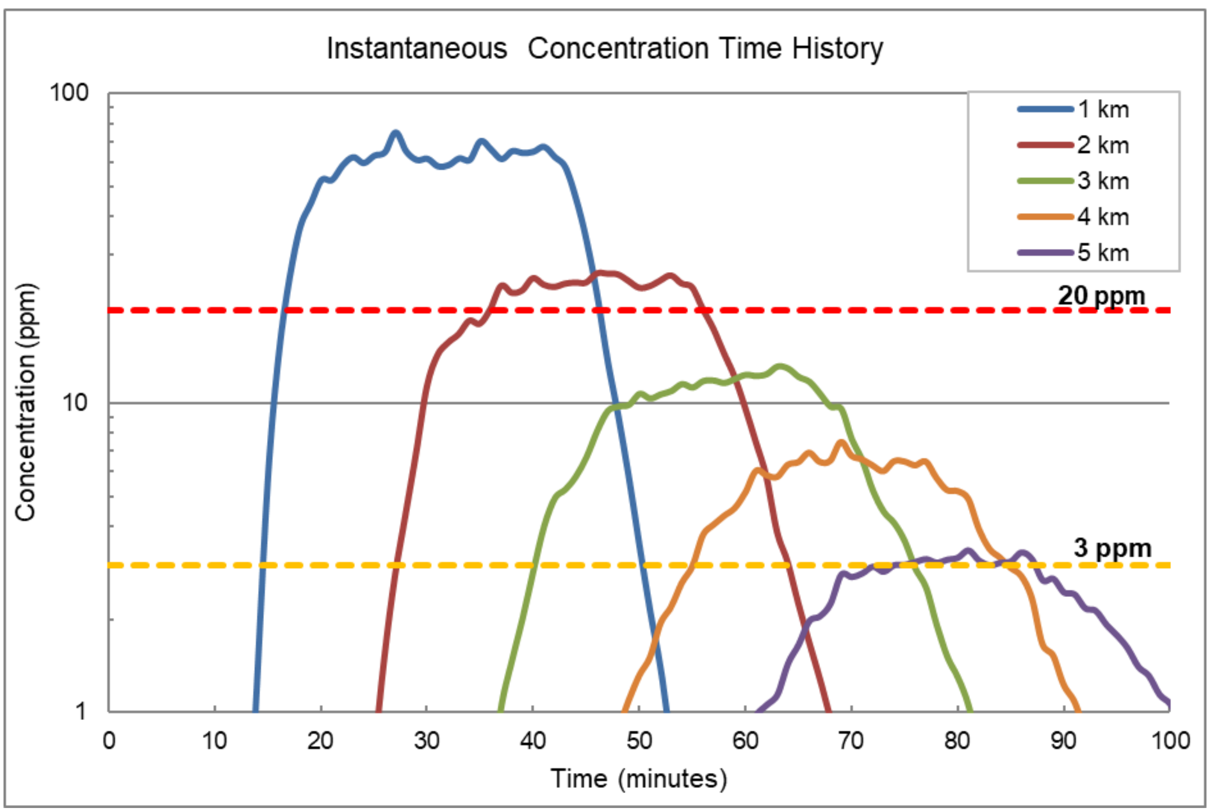


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	3.20	1.44
Kilometers	5.15	2.32
Maximum Crosswind Width		
Miles	0.61	0.19
Kilometers	0.98	0.31
Area Coverage		
Sq. Miles	1.38	0.24
Sq. Kilometers	3.57	0.62

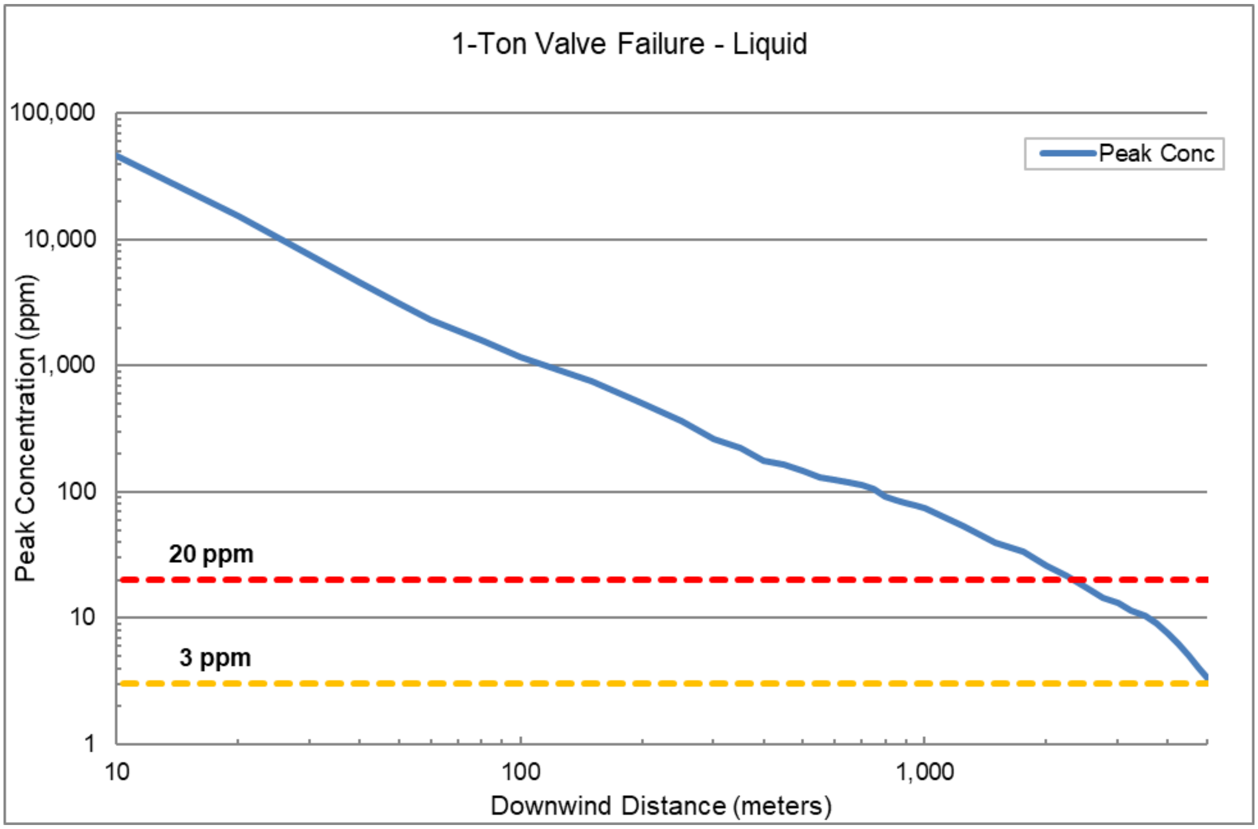
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.2.8 Alternative-Case 1-Ton Valve Failure (liquid) Scenario – D Stability

1-ton container liquid valve remains open. Full release of contents in approximately 10 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Valve	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	5/16 inch	0.79 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	72 lbs./min	32.7 kg/min
Release Duration	27.8 minutes	
Total Mass Released	2000 lbs.	907.2 kg
Gaussian Spread[1]	0.52 inch	1.32 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

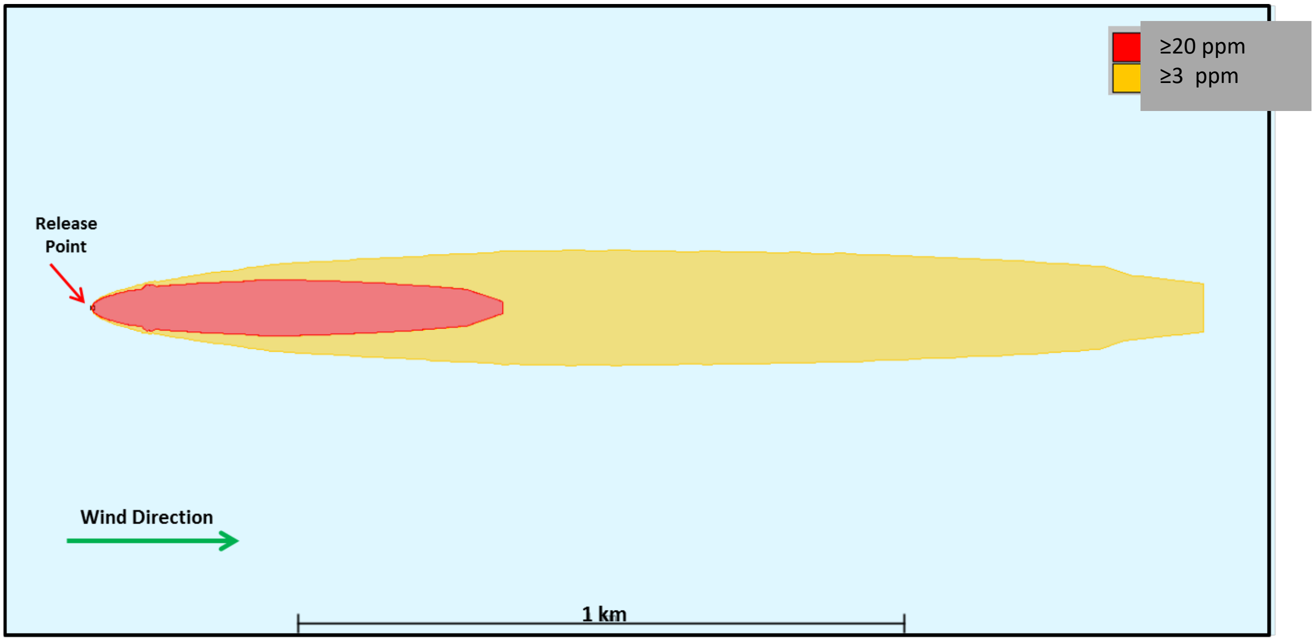
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

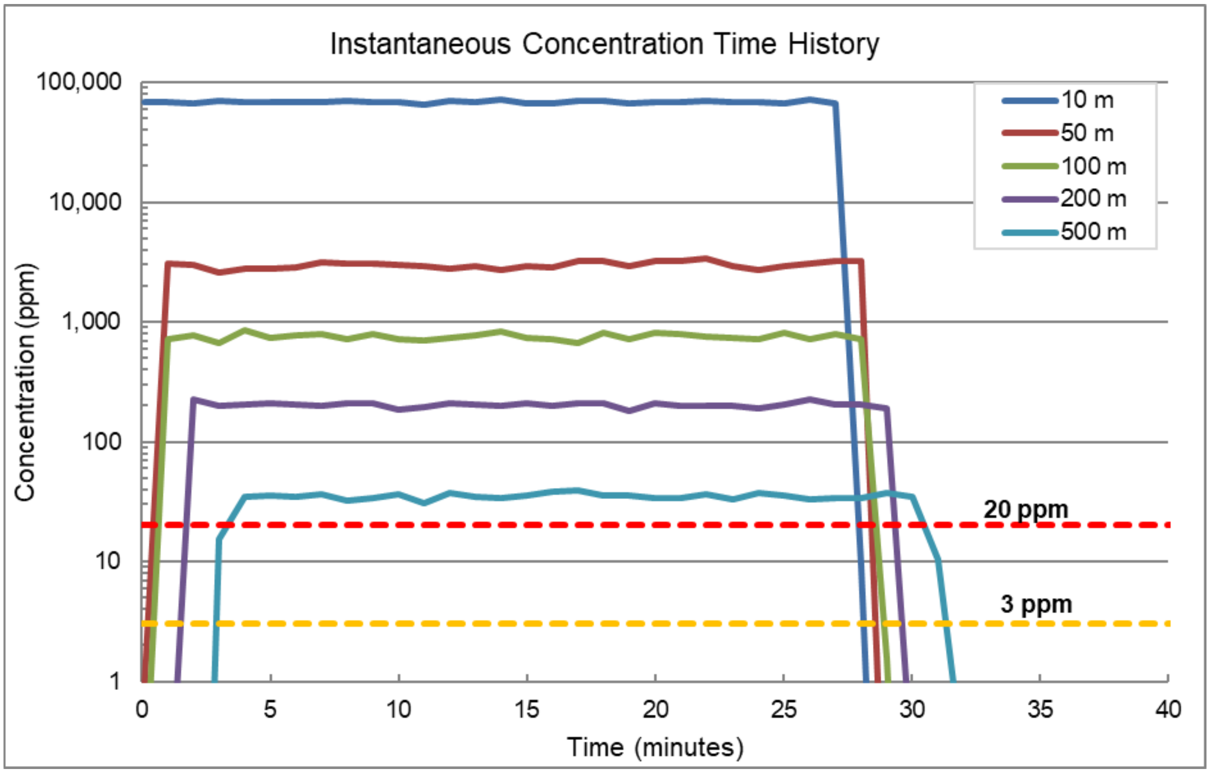
1-Ton Valve Failure (Liquid)

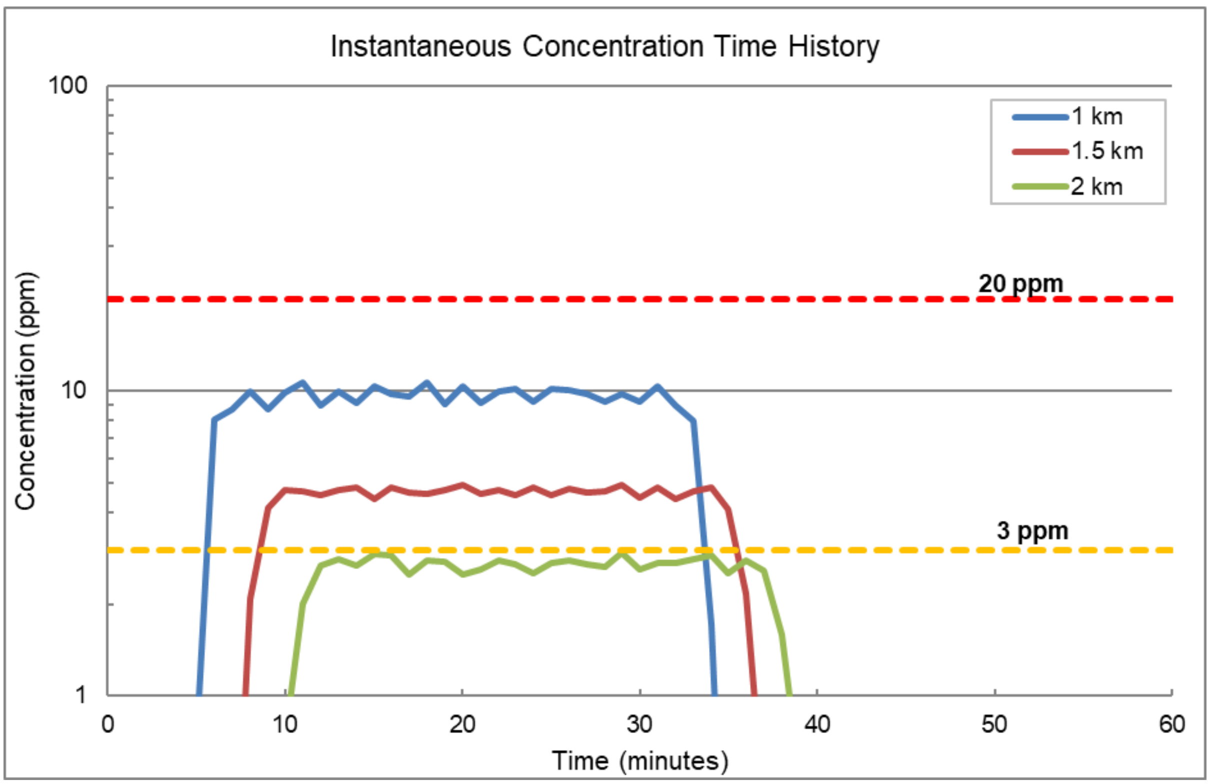


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.14	0.42
Kilometers	1.84	0.68
Maximum Crosswind Width		
Miles	0.109	0.053
Kilometers	0.176	0.086
Area Coverage		
Sq. Miles	0.10	0.018
Sq. Kilometers	0.26	0.046

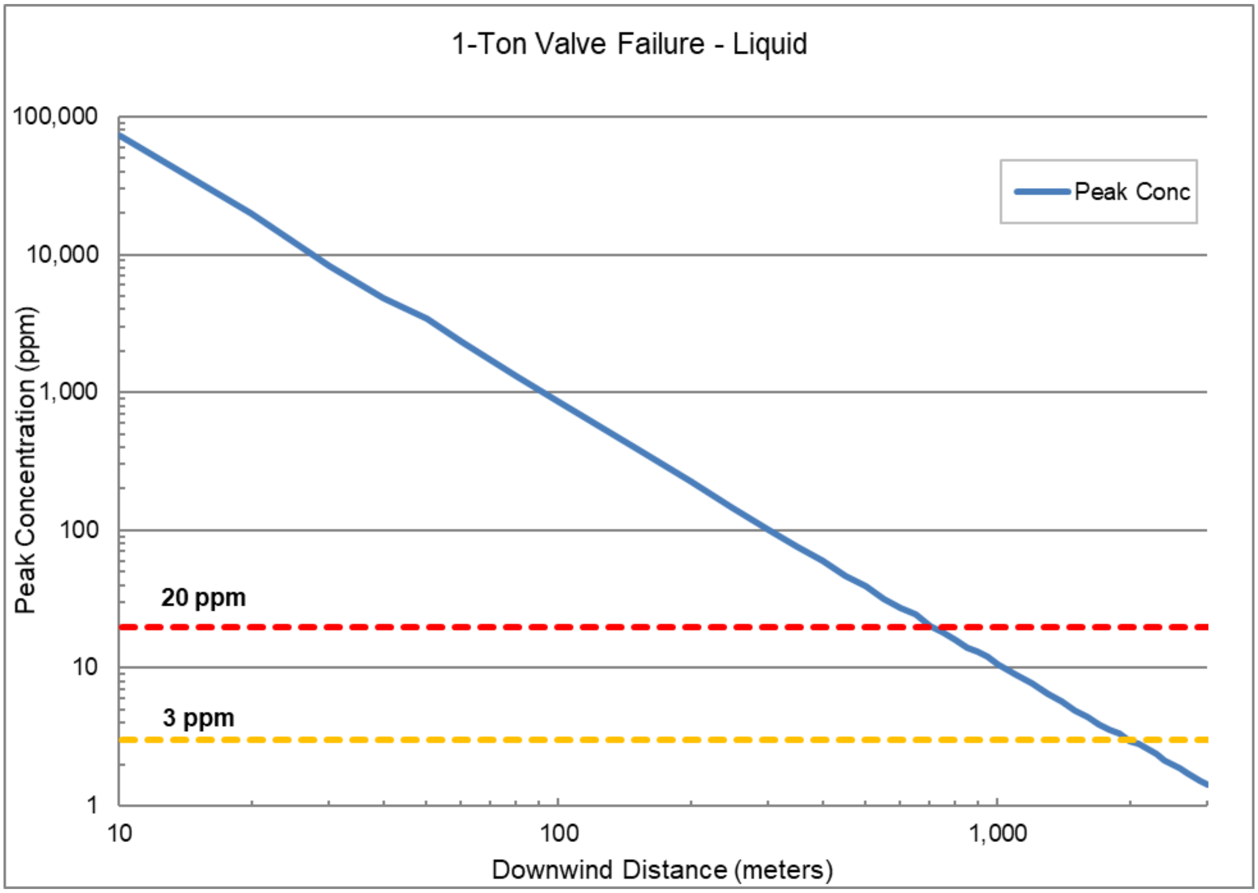
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.3 Cargo Tank Scenario Modeling Results

5.3.1 Worst-Case 17-Ton Chlorine Highway Cargo Tank Scenario – F Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	34,000 lb.	15,422.1 kg
Total Mass Released	34,000 lb.	15,422.1 kg
Release Duration	10 minutes	
Release Rate	3,400 lb./min	1,542.2 kg/min
Gaussian Spread[1]	6.56 ft	2.0 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 °F	-34.04 °C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 °F	25 °C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

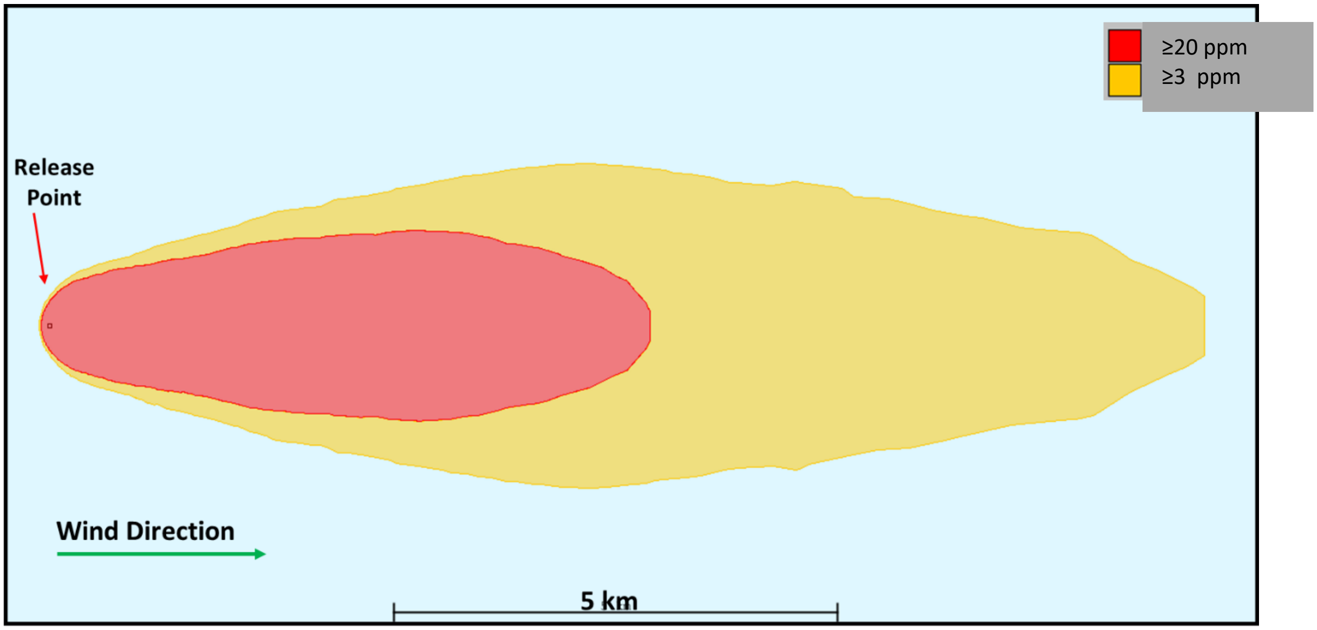
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction / plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

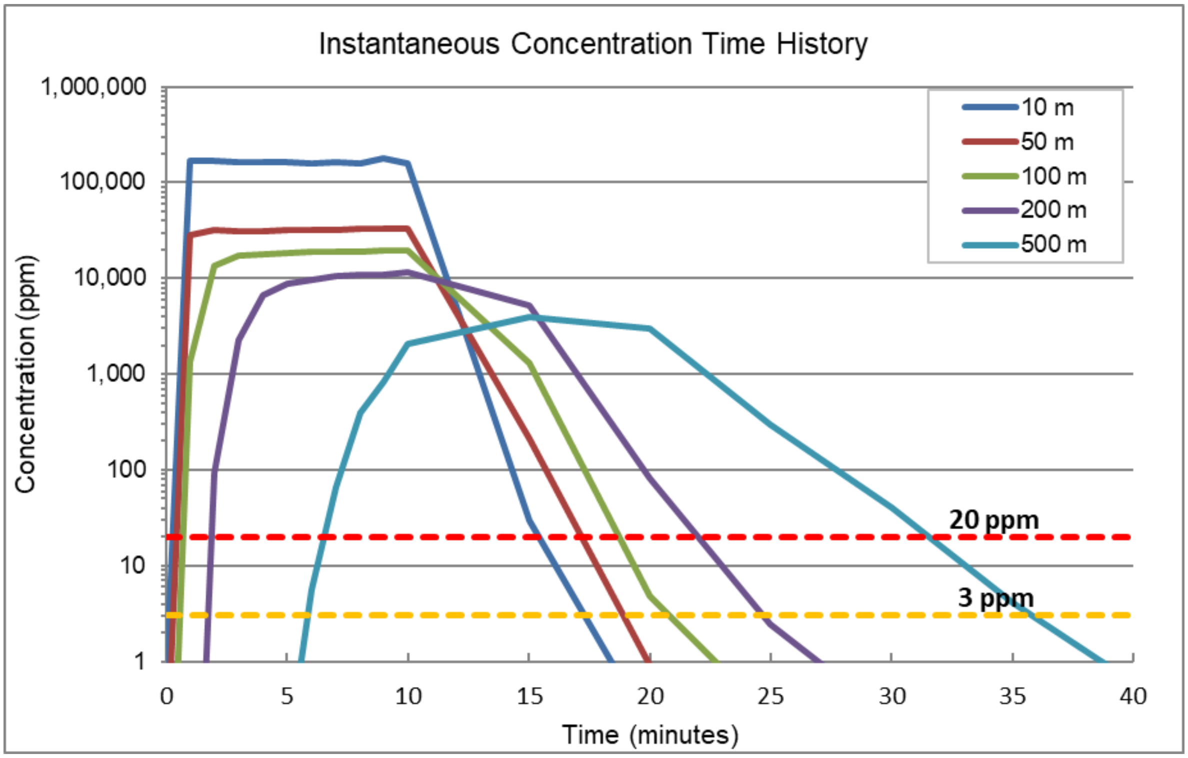
17-Ton Chlorine Highway Cargo Tank

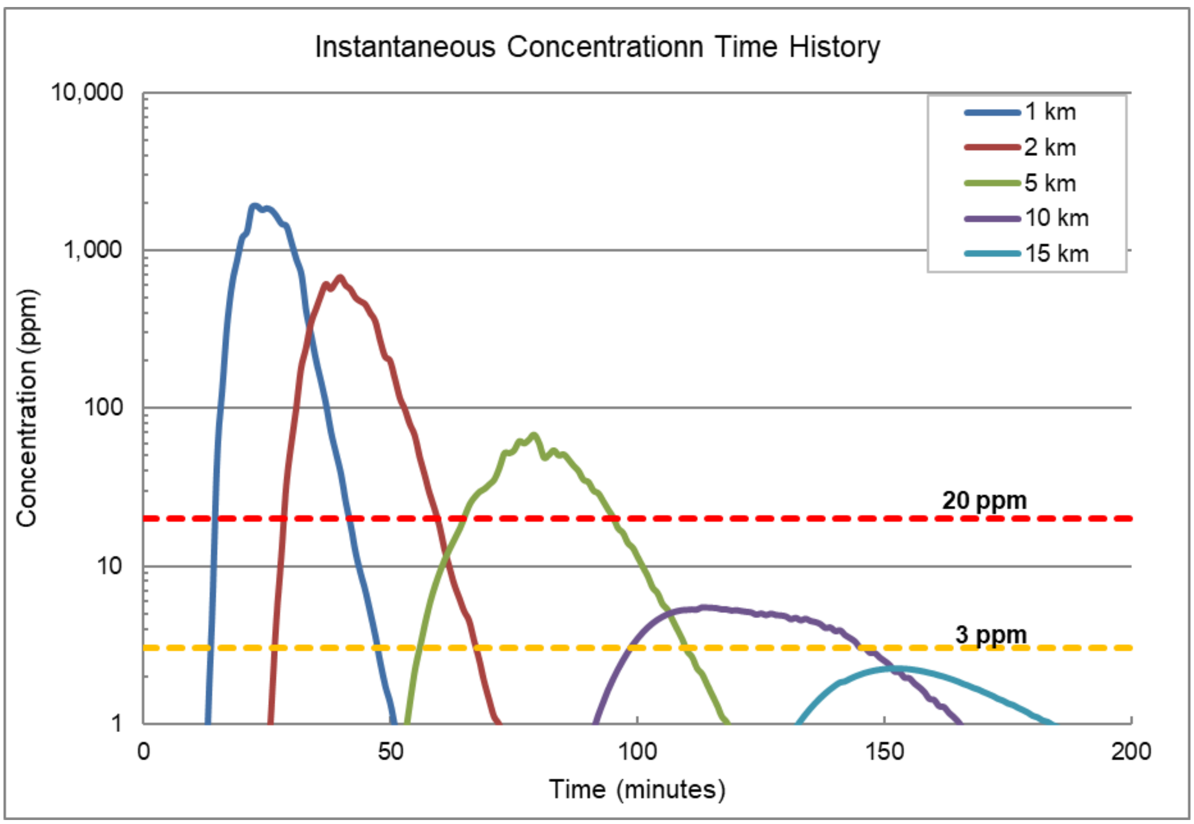


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	8.14	4.21
Kilometers	13.10	6.77
Maximum Crosswind Width		
Miles	2.10	1.23
Kilometers	3.38	1.98
Area Coverage		
Sq. Miles	12.17	4.00
Sq. Kilometers	31.51	10.36

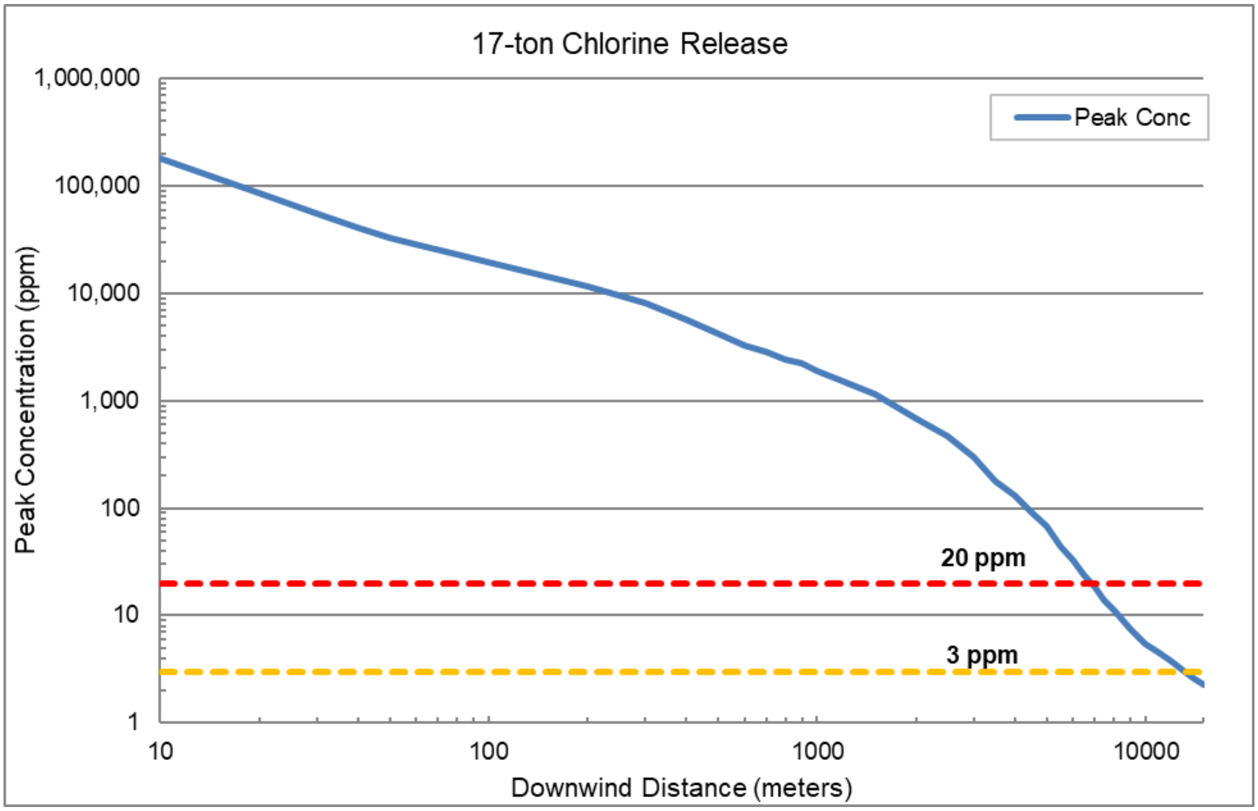
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.3.2 Worst-Case 17-Ton Chlorine Highway Cargo Tank Scenario – D Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	34,000 lb.	15,422.1 kg
Total Mass Released	34,000 lb.	15,422.1 kg
Release Duration	10 minutes	
Release Rate	3,400 lb./min	1,542.2 kg/min
Gaussian Spread[1]	6.56 ft	2.0 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 °F	-34.04 °C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 °F	25 °C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

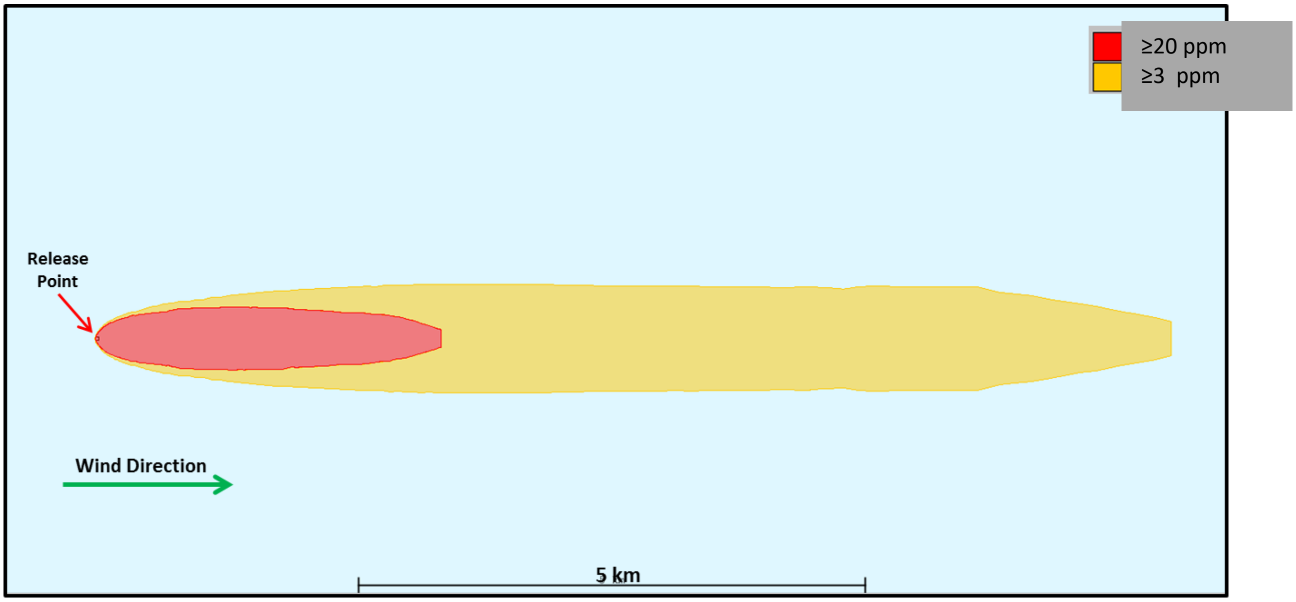
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction / plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

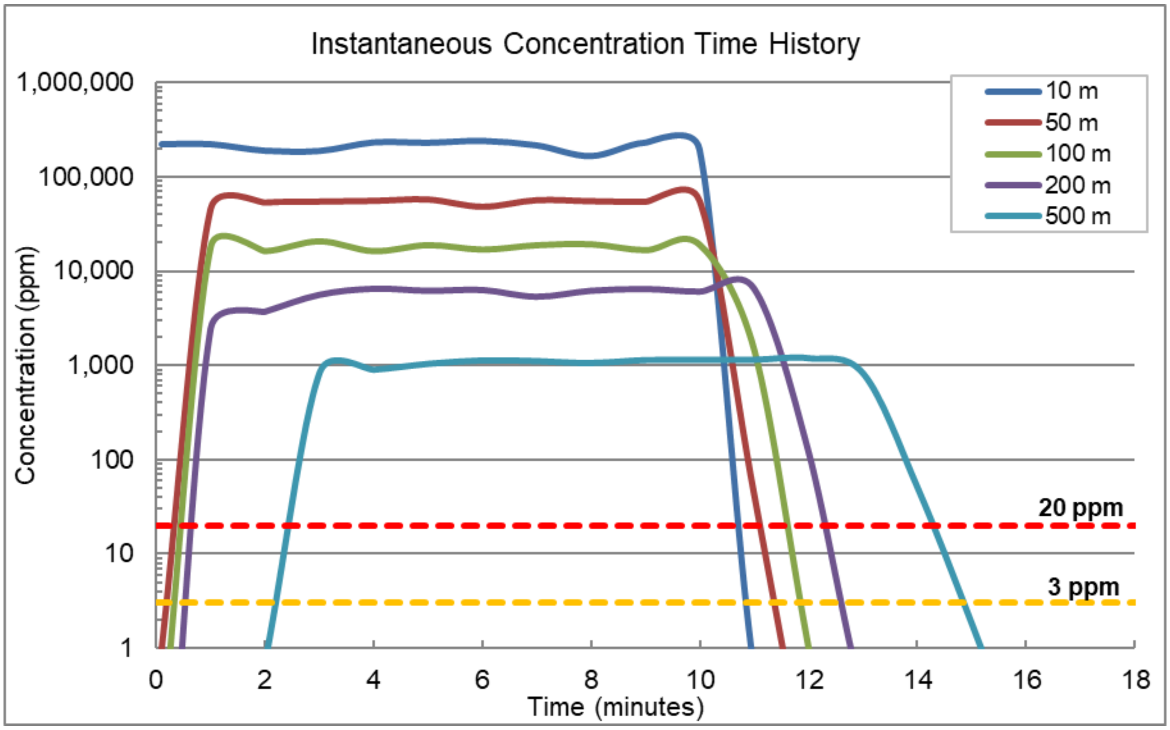
17-Ton Chlorine Highway Cargo Tank

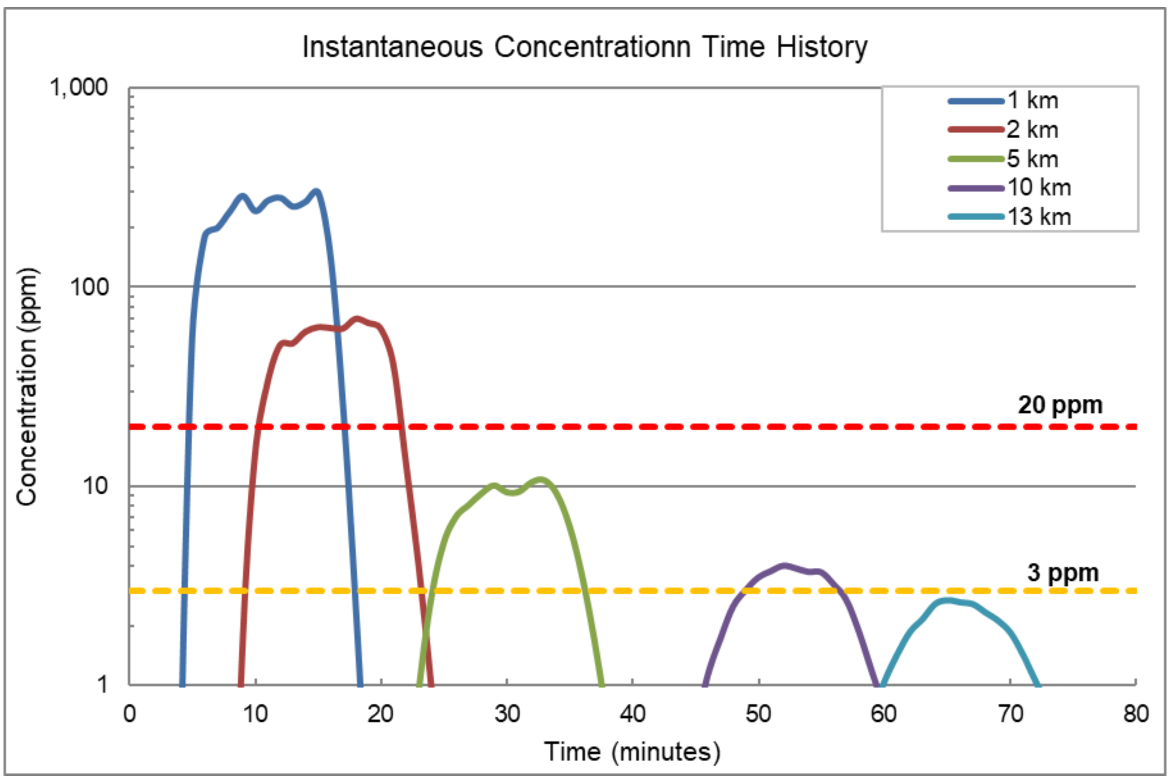


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	6.59	2.12
Kilometers	10.61	3.41
Maximum Crosswind Width		
Miles	0.62	0.35
Kilometers	1.00	0.57
Area Coverage		
Sq. Miles	3.45	0.60
Sq. Kilometers	8.92	1.56

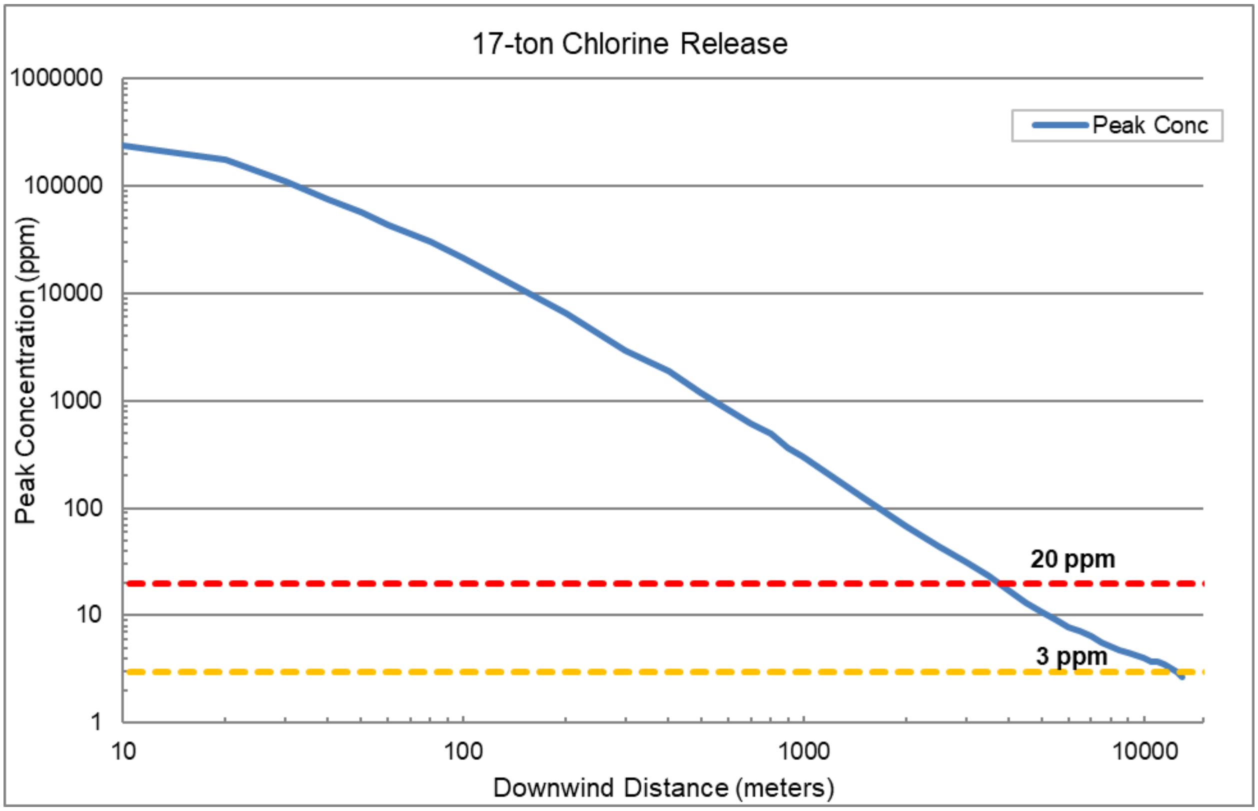
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.4 Rail Tank Car Scenario Modeling Results

5.4.1 Worst-Case 90-Ton Chlorine Railcar Scenario – F Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	180,000 lb.	81,646.6 kg
Total Mass Released	180,000 lb.	81,646.6 kg
Release Duration	10 minutes	
Release Rate	18,000 lb./min	8,164.7 kg/min
Gaussian Spread[1]	15.1 ft	4.6 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculations)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

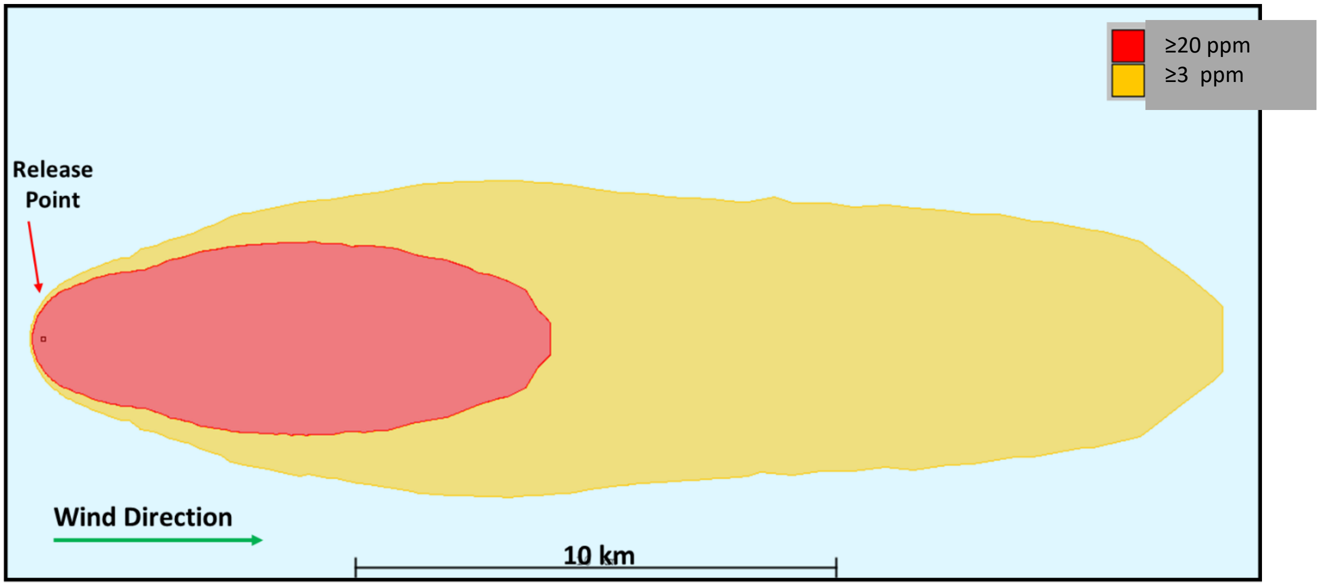
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

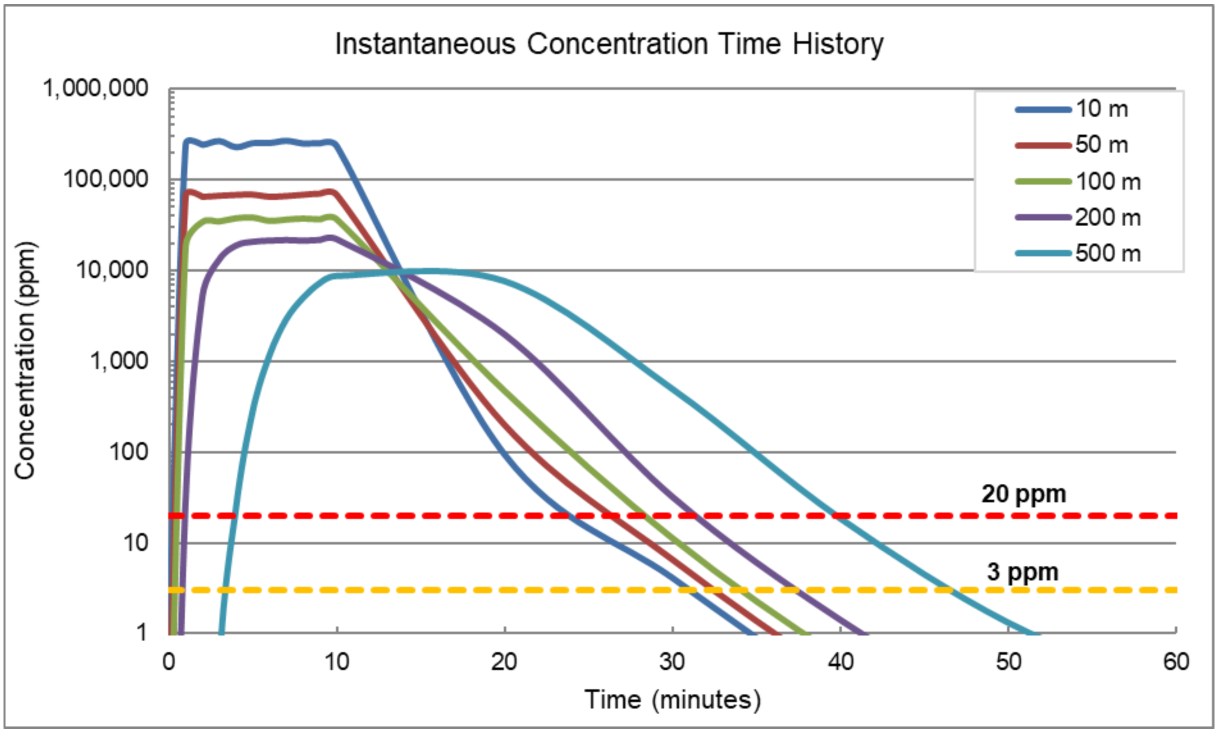
90-Ton Chlorine Railcar

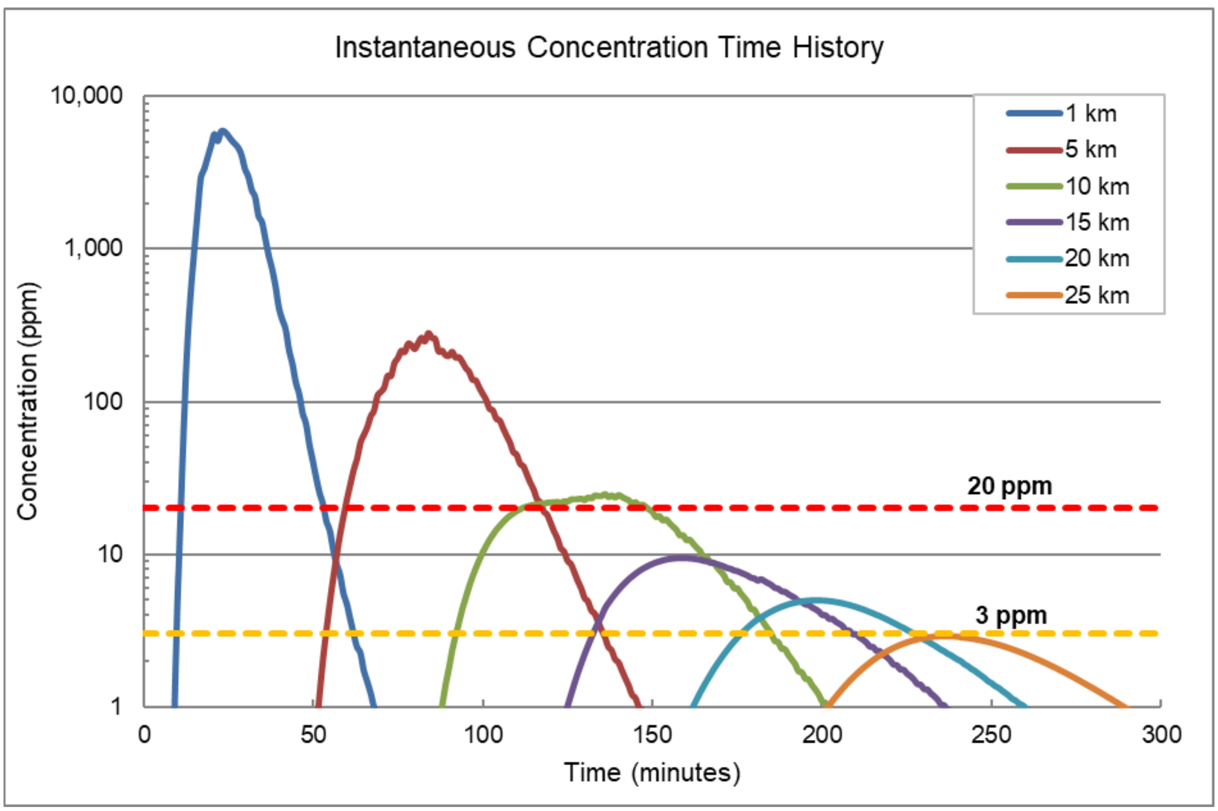


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	15.32	6.60
Kilometers	24.66	10.62
Maximum Crosswind Width		
Miles	3.81	2.31
Kilometers	6.13	3.71
Area Coverage		
Sq. Miles	45.09	11.97
Sq. Kilometers	116.78	31.01

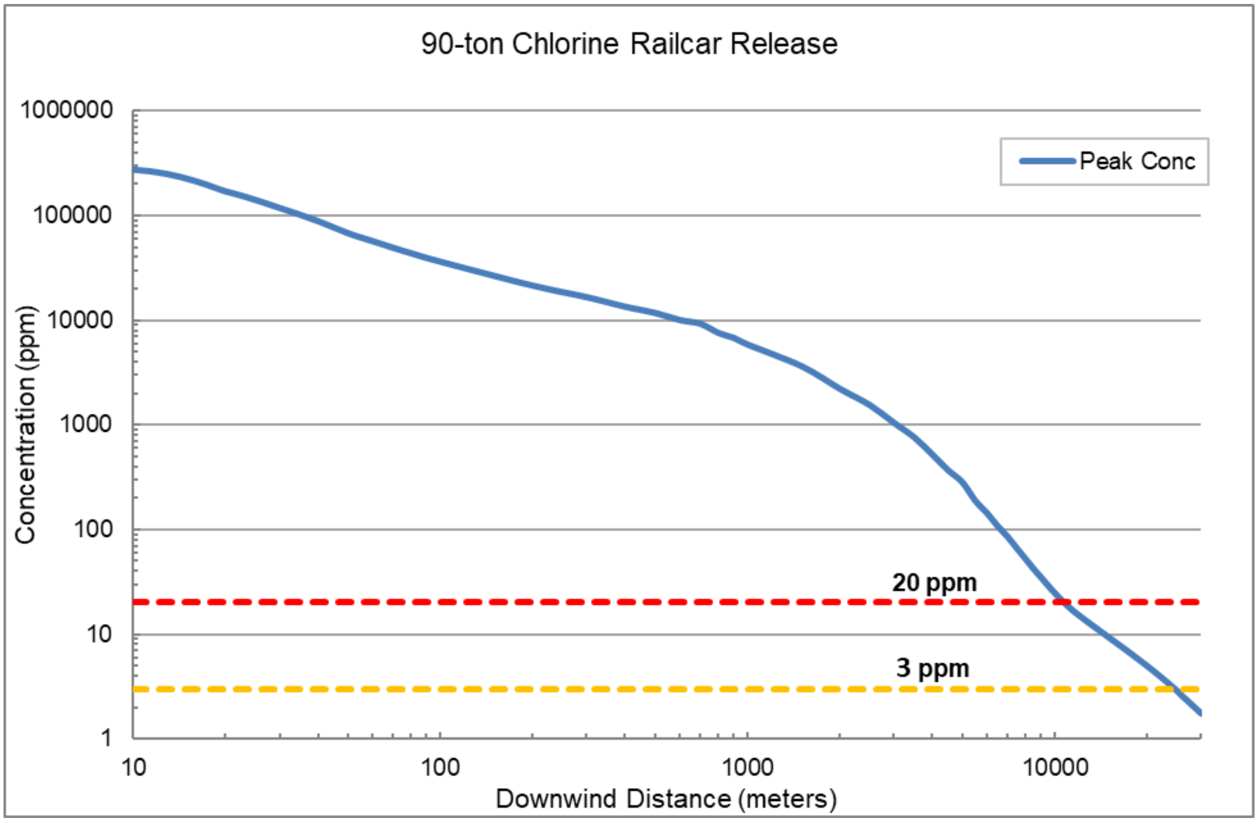
2 – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.4.2 Alternative-Case 90-Ton Chlorine Railcar Scenario – D Stability

Source Description	U.S. Standard Units	Metric Units
Container Type	Tank	
Release Mechanism	Rupture	
Hole Elevation	Rupture at base of tank / Ground level	
Opening Diameter	NA	
Release State	Modeled as all vapor release	
Contents Mass	180,000 lb.	81,646.6 kg
Total Mass Released	180,000 lb.	81,646.6 kg
Release Duration	10 minutes	
Release Rate	18,000 lb./min	8,164.7 kg/min
Gaussian Spread[1]	15.1 ft	4.6 m
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculations)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

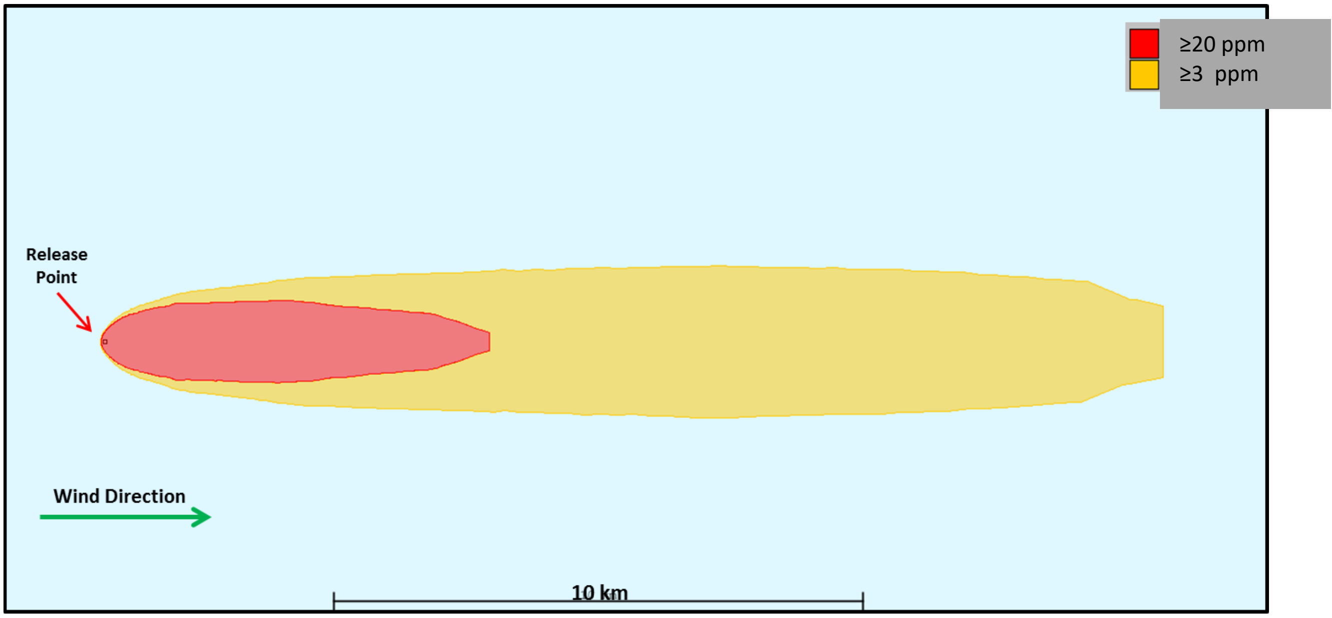
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where 95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

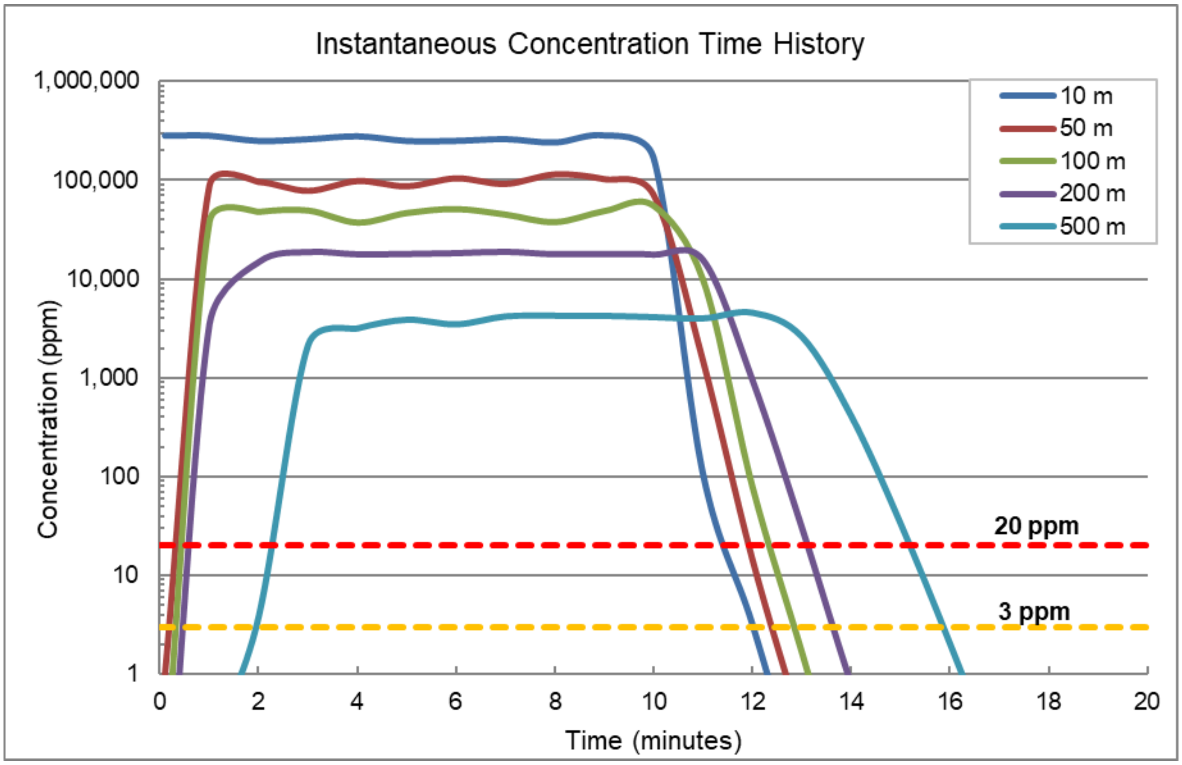
90-Ton Chlorine Railcar

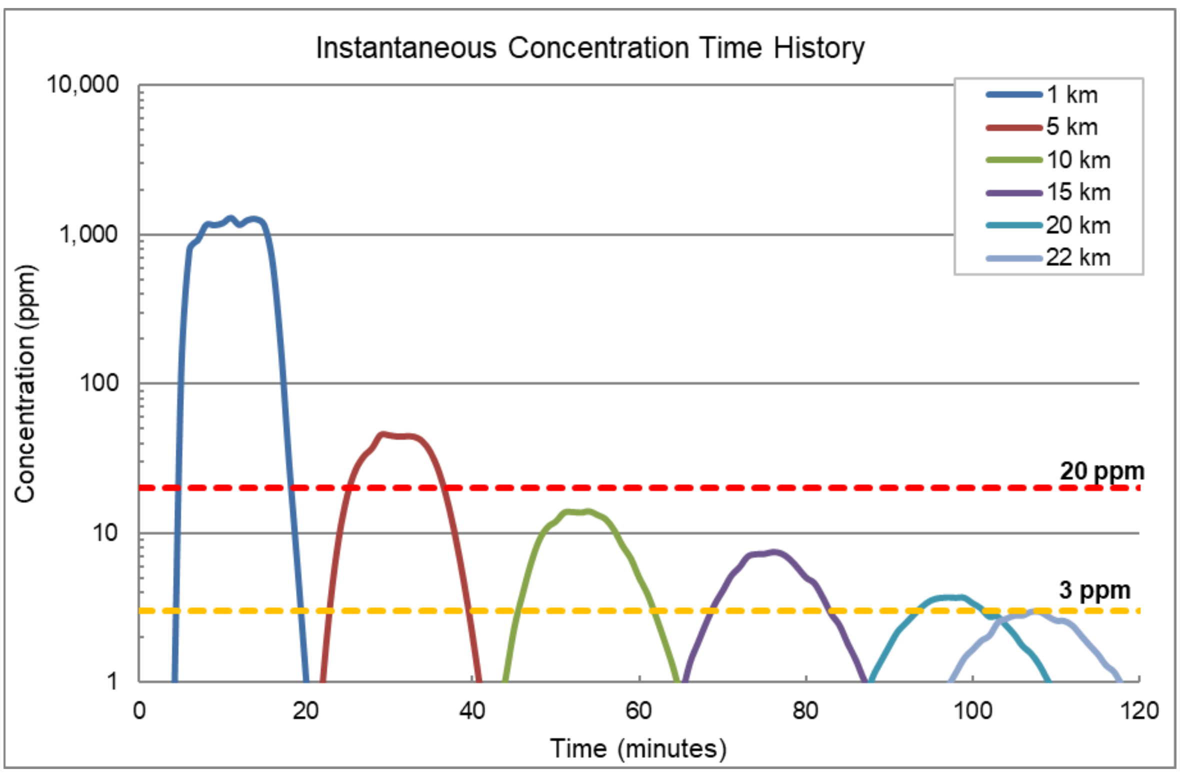


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	12.47	4.54
Kilometers	20.07	7.30
Maximum Crosswind Width		
Miles	1.65	0.90
Kilometers	2.65	1.45
Area Coverage		
Sq. Miles	17.31	3.17
Sq. Kilometers	44.83	8.21

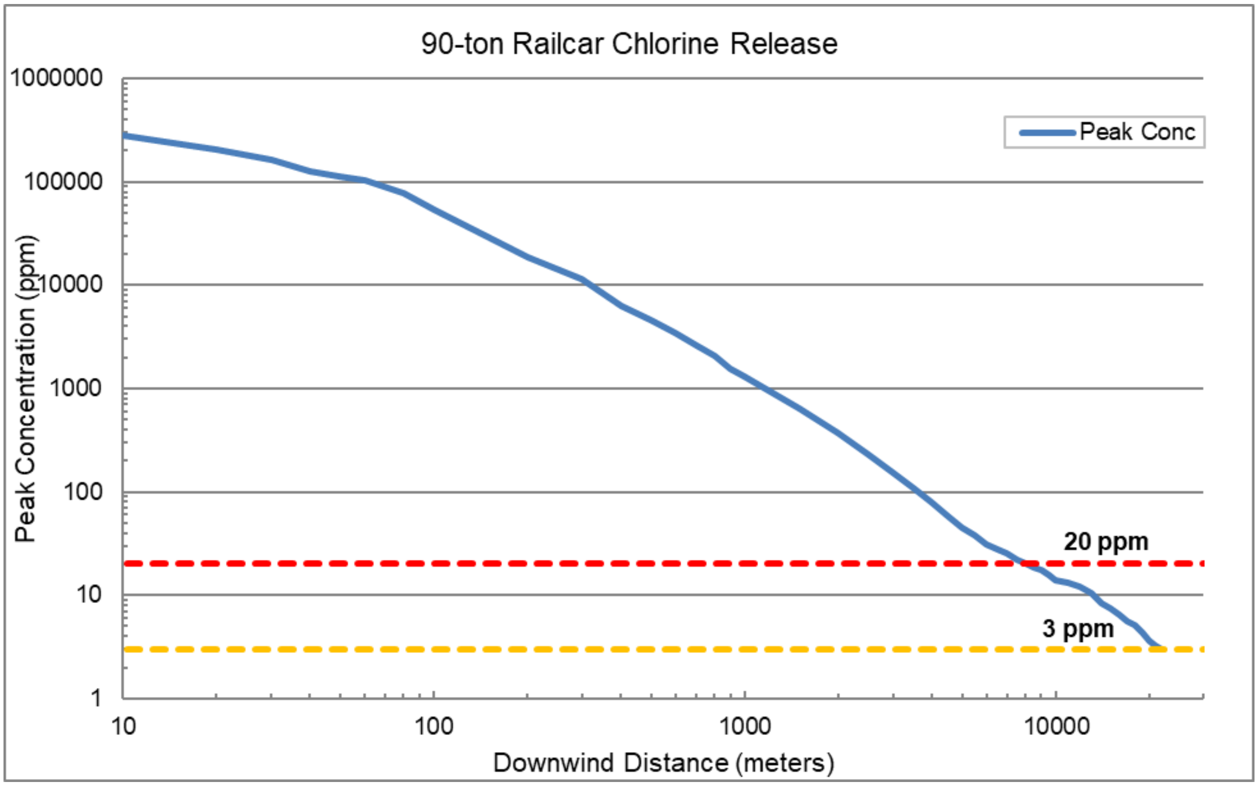
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.4.3 Alternative-Case 90 Ton Relief Valve Scenario – F Stability

A rail tank car is overfilled with chlorine; the pressure rises and the relief valve opens; in reality, the relief valve will open and close repeatedly; the frequency of opening is dependent on heat transferred to the car from the environment; for modeling purposes, it is assumed the relief valve remains open for 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Railroad Tank Car	
Release Mechanism	Over Pressure	
Hole Elevation	13.5 ft.	4.1 m
Opening Diameter	1.04 inch	2.64 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	180,000 lbs.	81,647 kg
Release Rate	141 lbs./min	64.0 kg/min
Release Duration	30 minutes	
Total Mass Released	4230 lbs.	1918.7 kg
Gaussian Spread[1]	1.73 inch	4.40 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

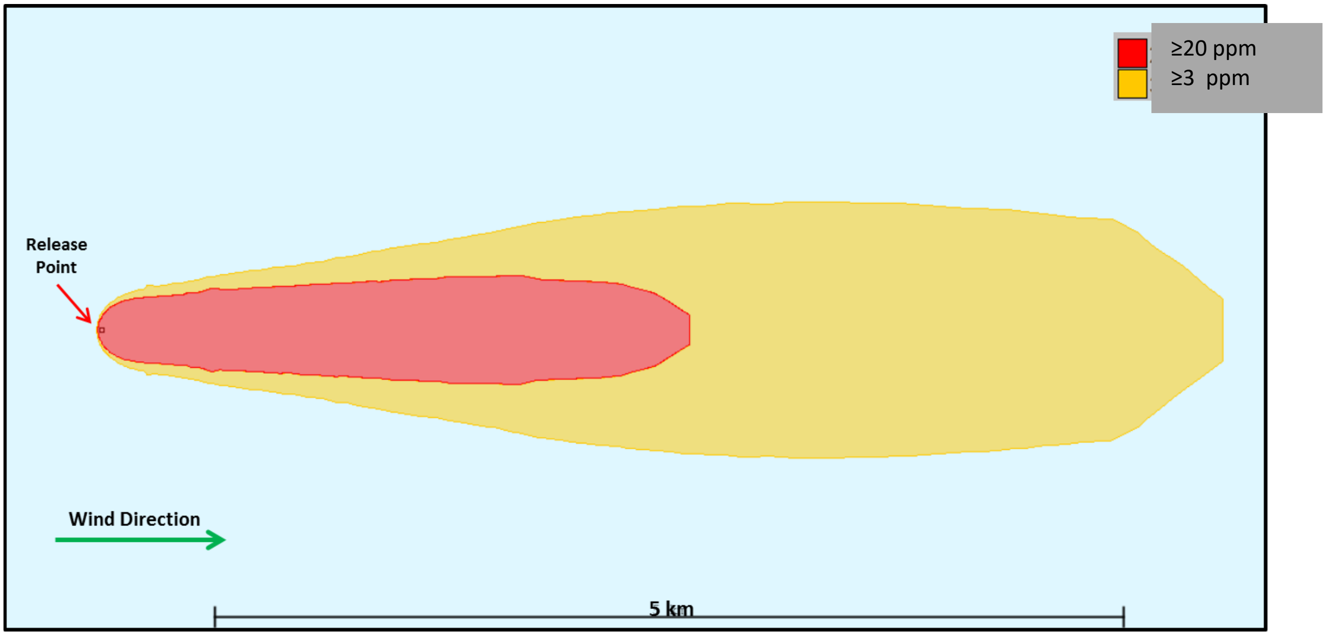
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

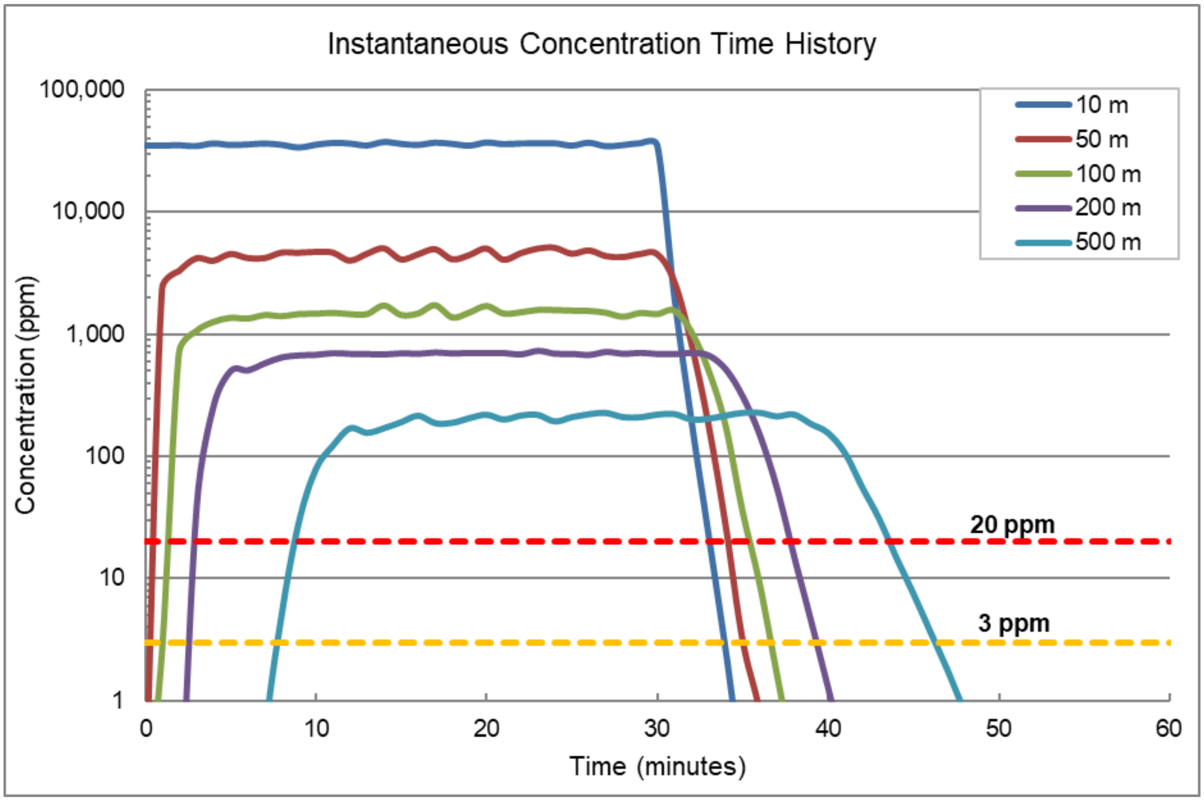
90-Ton Railcar Relief Valve

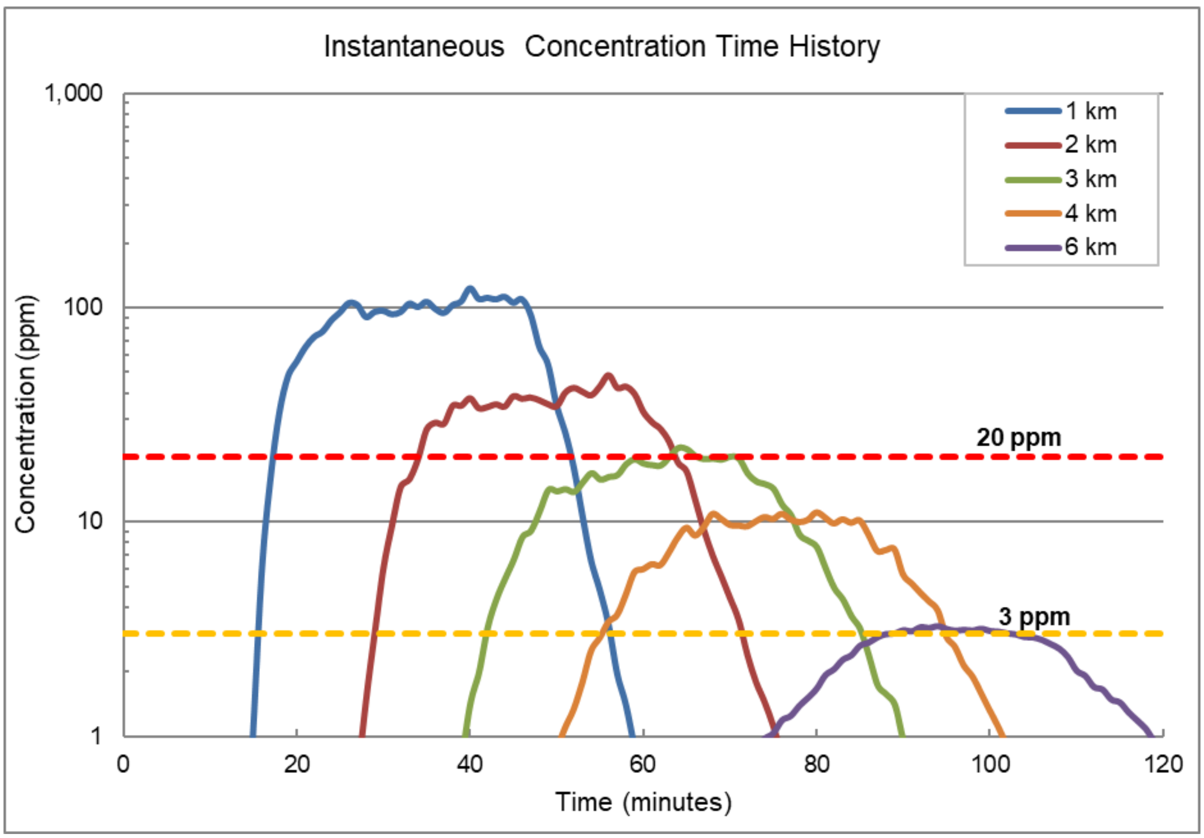


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	3.85	2.01
Kilometers	6.19	3.24
Maximum Crosswind Width		
Miles	0.81	0.34
Kilometers	1.31	0.55
Area Coverage		
Sq. Miles	2.33	0.55
Sq. Kilometers	6.04	1.43

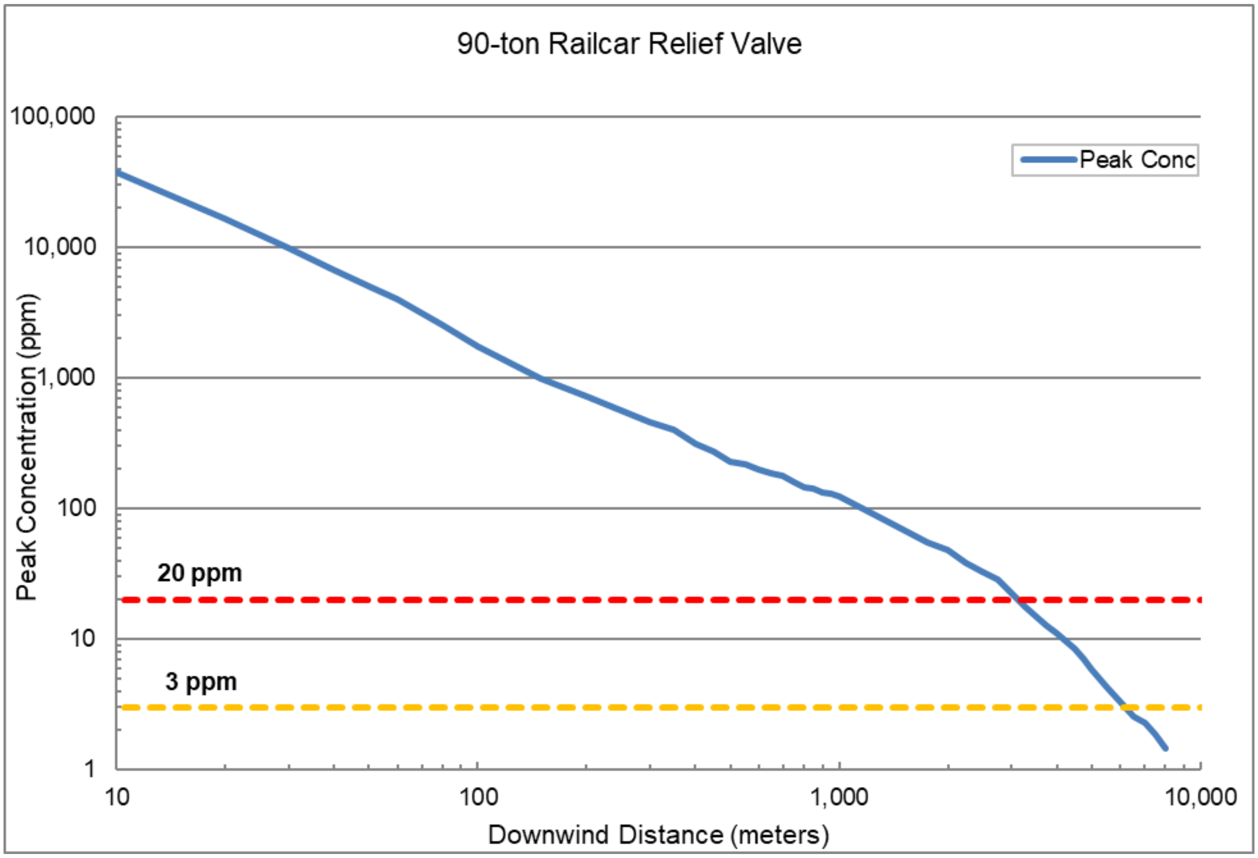
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.4.4 Alternative-Case 90 Ton Relief Valve Scenario – D Stability

A rail tank car is overfilled with chlorine; the pressure rises and the relief valve opens; in reality, the relief valve will open and close repeatedly; the frequency of opening is dependent on heat transferred to the car from the environment; for modeling purposes, it is assumed the relief valve remains open for 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Railroad Tank Car	
Release Mechanism	Over Pressure	
Hole Elevation	13.5 ft.	4.1 m
Opening Diameter	1.04 inch	2.64 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	180,000 lbs.	81,647 kg
Release Rate	141 lbs./min	64.0 kg/min
Release Duration	30 minutes	
Total Mass Released	4230 lbs.	1918.7 kg
Gaussian Spread[1]	1.73 inch	4.40 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

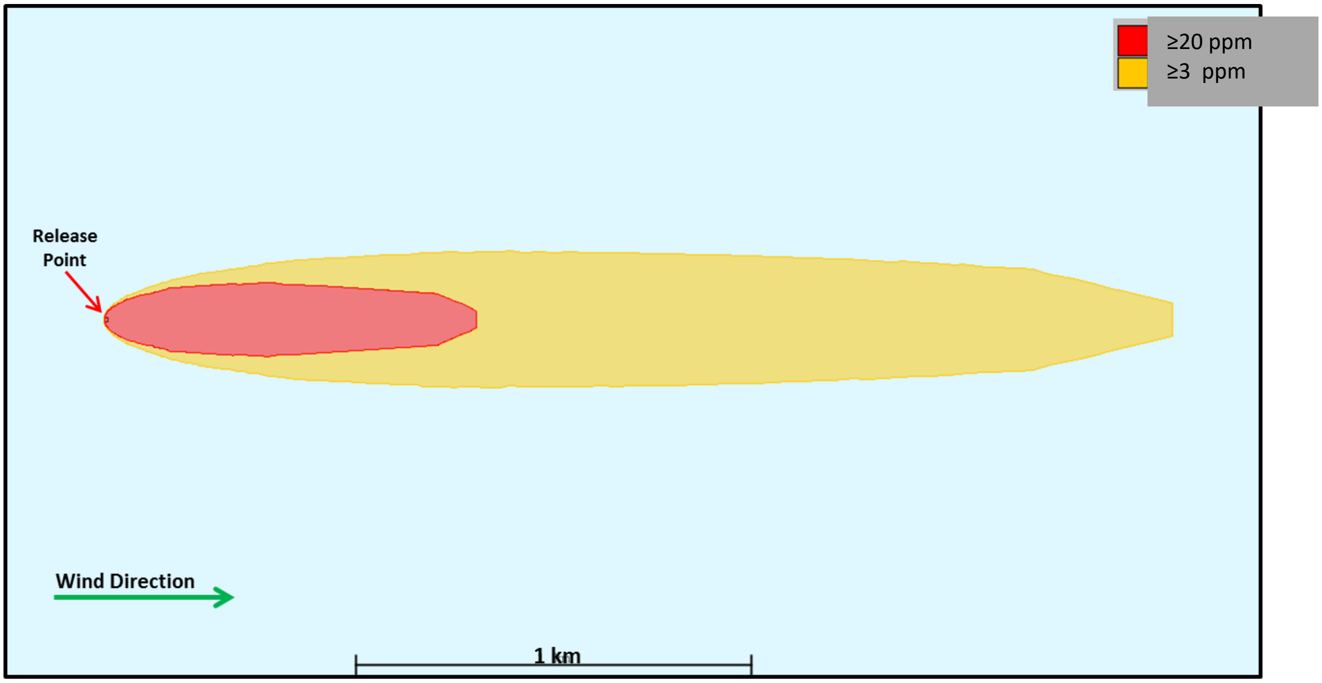
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

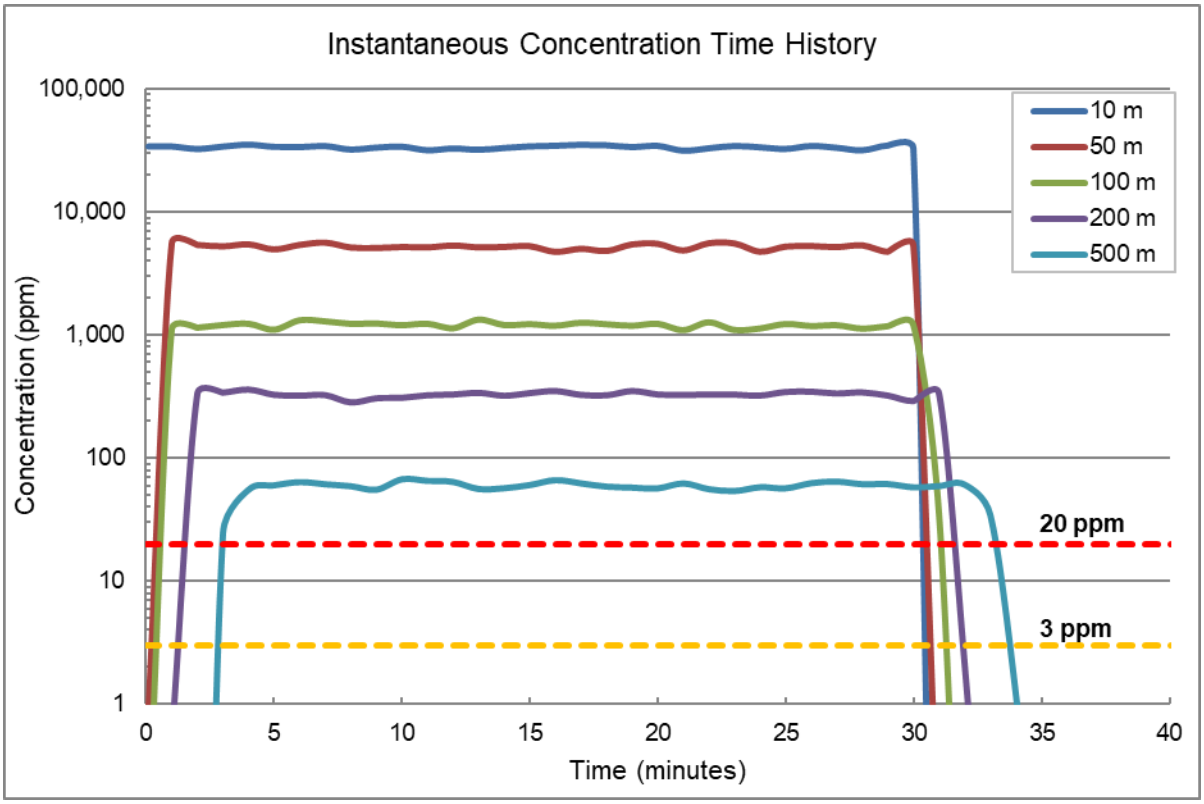
90-Ton Railcar Relief Valve

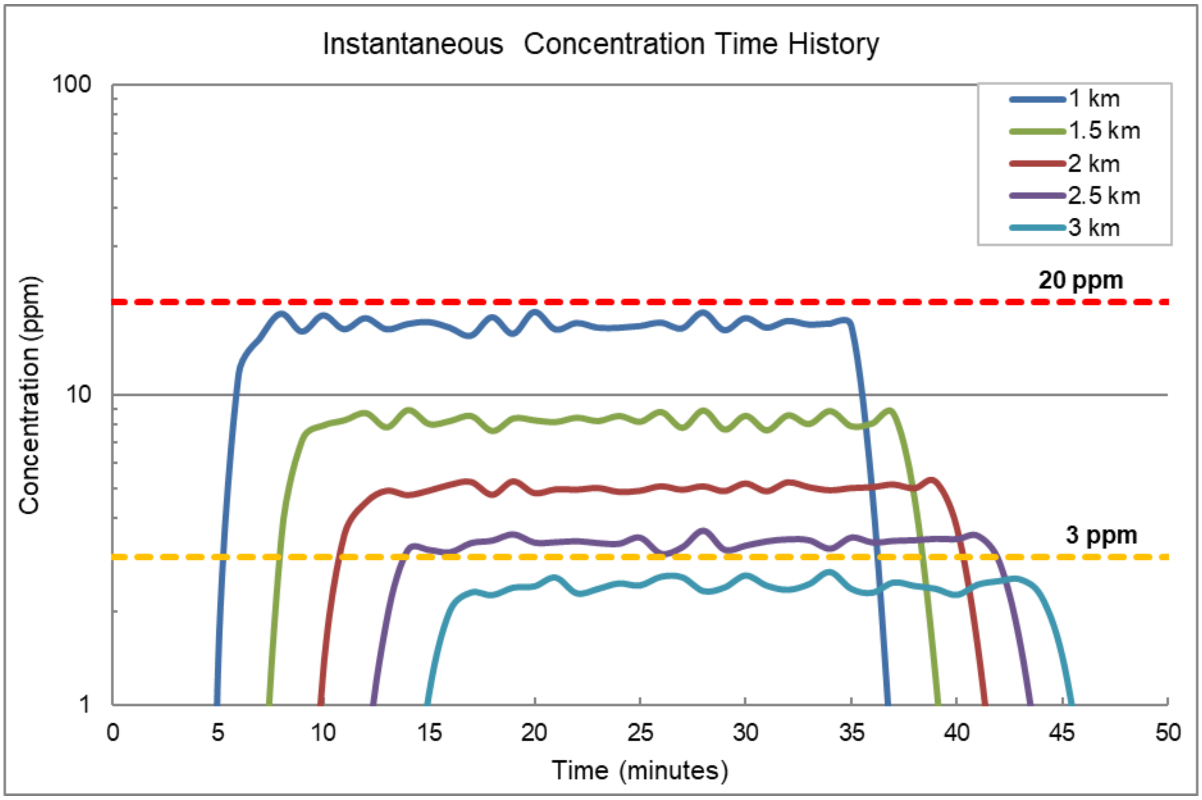


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.68	0.58
Kilometers	2.70	0.94
Maximum Crosswind Width		
Miles	0.20	0.10
Kilometers	0.32	0.17
Area Coverage		
Sq. Miles	0.27	0.05
Sq. Kilometers	0.69	0.13

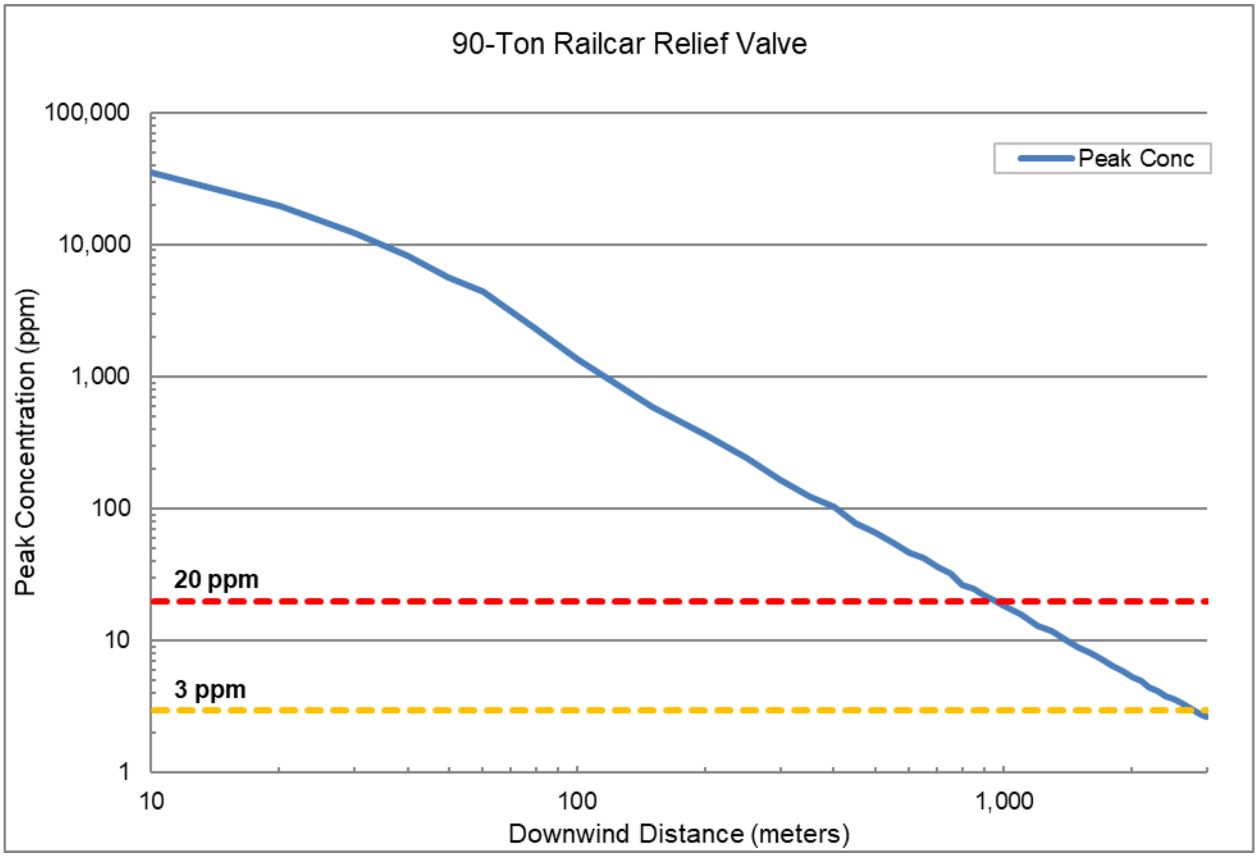
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5 PIPING AND TUBING SCENARIO MODELING RESULTS

5.5.1 Alternative-Case 1-Inch Piping Failure (gas) Scenario – F Stability

A 1-inch (2.54 cm) schedule 80 pipe is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Pipe	
Release Mechanism	Failure	
Hole Elevation	15.0 ft.	4.6 m
Opening Diameter	1.0 inch	2.54 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	136.8 lbs./min	62.1 kg/min
Release Duration	30 minutes	
Total Mass Released	4104 lbs.	1862 kg
Gaussian Spread[1]	1.67 inch	4.23 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

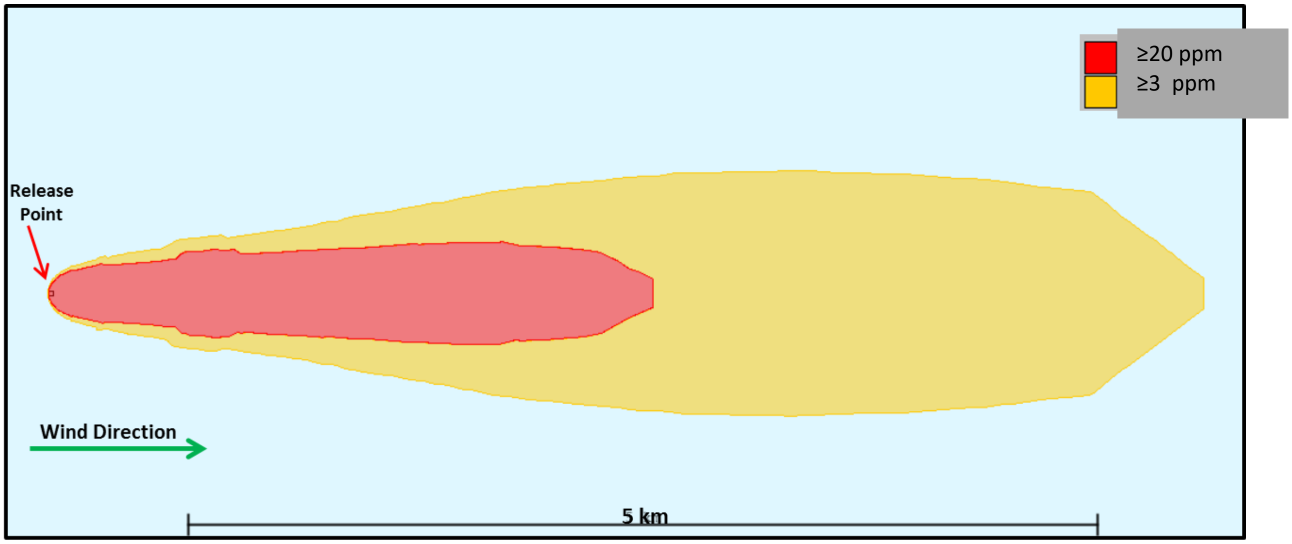
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

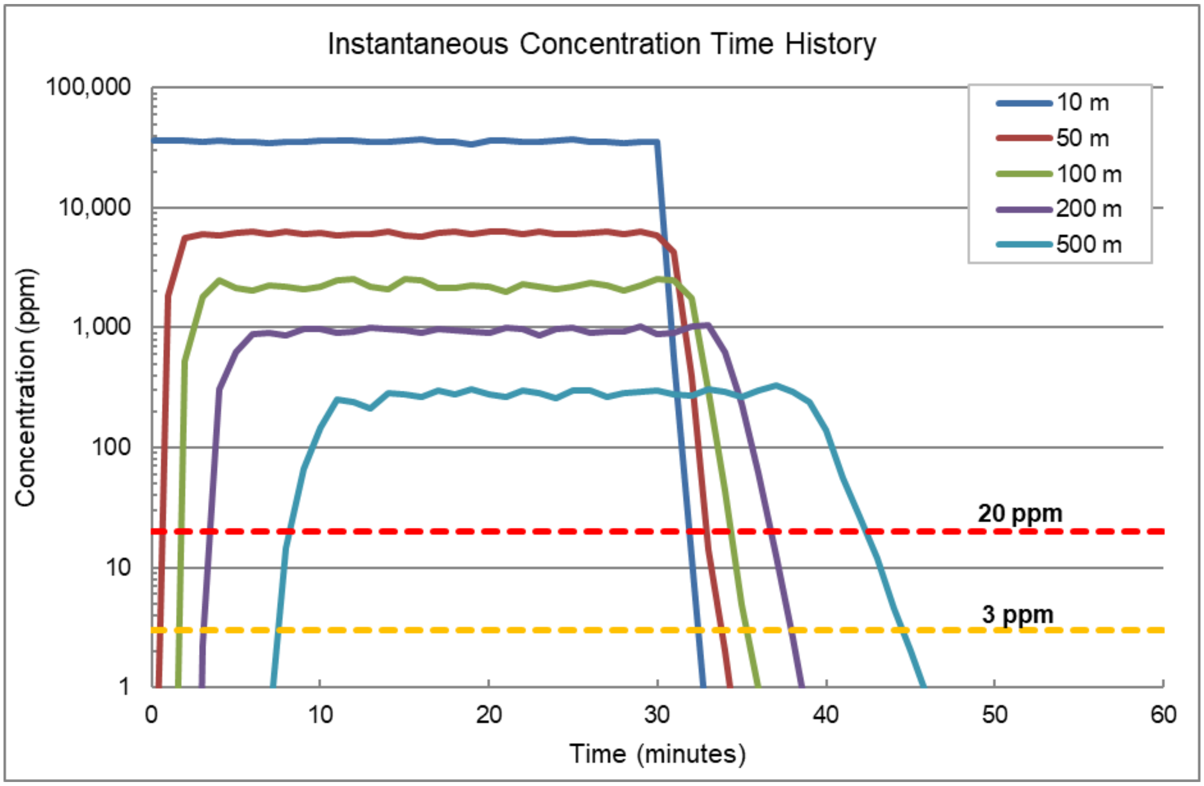
1-inch Pipe Failure (Gas)

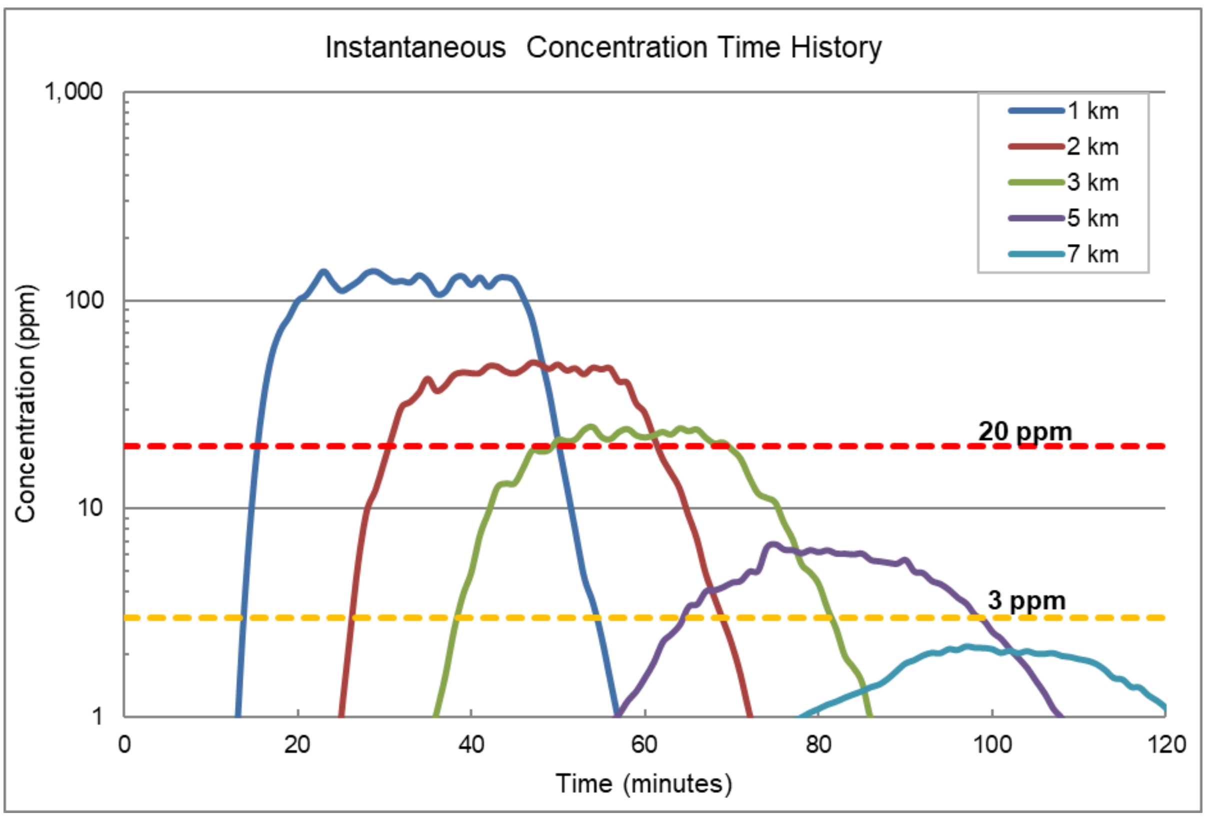


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	3.95	2.06
Kilometers	6.35	3.32
Maximum Crosswind Width		
Miles	0.78	0.32
Kilometers	1.25	0.52
Area Coverage		
Sq. Miles	2.22	0.52
Sq. Kilometers	5.76	1.35

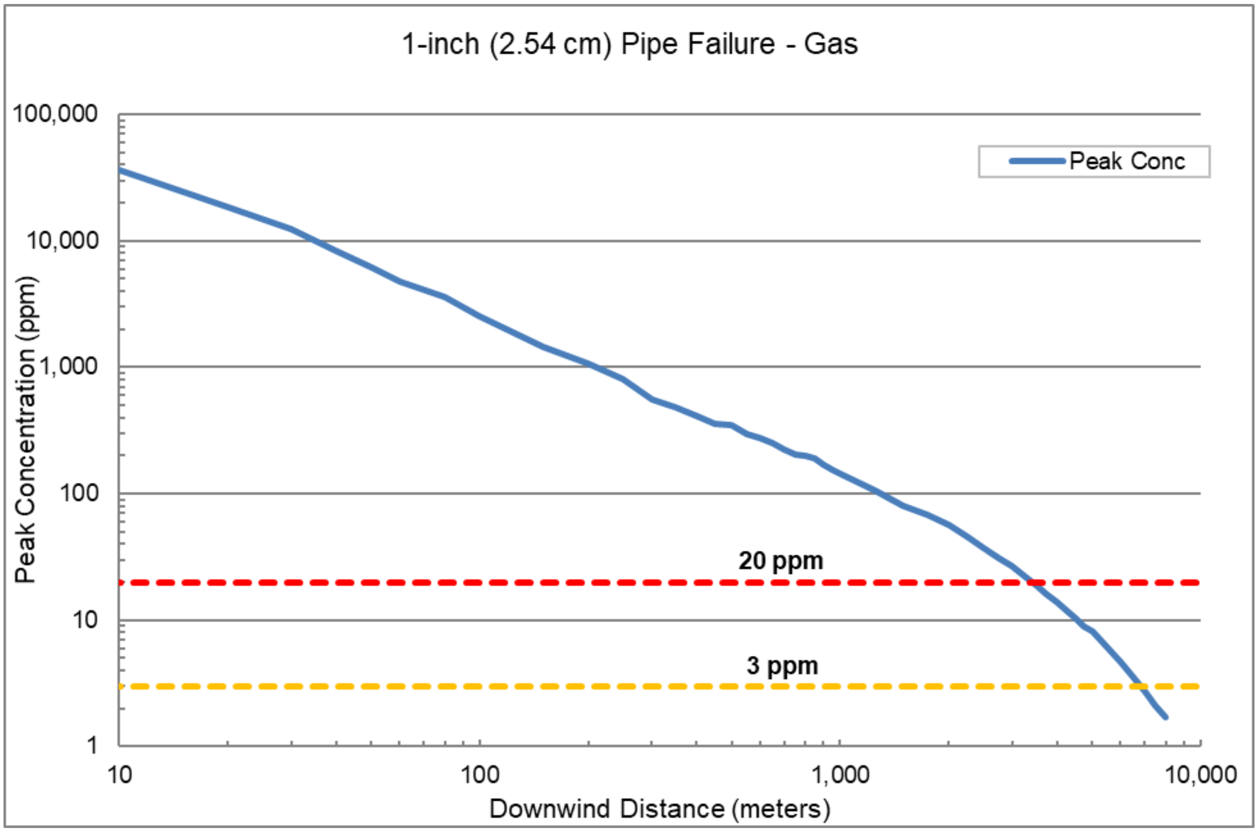
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.2 Alternative-Case 1-Inch (2.54 cm) Piping Failure (gas) Scenario – D Stability

A 1-inch schedule 80 pipe is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Pipe	
Release Mechanism	Failure	
Hole Elevation	15.0 ft.	4.6 m
Opening Diameter	1.0 inch	2.54 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	136.8 lbs./min	62.1 kg/min
Release Duration	30 minutes	
Total Mass Released	4104 lbs.	1862 kg
Gaussian Spread[1]	1.67 inch	4.23 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

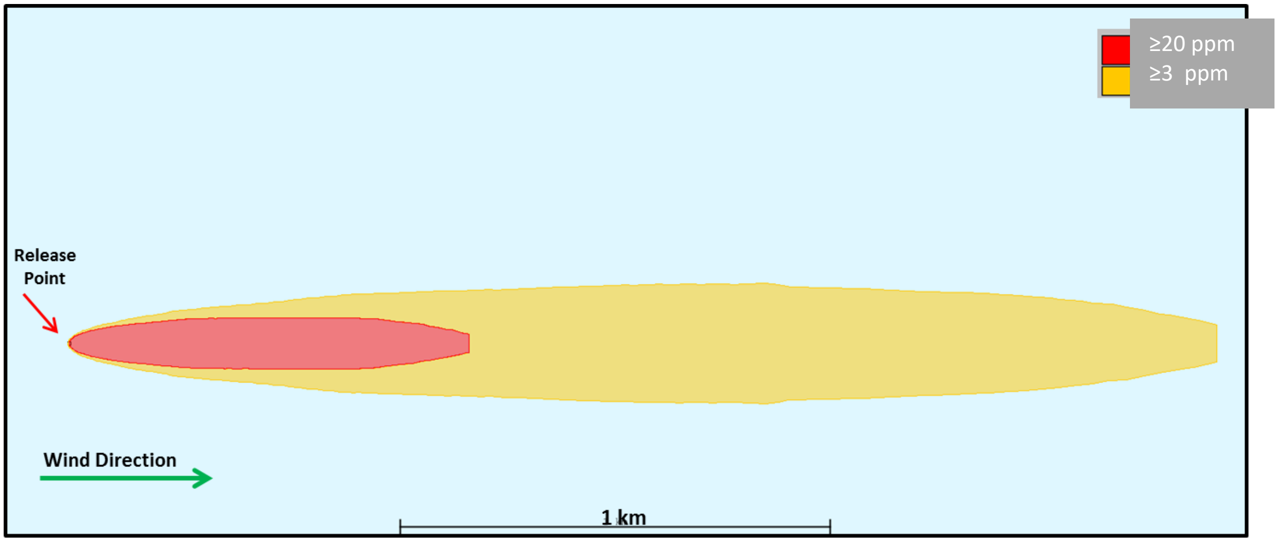
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

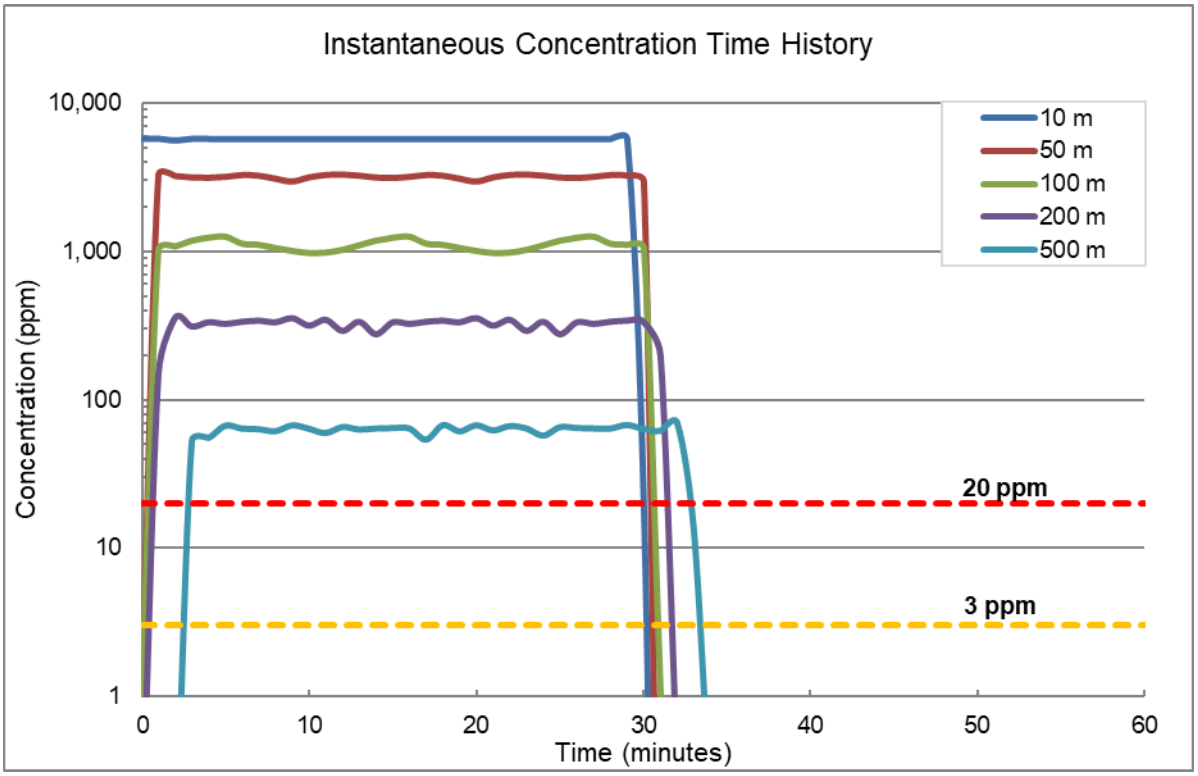
1-inch Pipe Failure (Gas)

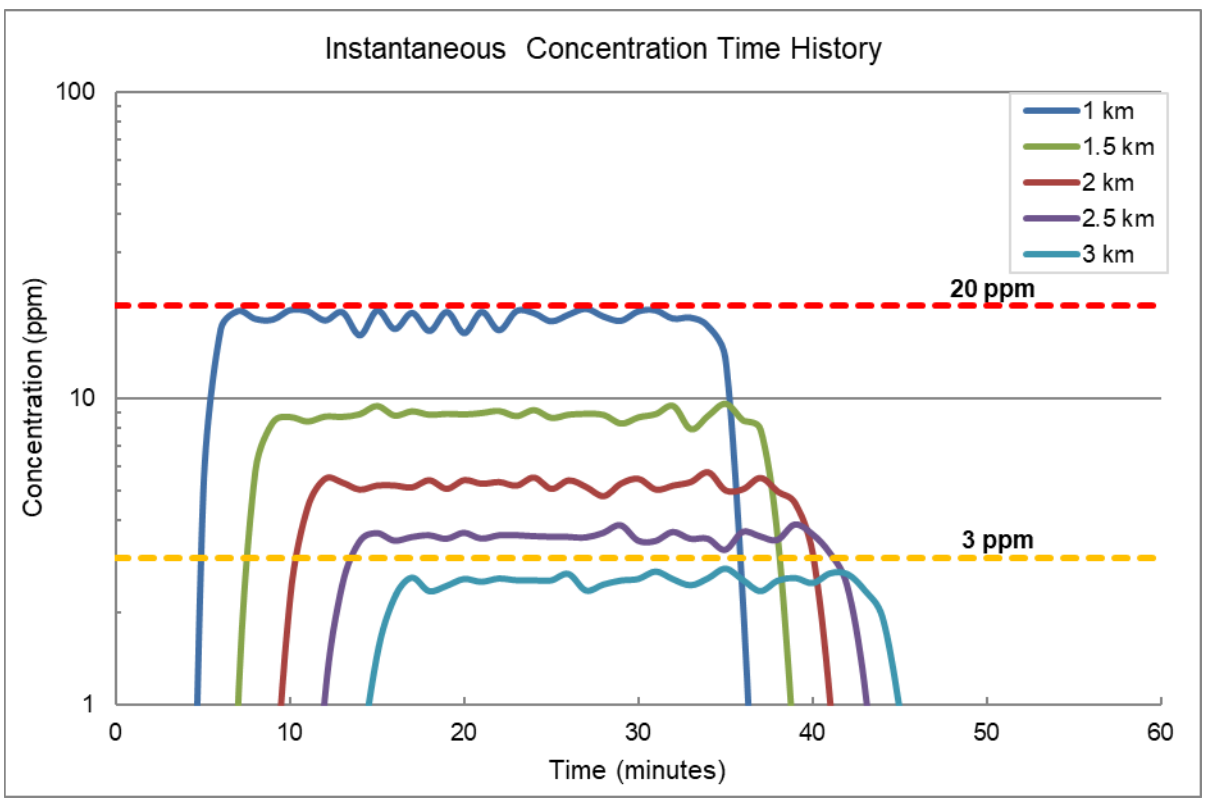


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.67	0.58
Kilometers	2.68	0.93
Maximum Crosswind Width		
Miles	0.16	0.07
Kilometers	0.26	0.11
Area Coverage		
Sq. Miles	0.21	0.03
Sq. Kilometers	0.53	0.08

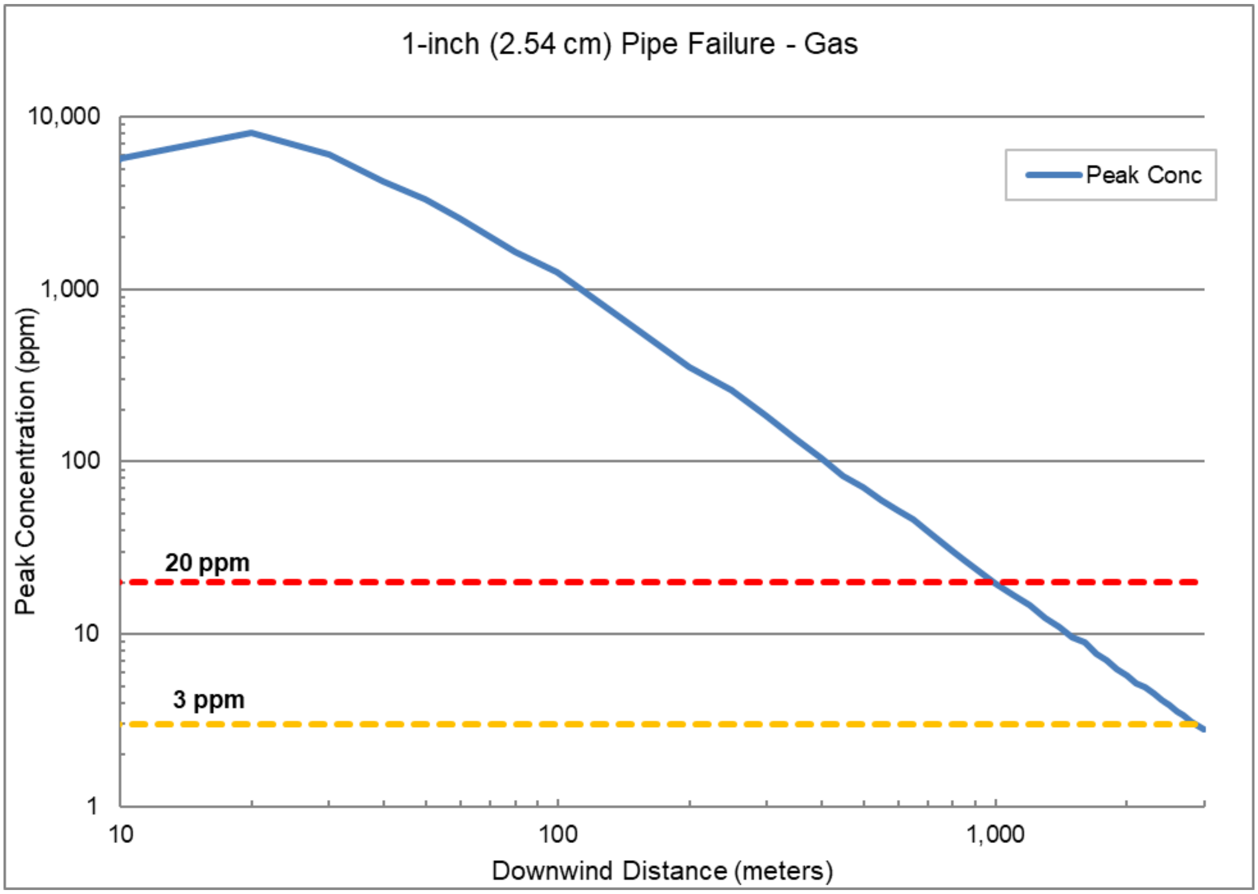
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.3 Alternative-Case 1-Inch Piping Failure (liquid) Scenario – F Stability

A 1-inch (2.54 cm) schedule 80 pipe is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Pipe	
Release Mechanism	Failure	
Hole Elevation	15.0 ft.	4.6 m
Opening Diameter	1.0 inch	2.54 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	733 lbs./min	332.5 kg/min
Release Duration	30 minutes	
Total Mass Released	21990 lbs.	9974 kg
Gaussian Spread[1]	1.67 inch	4.23 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

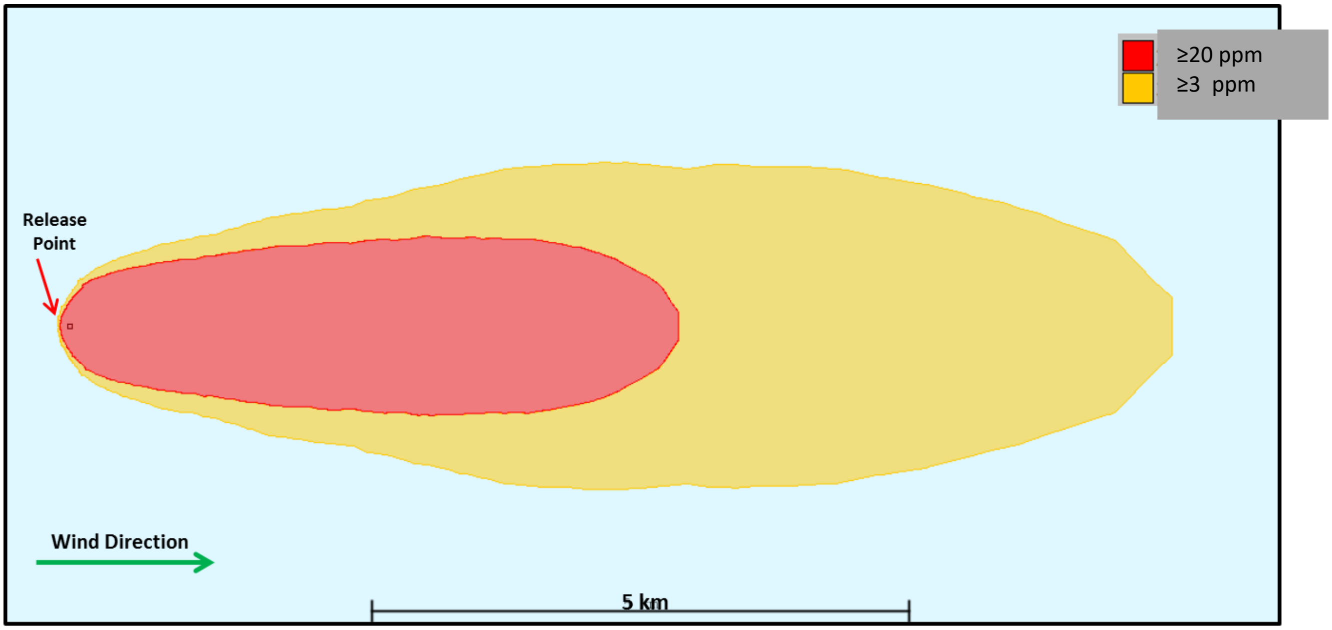
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

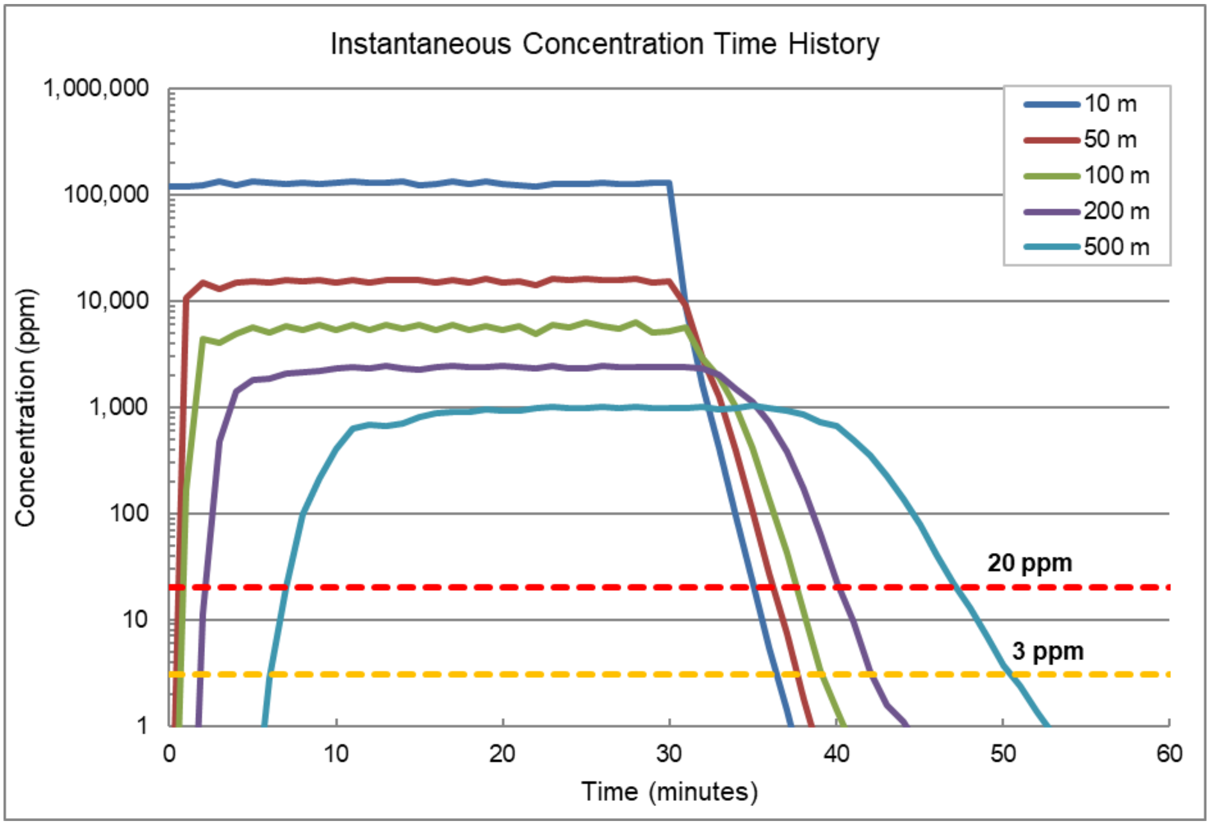
1-inch (2.54 cm) Pipe Failure (Liquid)

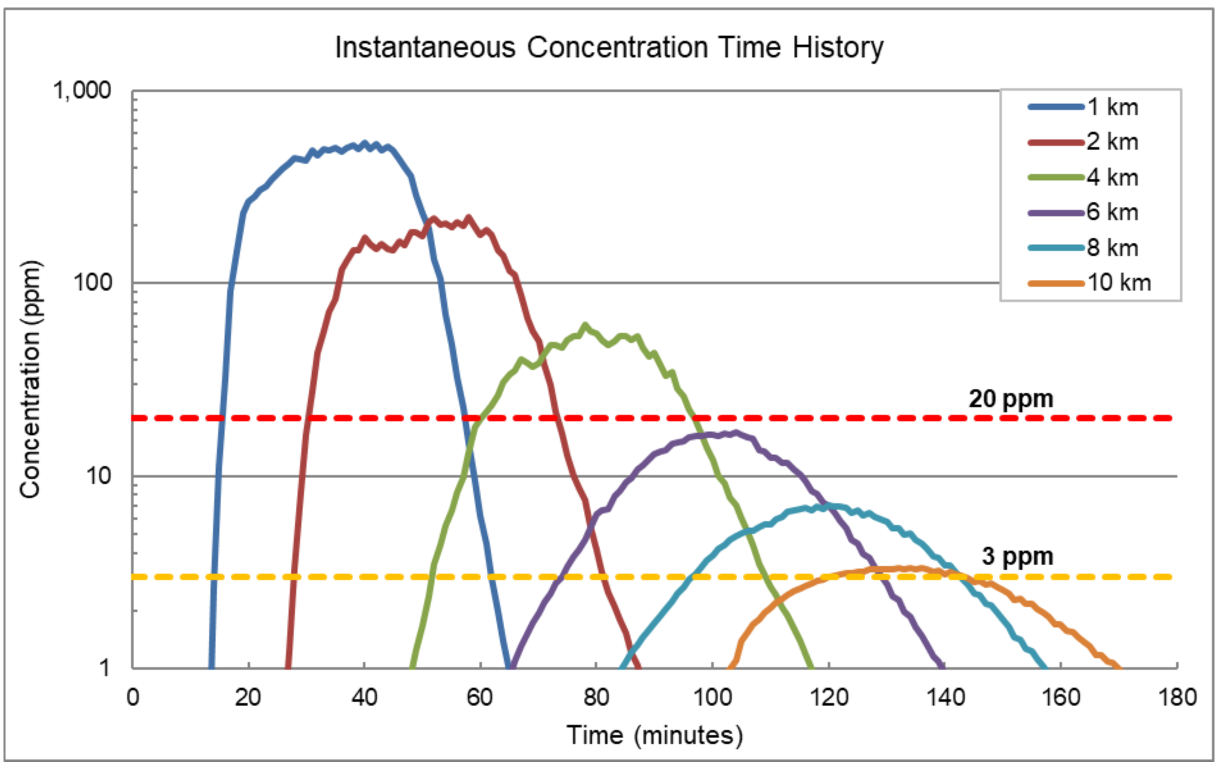


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	6.42	3.53
Kilometers	10.32	5.69
Maximum Crosswind Width		
Miles	1.75	0.96
Kilometers	2.81	1.55
Area Coverage		
Sq. Miles	8.58	2.75
Sq. Kilometers	22.22	7.13

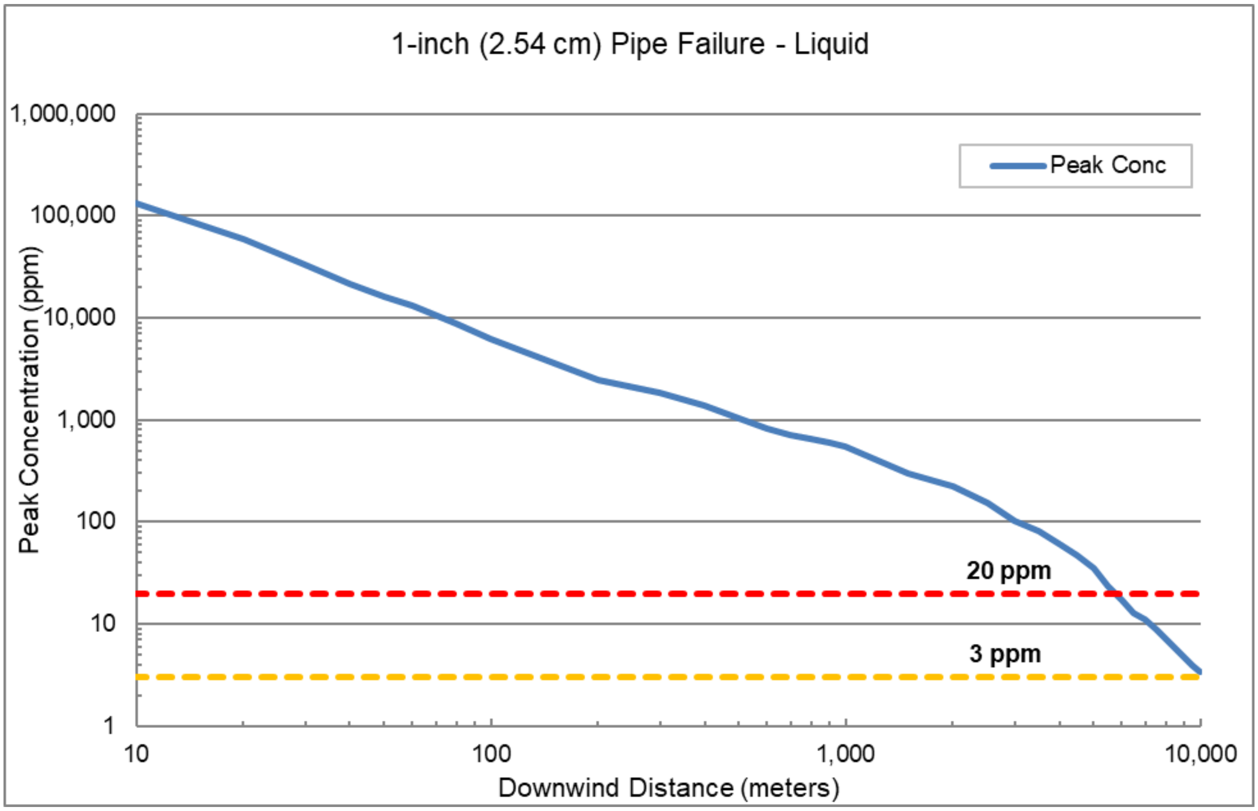
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.4 Alternative-Case 1-Inch (2.54 cm) Piping Failure (liquid) Scenario – D Stability

A 1-inch (2.54 cm) schedule 80 pipe is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	**U.S. Standard Units**	**Metric Units**
Container Type	Pipe	
Release Mechanism	Failure	
Hole Elevation	15.0 ft.	4.6 m
Opening Diameter	1.0 inch	2.54 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	733 lbs./min	332.5 kg/min
Release Duration	30 minutes	
Total Mass Released	21990 lbs.	9974.5 kg
Gaussian Spread[1]	1.67 inch	4.23 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	**U.S. Standard Units**	**Metric Units**
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

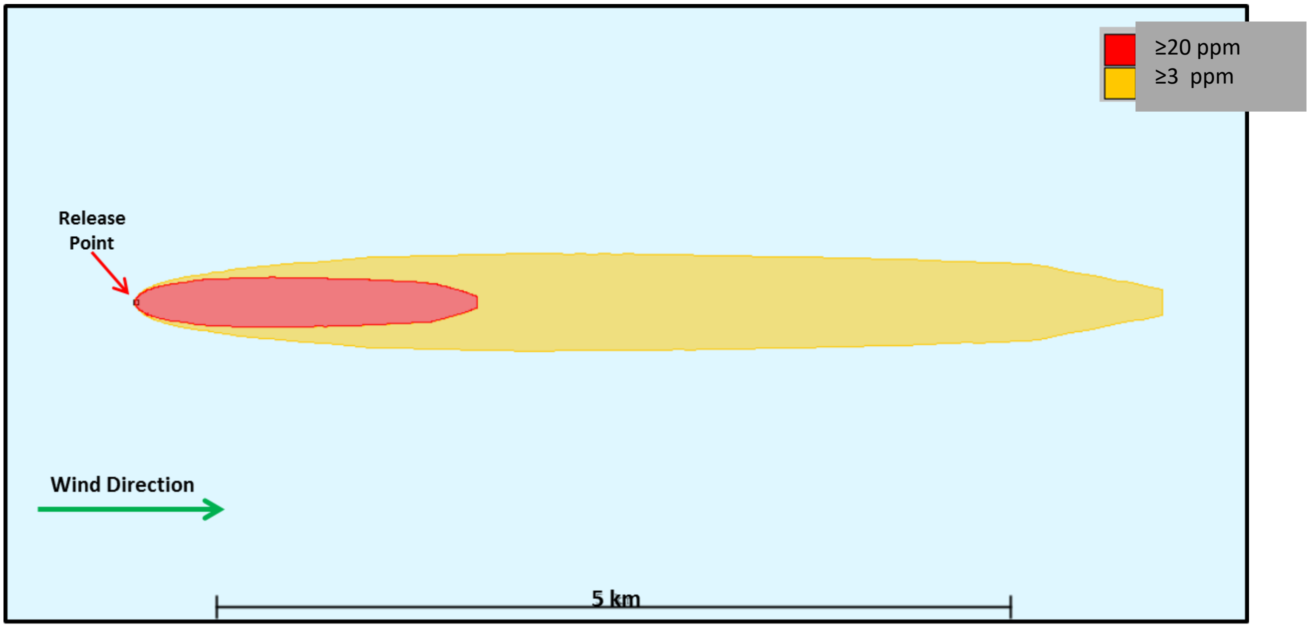
Receptor / Sampler	**U.S. Standard Units**	**Metric Units**
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

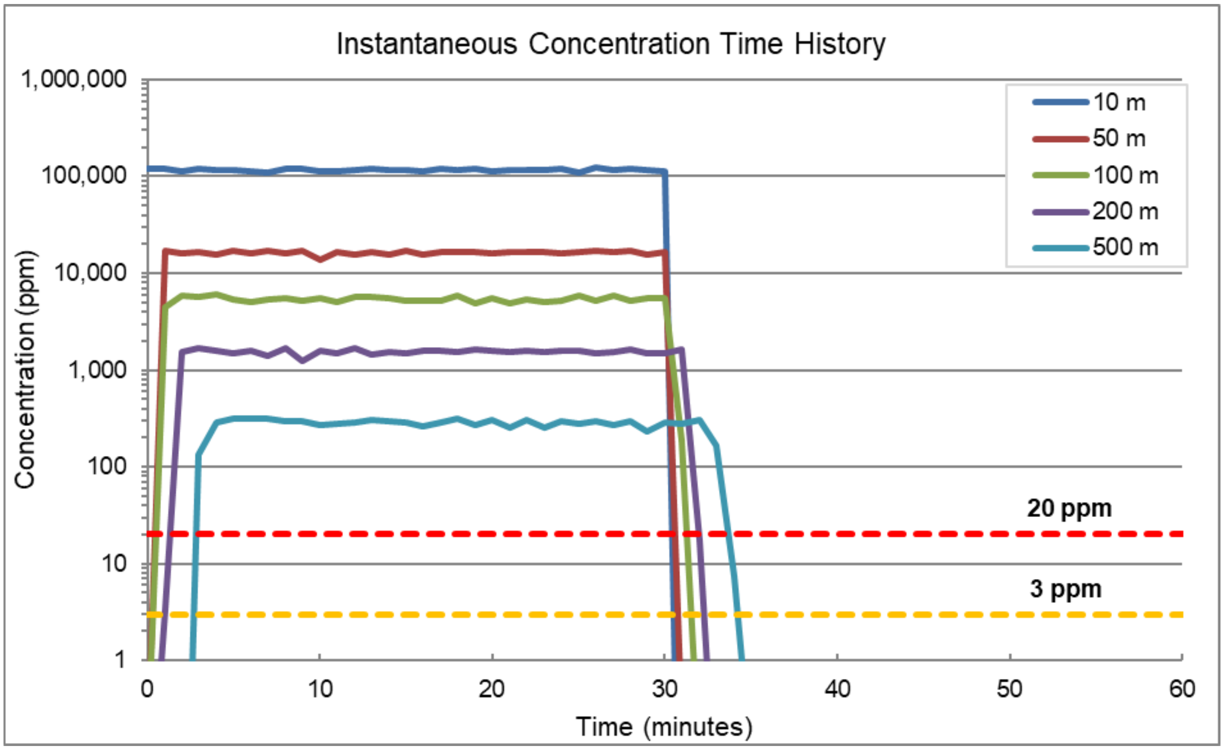
1-inch (2.54 cm) Pipe Failure (Liquid)

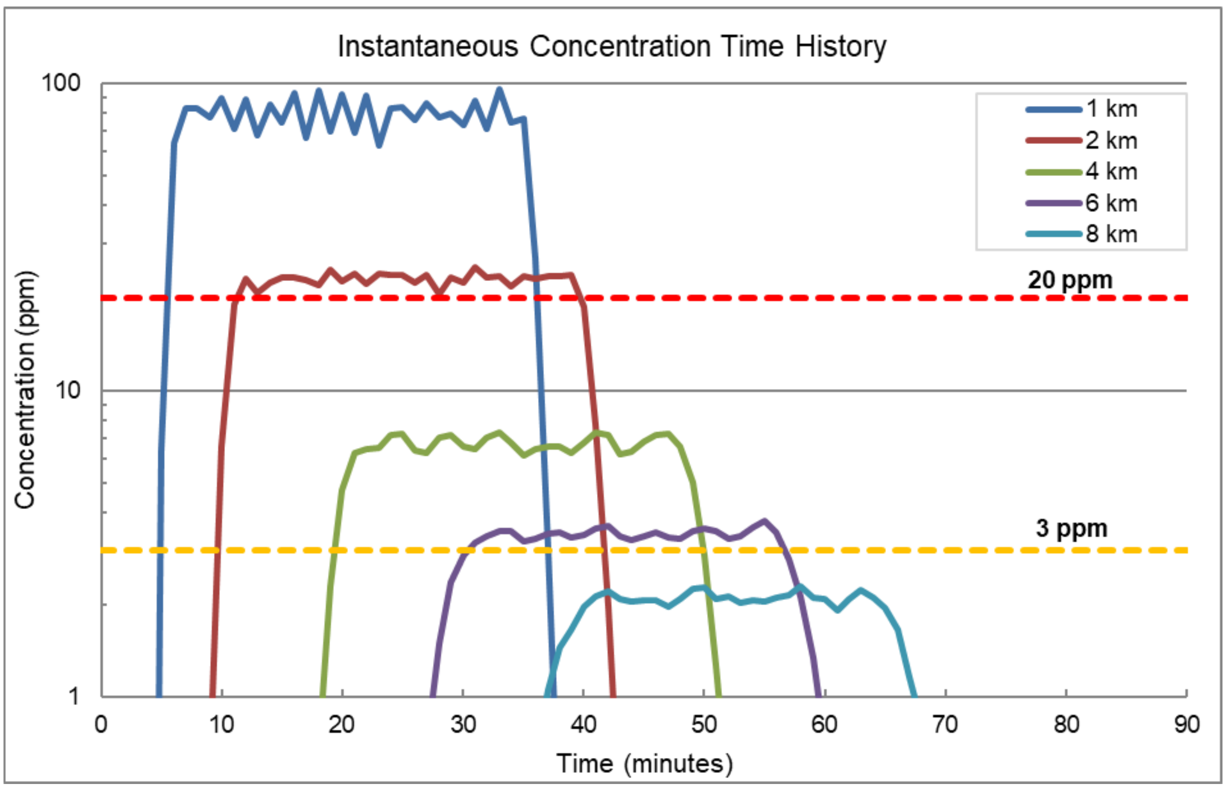


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	4.03	1.34
Kilometers	6.49	2.16
Maximum Crosswind Width		
Miles	0.36	0.19
Kilometers	0.58	0.30
Area Coverage		
Sq. Miles	1.16	0.20
Sq. Kilometers	3.01	0.51

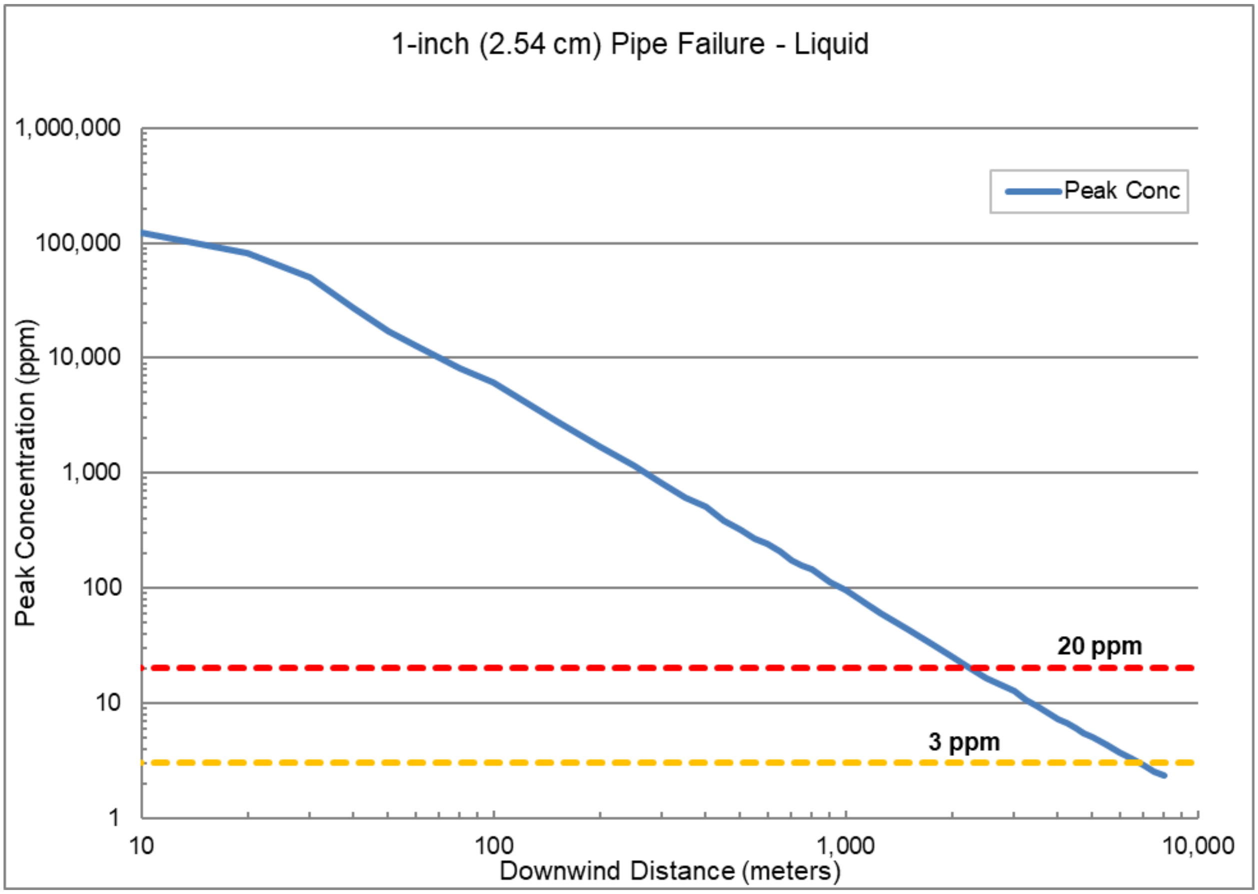
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.5 Alternative-Case ¼-Inch (0.635 cm) Tubing Failure (gas) Scenario – F Stability

A ¼ -inch (0.635 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	¼ inch	0.635 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	8.33 lbs./min	3.78 kg/min
Release Duration	30 minutes	
Total Mass Released	249.9 lbs.	113.4 kg
Gaussian Spread[1]	0.42 inch	1.06 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

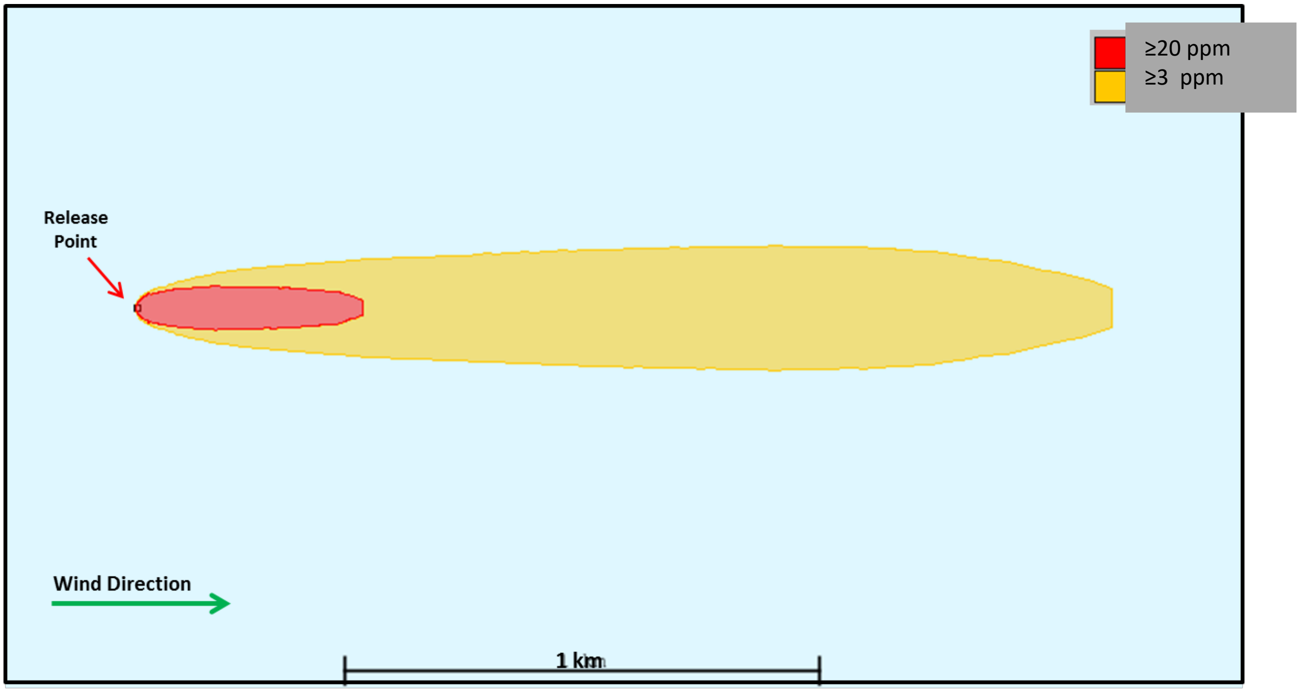
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

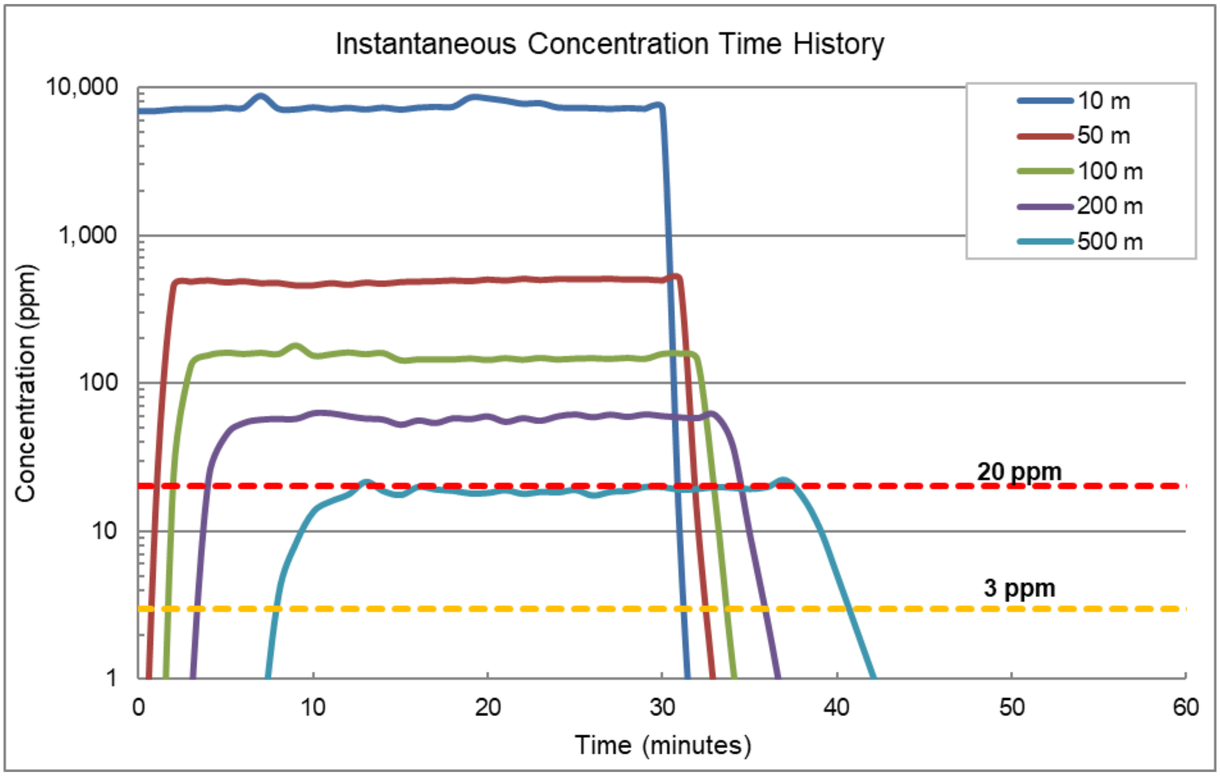
¼ -inch (0.635 cm) Tube Failure (Gas)

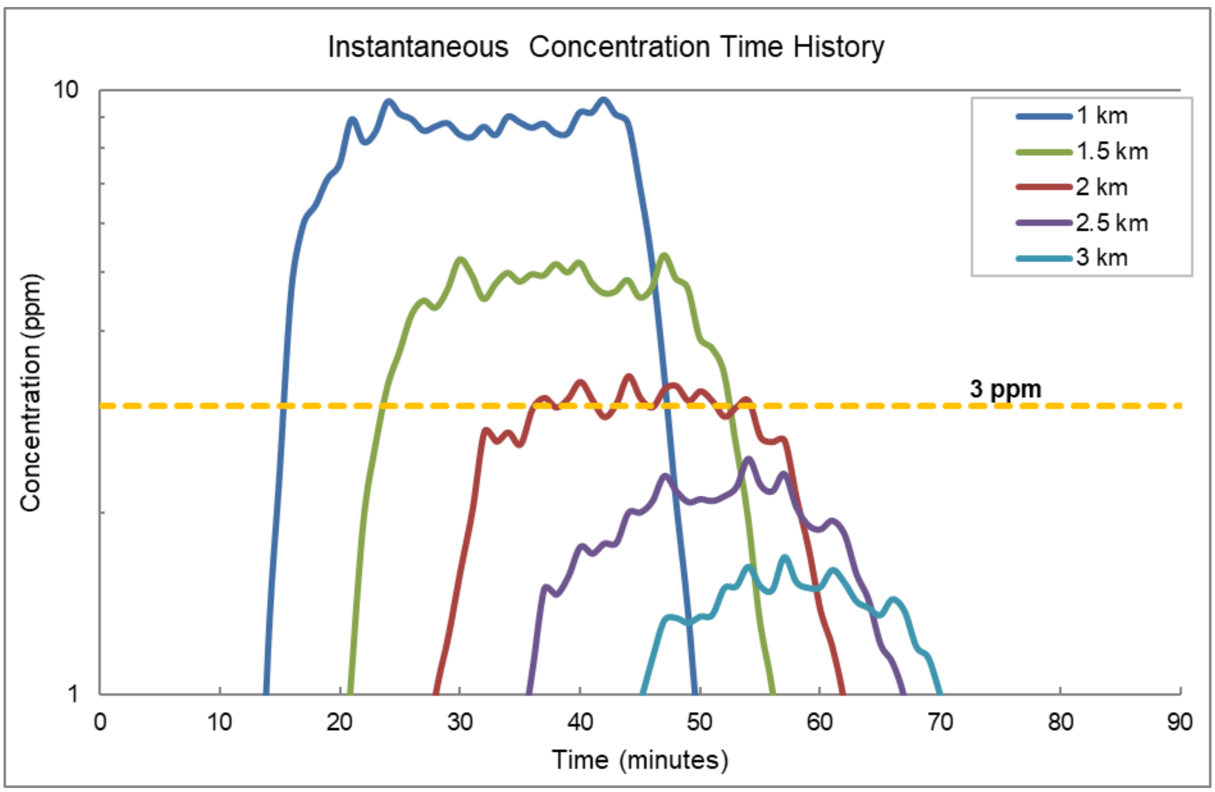


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.28	0.30
Kilometers	2.06	0.48
Maximum Crosswind Width		
Miles	0.15	0.053
Kilometers	0.24	0.085
Area Coverage		
Sq. Miles	0.15	0.013
Sq. Kilometers	0.40	0.033

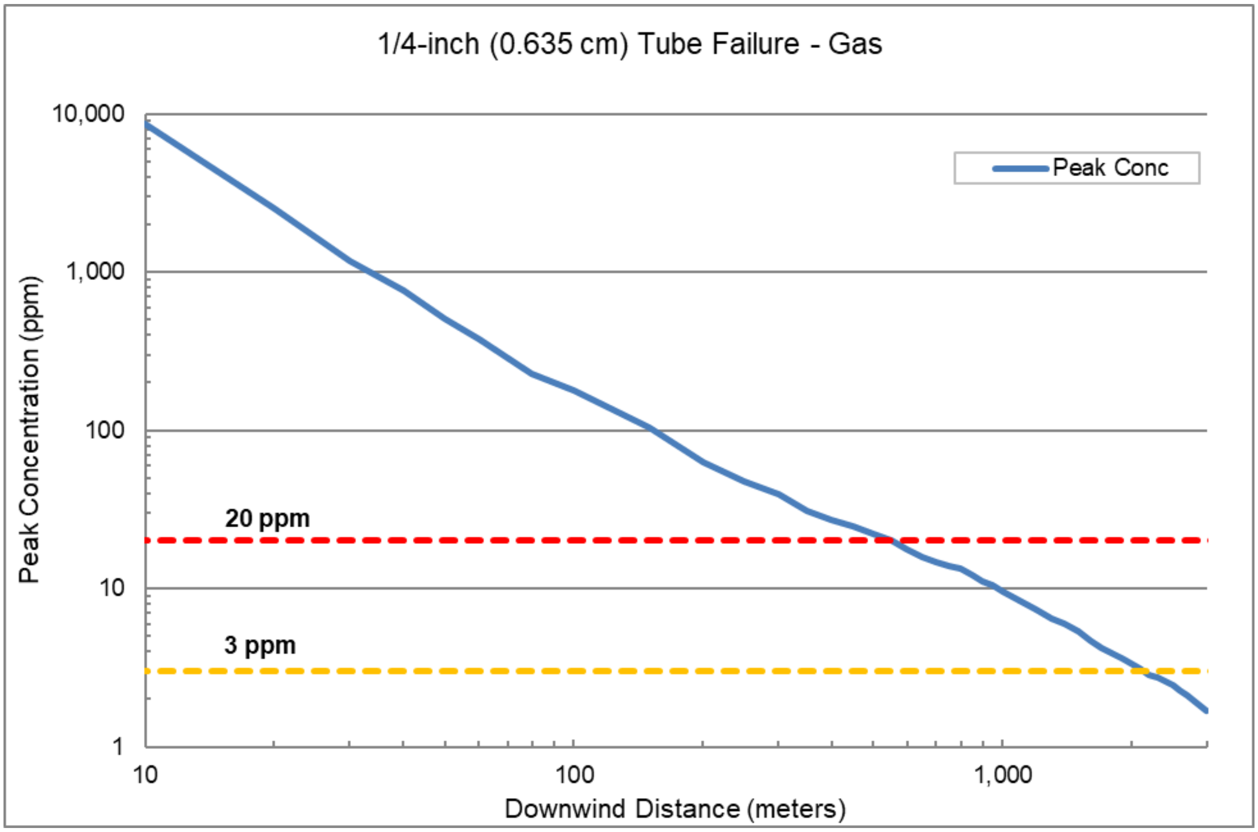
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.6 Alternative-Case ¼-Inch (0.635 cm) Tubing Failure (gas) Scenario – D Stability

A ¼ -inch (0.635 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	¼ inch	0.635 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	8.33 lbs./min	3.78 kg/min
Release Duration	30 minutes	
Total Mass Released	249.9 lbs.	113.4 kg
Gaussian Spread[1]	0.42 inch	1.06 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

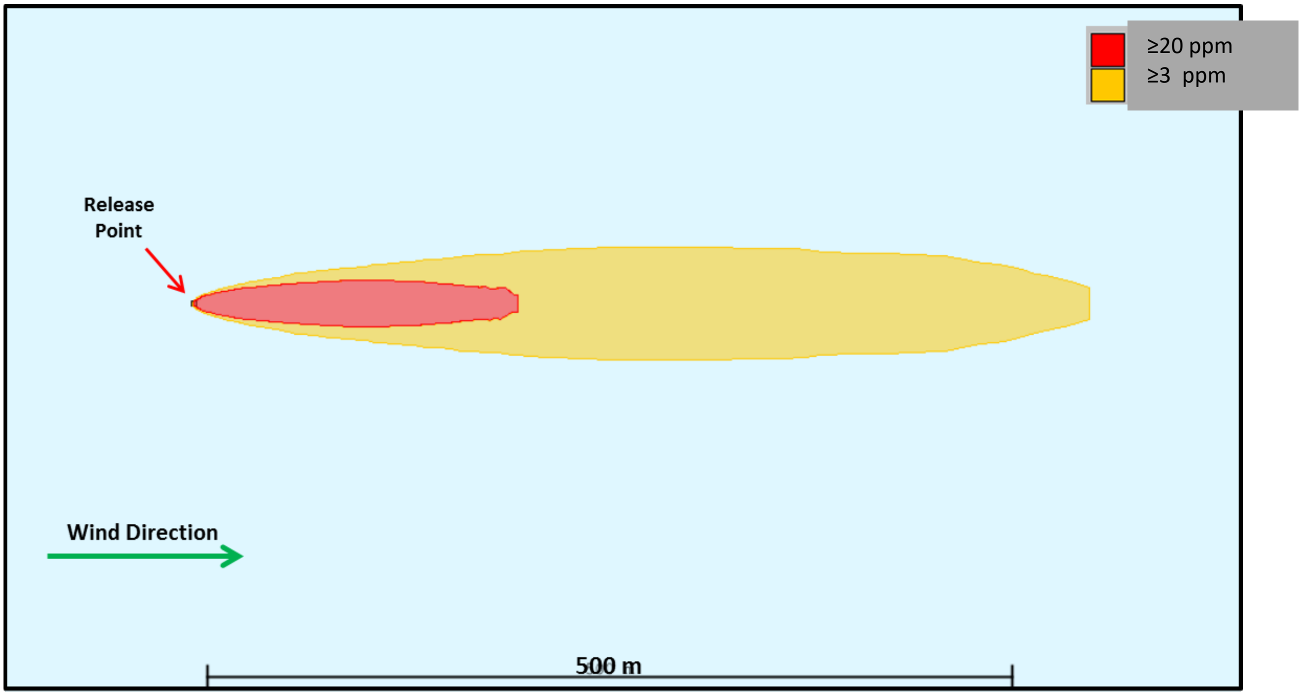
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

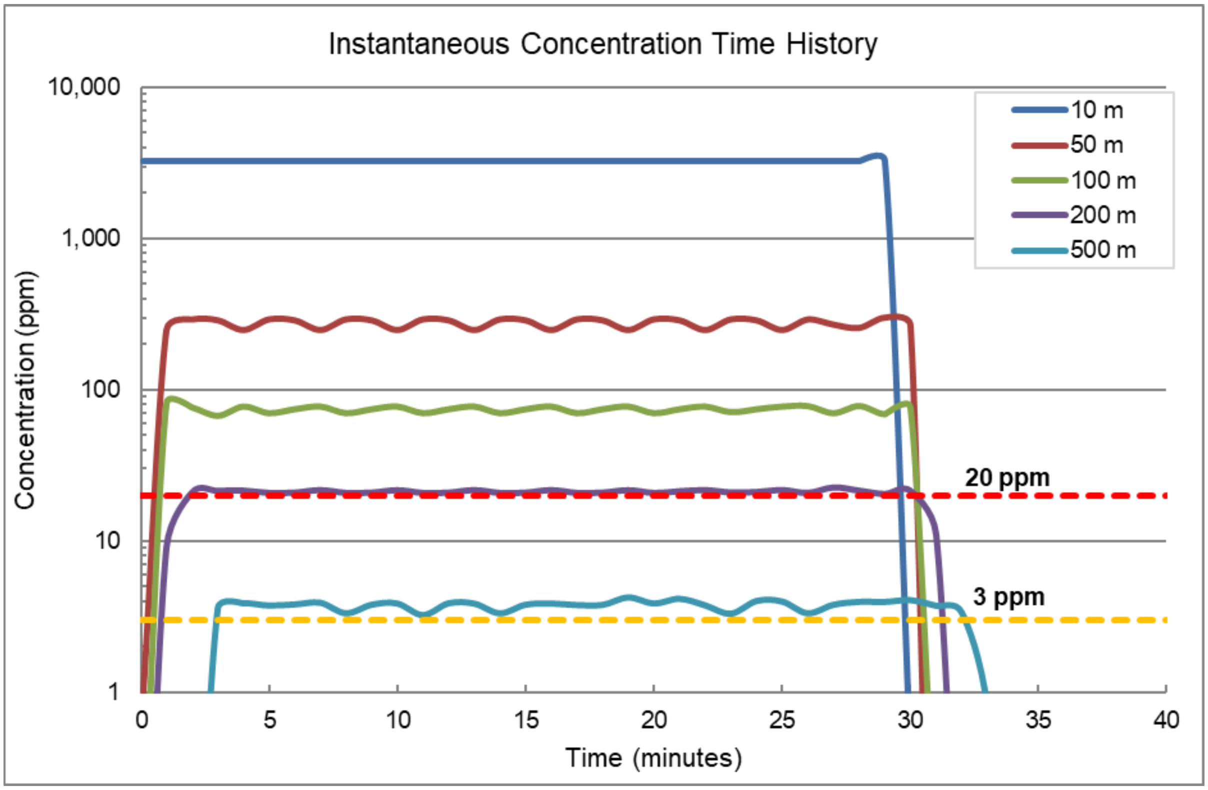
¼ -inch (0.635 cm) Tube Failure (Gas)

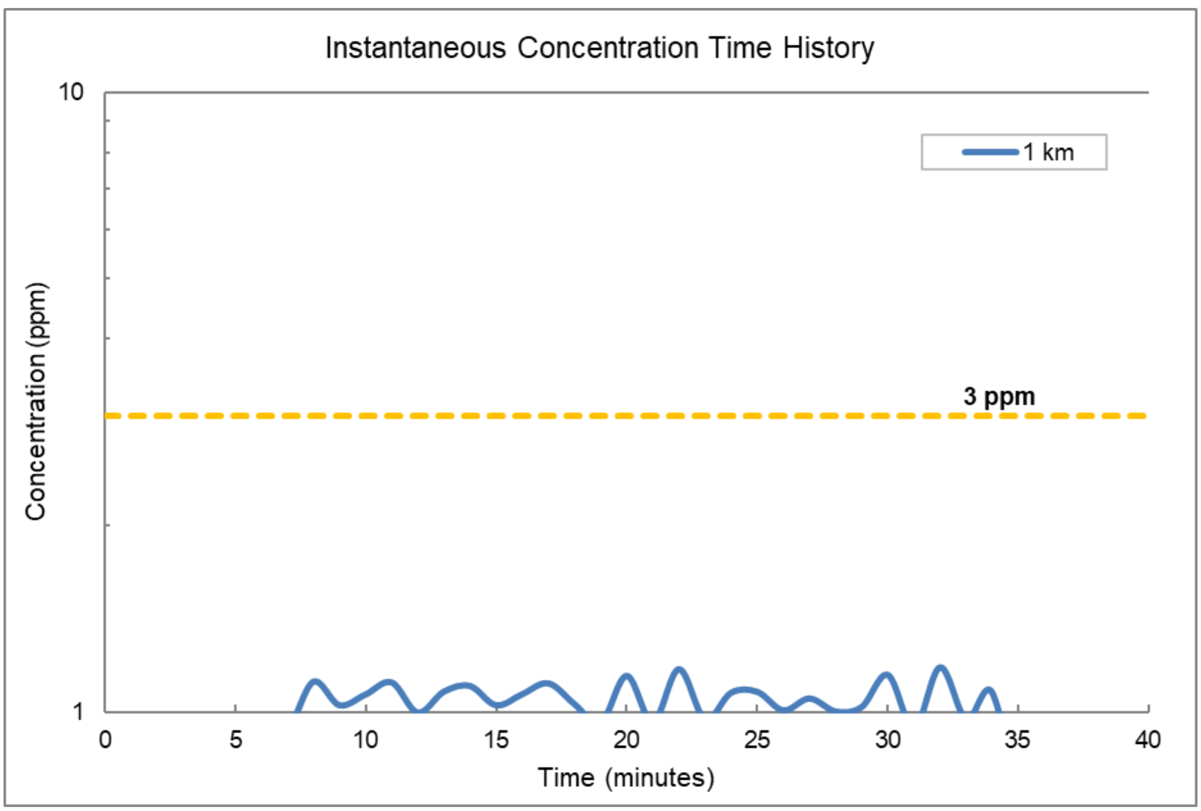


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.37	0.13
Kilometers	0.59	0.21
Maximum Crosswind Width		
Miles	0.039	0.016
Kilometers	0.063	0.026
Area Coverage		
Sq. Miles	0.0119	0.0018
Sq. Kilometers	0.0308	0.0045

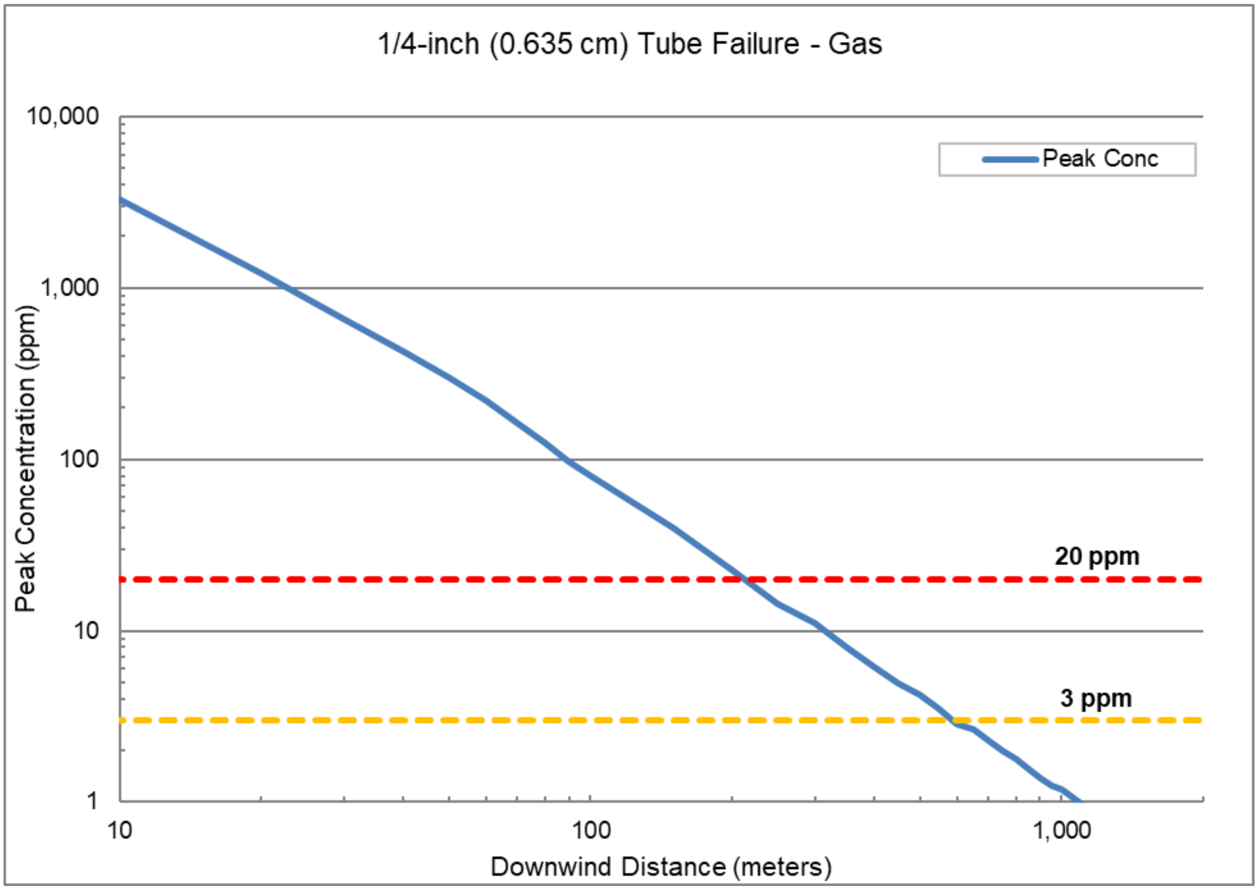
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.7 Alternative-Case ¼-Inch (0.635 cm) Tubing Failure (liquid) Scenario – F Stability

A ¼ -inch (0.635 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	**U.S. Standard Units**	**Metric Units**
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	¼ inch	0.635 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	36.6 lbs./min	16.6 kg/min
Release Duration	30 minutes	
Total Mass Released	1098 lbs.	498 kg
Gaussian Spread[1]	0.42 inch	1.06 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	**U.S. Standard Units**	**Metric Units**
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

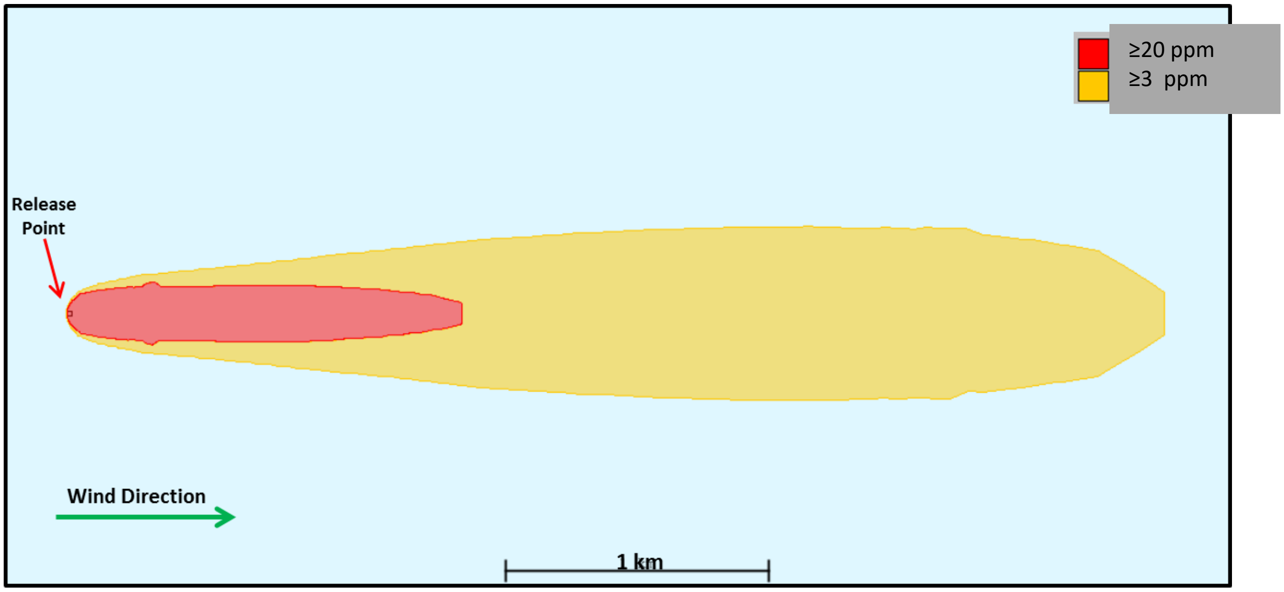
Receptor / Sampler	**U.S. Standard Units**	**Metric Units**
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

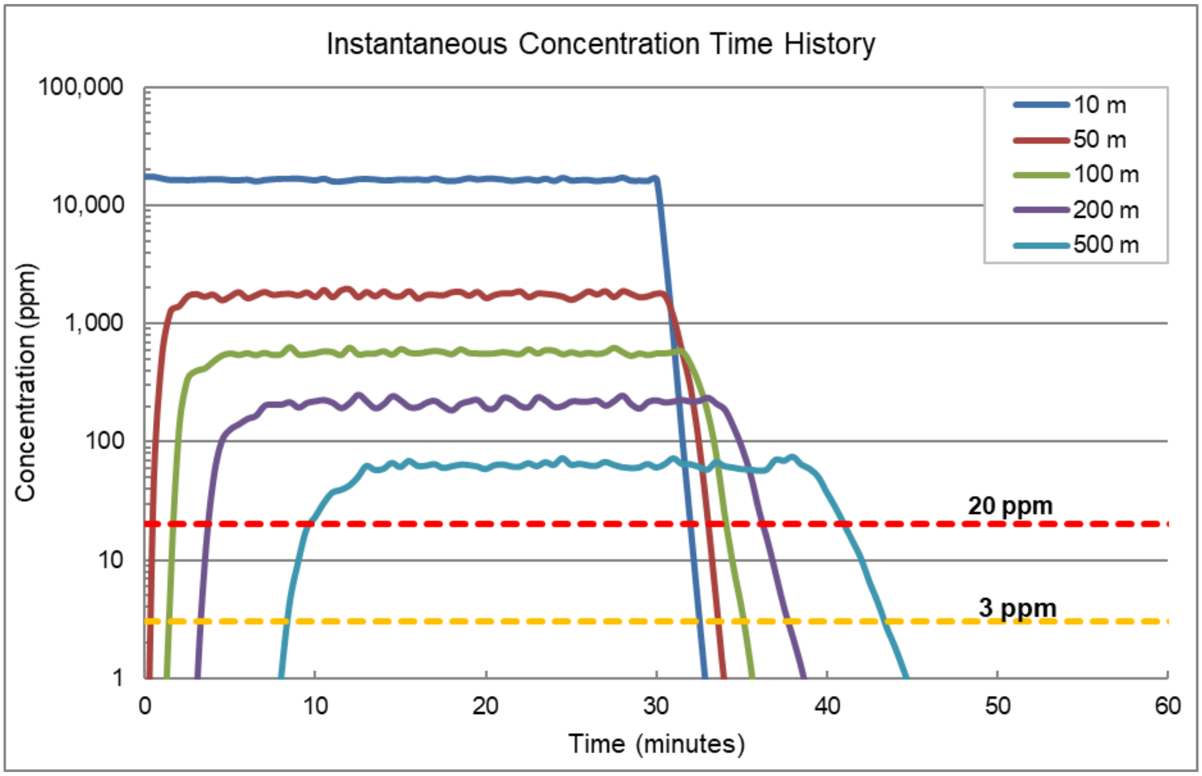
¼ -inch (0.635 cm) Tube Failure (Liquid)

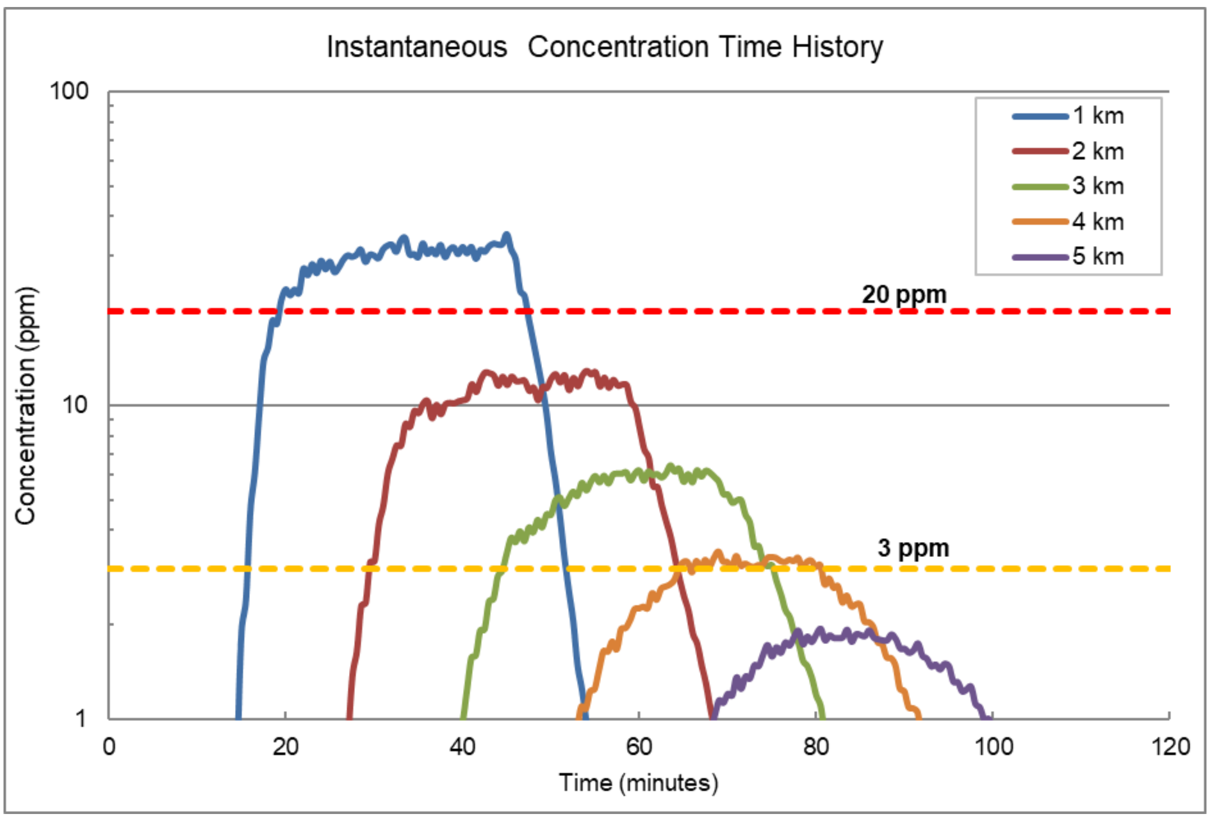


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	2.59	0.93
Kilometers	4.18	1.50
Maximum Crosswind Width		
Miles	0.41	0.19
Kilometers	0.66	0.31
Area Coverage		
Sq. Miles	0.77	0.10
Sq. Kilometers	1.98	0.26

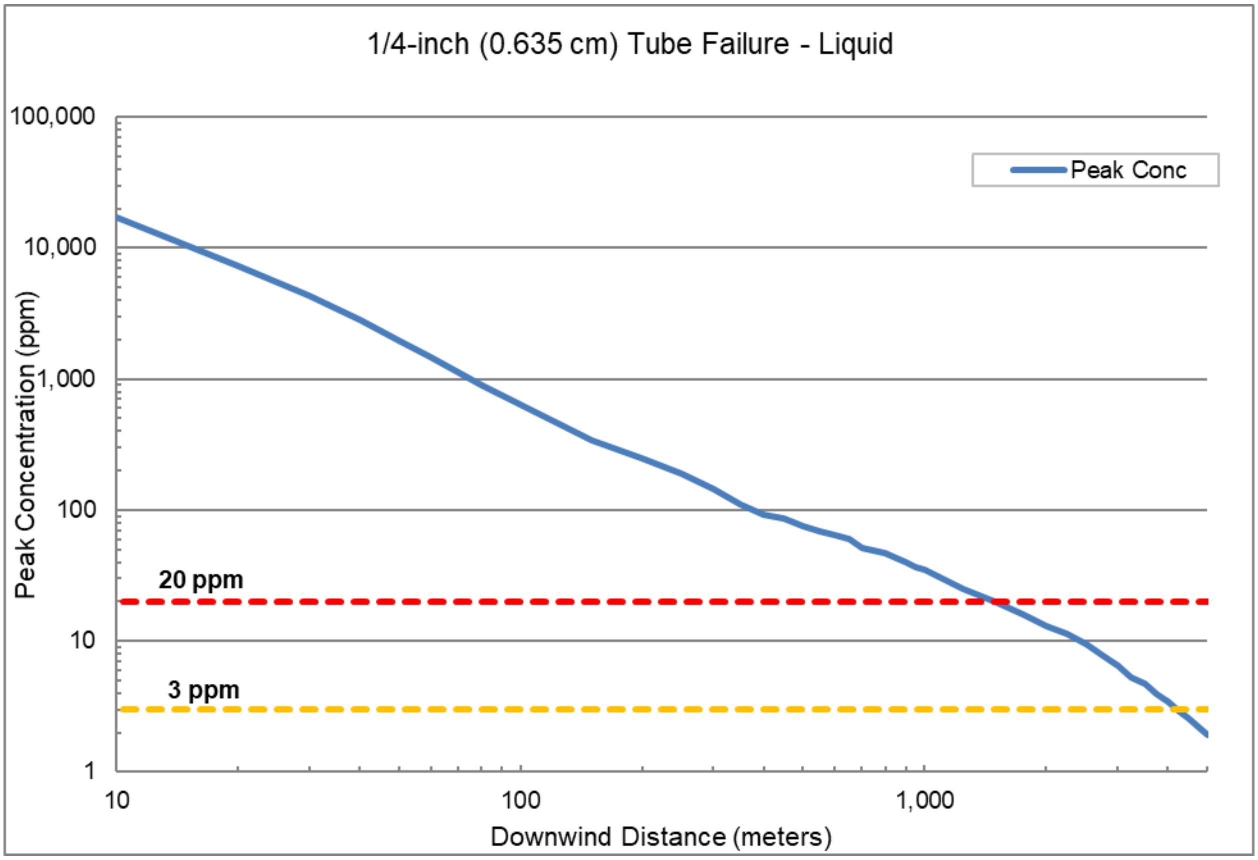
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.8 Alternative-Case ¼-Inch (0.635 cm) Tubing Failure (liquid) Scenario – D Stability

A ¼ -inch (0.635 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	**U.S. Standard Units**	**Metric Units**
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	¼ inch	0.635 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	36.6 lbs./min	16.6 kg/min
Release Duration	30 minutes	
Total Mass Released	1098 lbs.	498 kg
Gaussian Spread[1]	0.42 inch	1.06 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	**U.S. Standard Units**	**Metric Units**
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

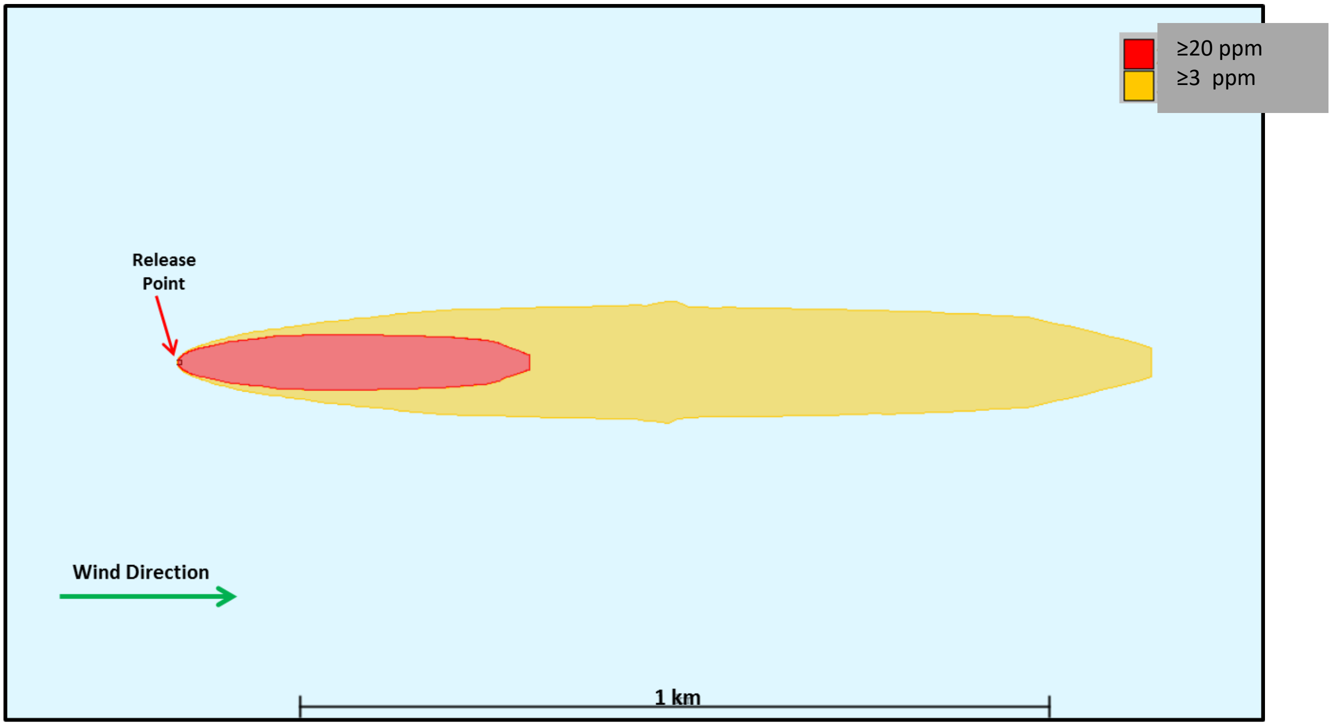
Receptor / Sampler	**U.S. Standard Units**	**Metric Units**
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

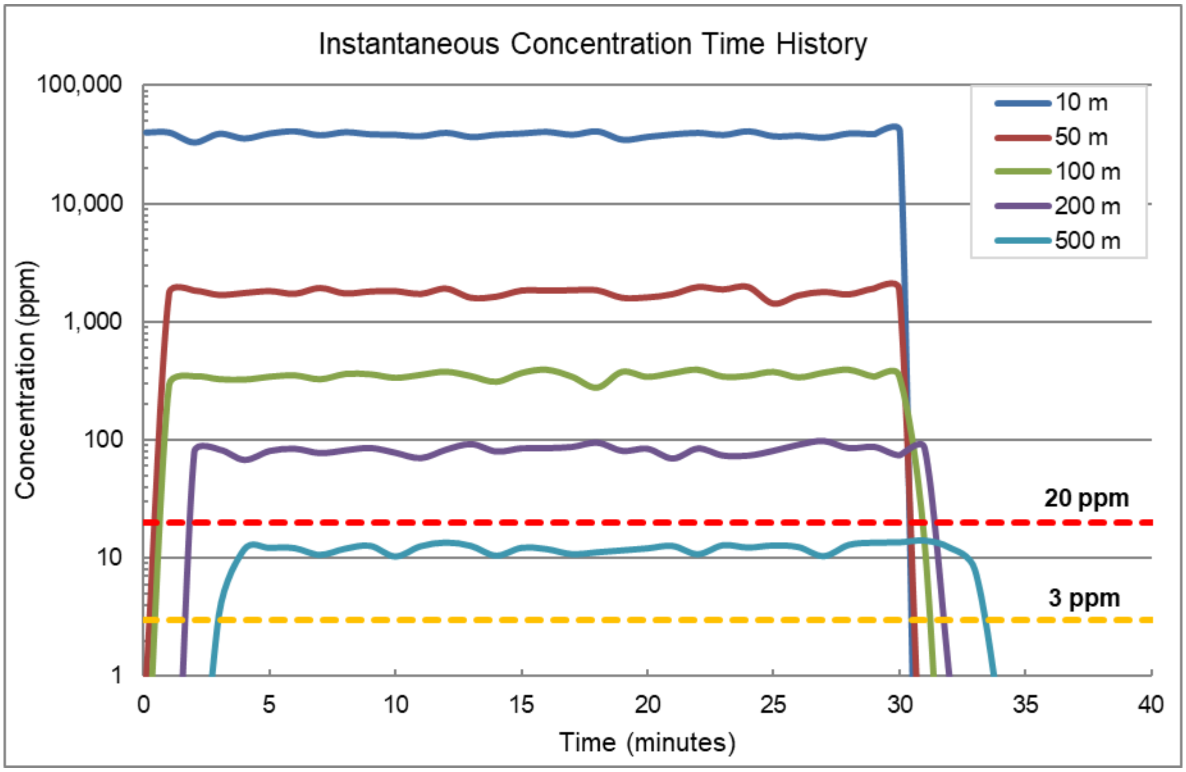
¼ -inch (0.635 cm) Tube Failure (Liquid)

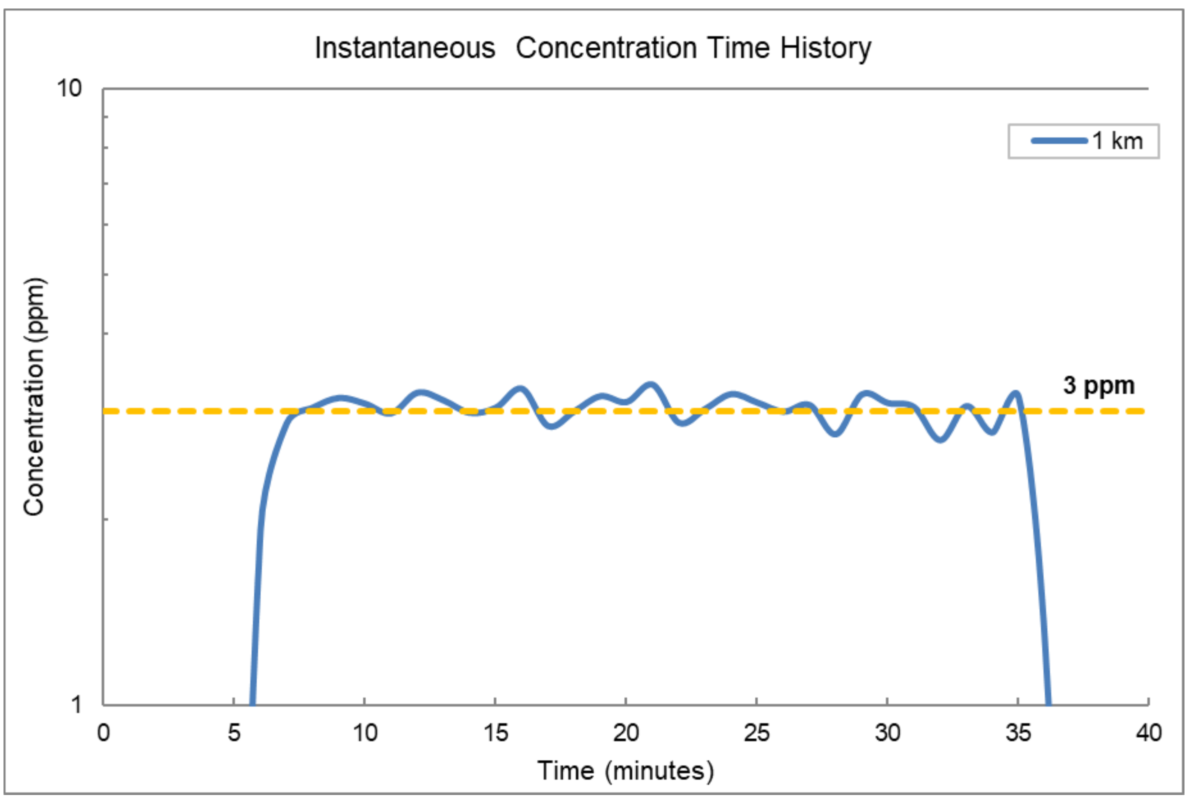


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.81	0.29
Kilometers	1.30	0.47
Maximum Crosswind Width		
Miles	0.091	0.043
Kilometers	0.147	0.069
Area Coverage		
Sq. Miles	0.057	0.0106
Sq. Kilometers	0.147	0.0263

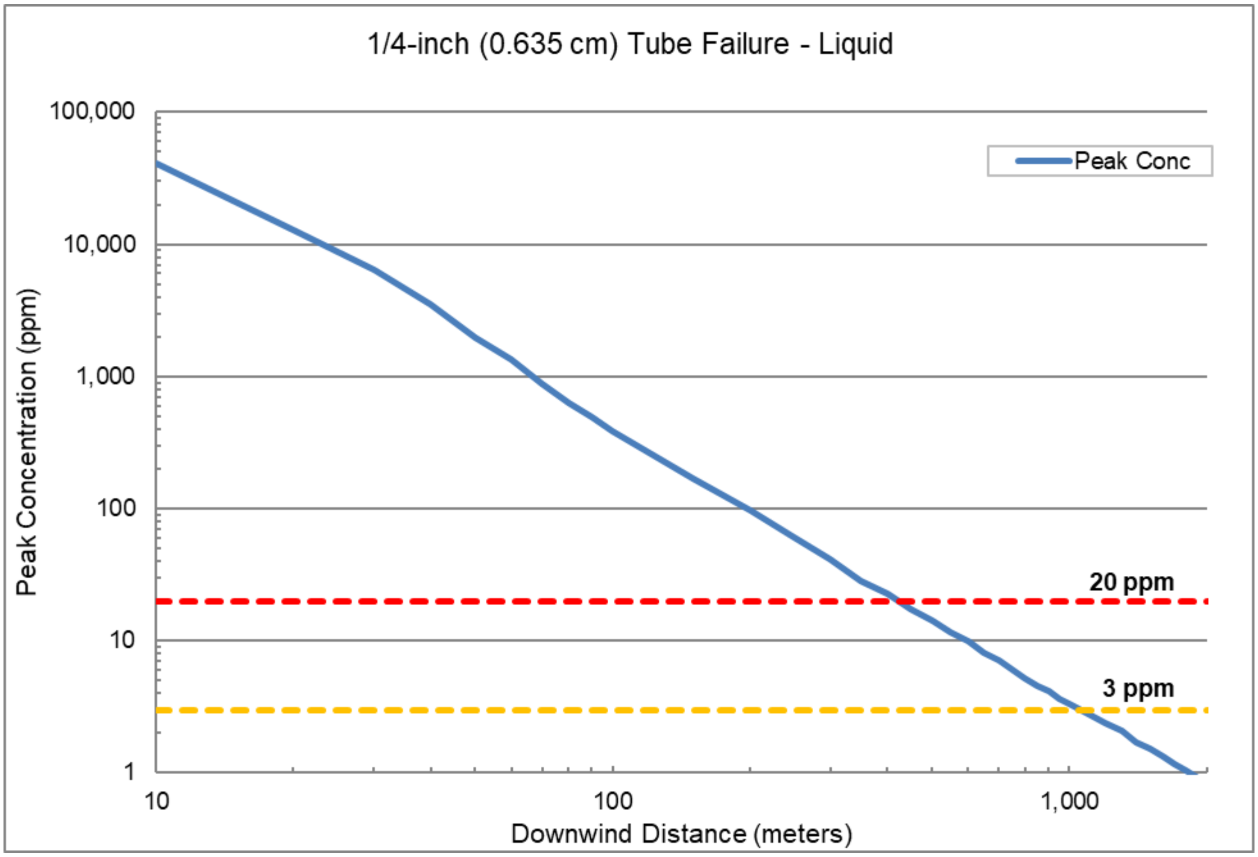
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.9 Alternative-Case ½-Inch (1.27 cm) Tubing Failure (gas) Scenario – F Stability

A ½ -inch (1.27 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	½ inch	1.27 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	36 lbs./min	16.33 kg/min
Release Duration	30 minutes	
Total Mass Released	1080 lbs.	489.9 kg
Gaussian Spread[1]	0.83 inch	2.12 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

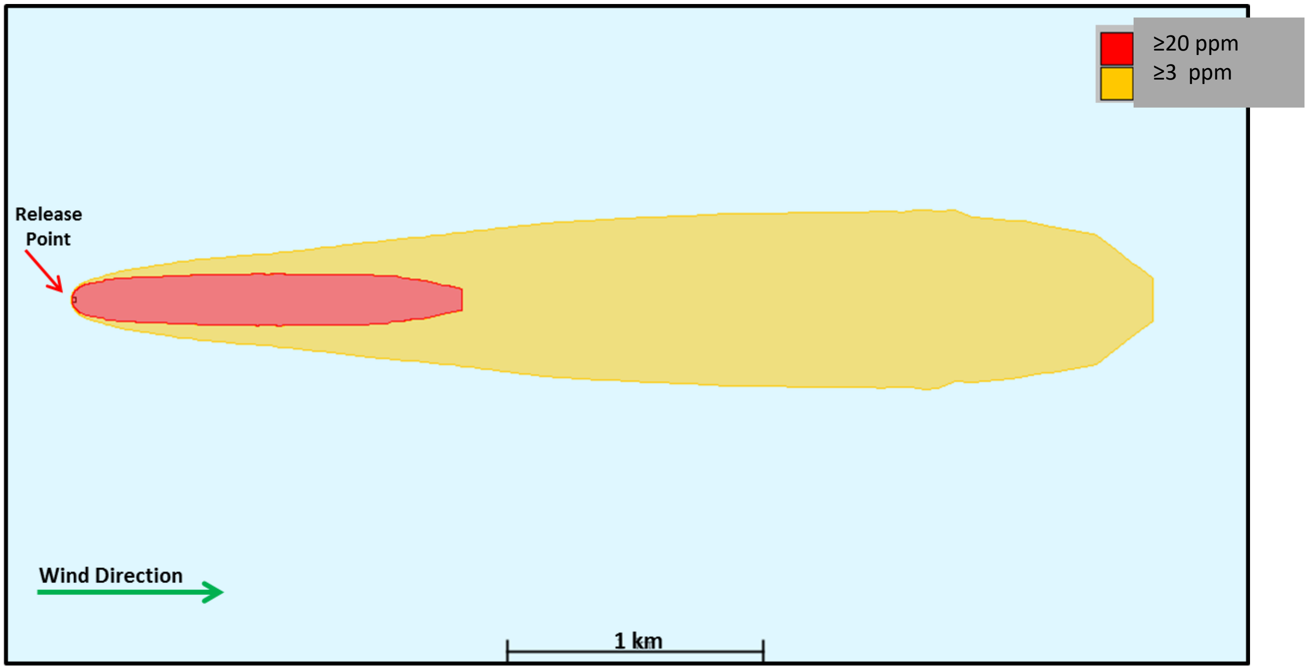
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

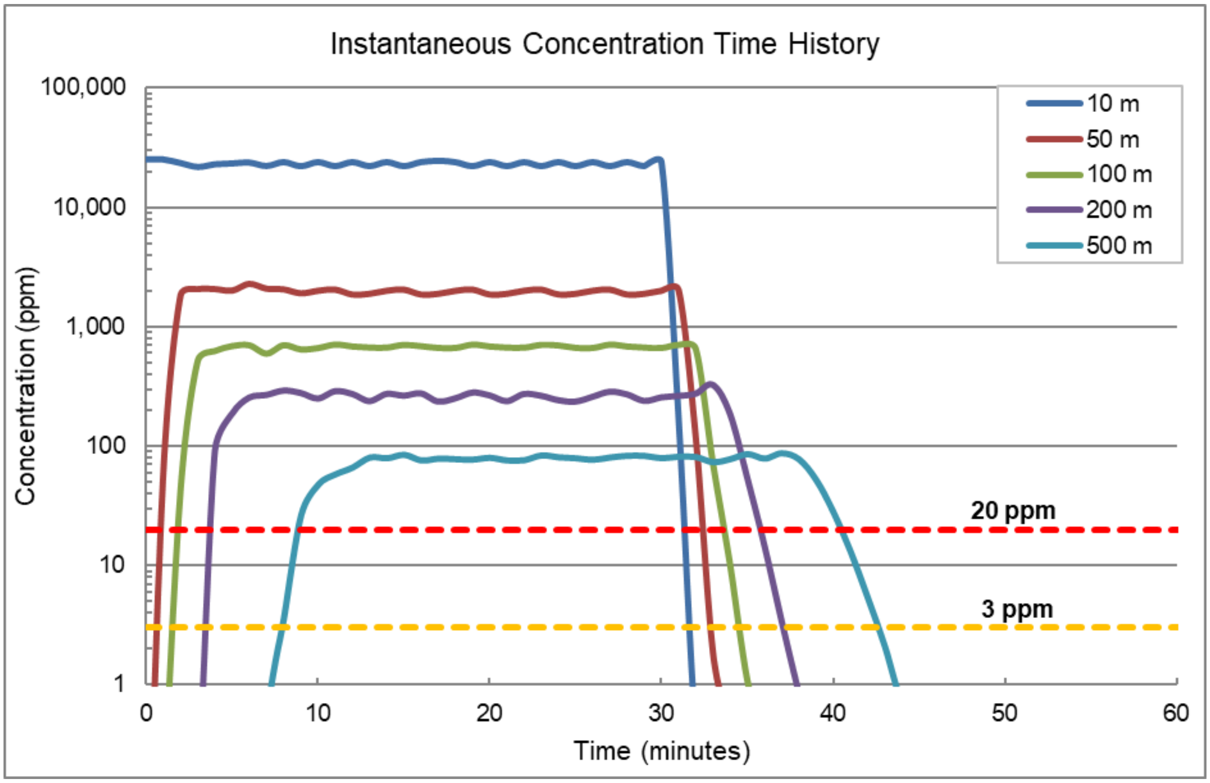
½ -inch (1.27 cm) Tube Failure (Gas)

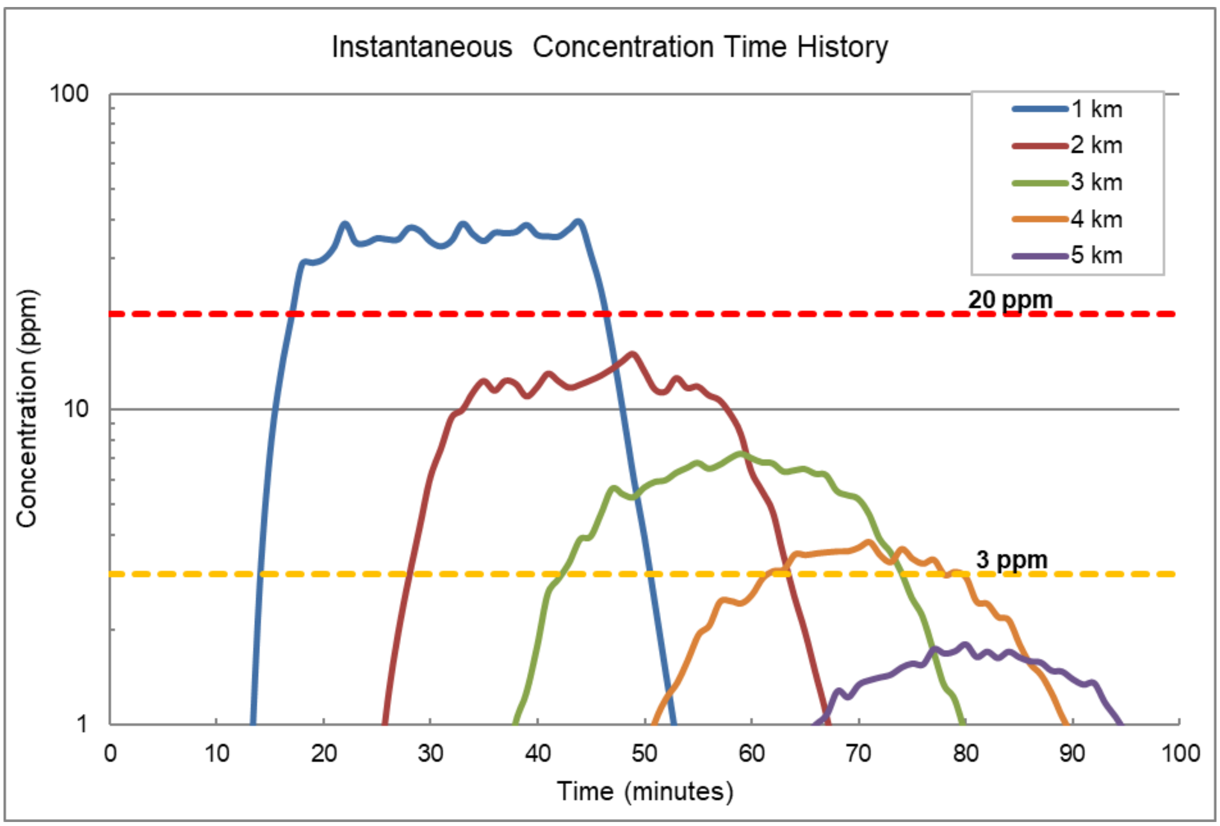


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	2.63	0.94
Kilometers	4.24	1.52
Maximum Crosswind Width		
Miles	0.39	0.11
Kilometers	0.635	0.18
Area Coverage		
Sq. Miles	0.78	0.09
Sq. Kilometers	2.03	0.25

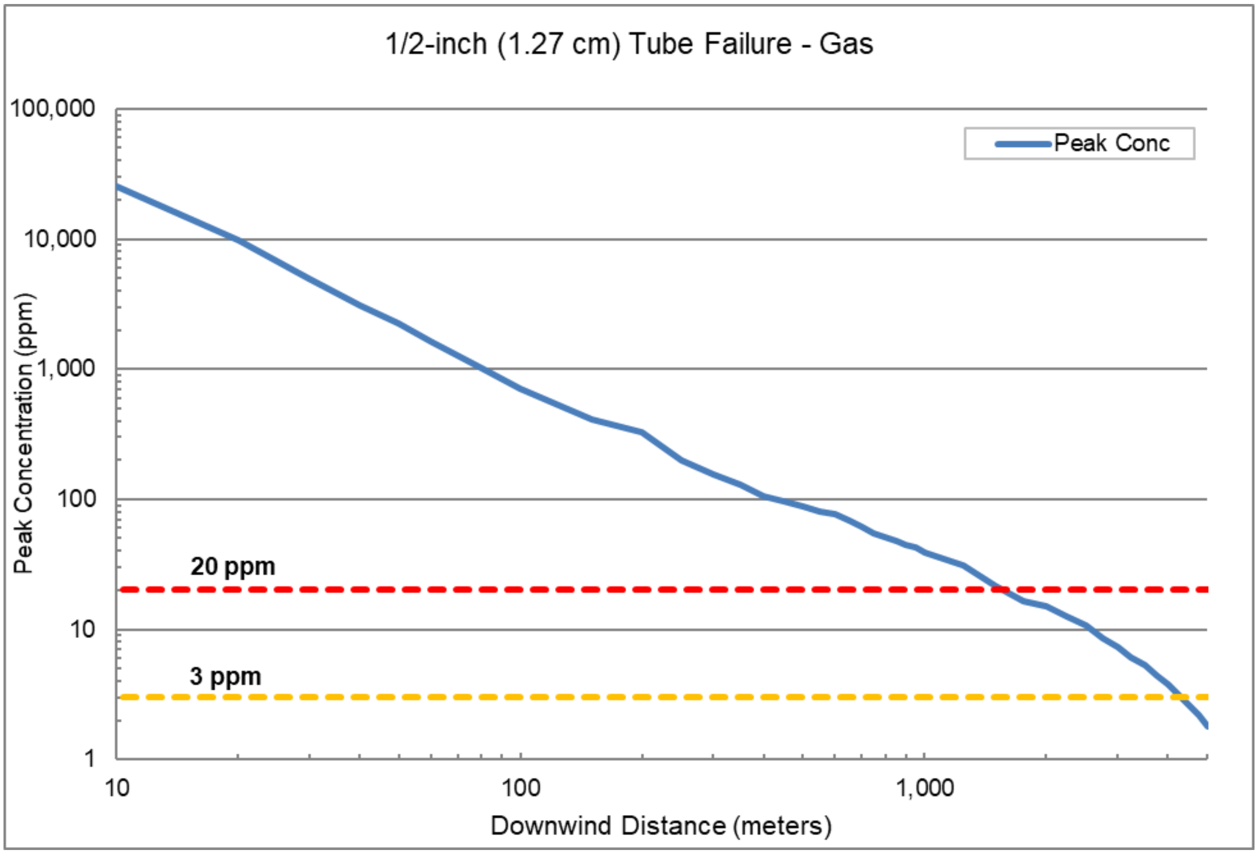
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.10 Alternative-Case ½-Inch (1.27 cm) Tubing Failure (gas) Scenario – D Stability

A ½ -inch (1.27 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	**U.S. Standard Units**	**Metric Units**
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	½ inch	1.27 cm
Release State	Gas	
Contents Mass	Infinite	
Release Rate	36 lbs./min	16.33 kg/min
Release Duration	30 minutes	
Total Mass Released	1080 lbs.	489.9 kg
Gaussian Spread[1]	0.83 inch	2.12 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ºF	-34.04 ºC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	**U.S. Standard Units**	**Metric Units**
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

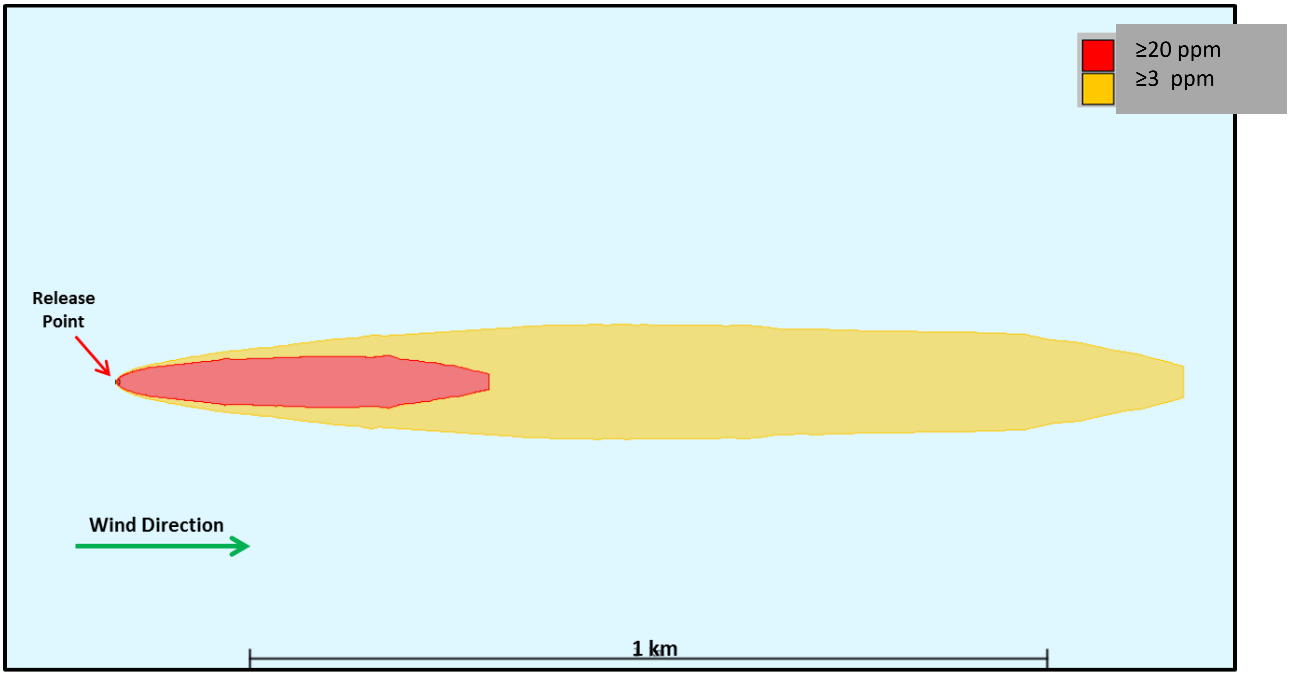
Receptor / Sampler	**U.S. Standard Units**	**Metric Units**
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

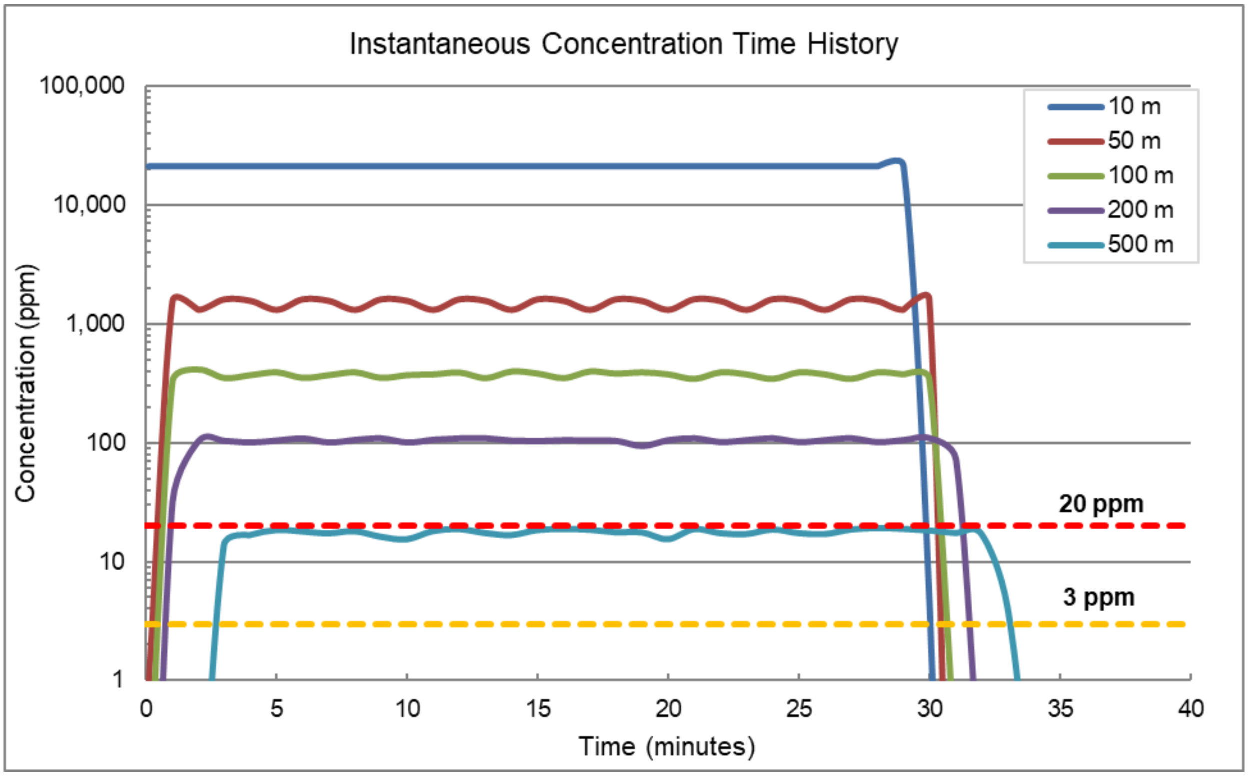
½ -inch (1.27 cm) Tube Failure (Gas)

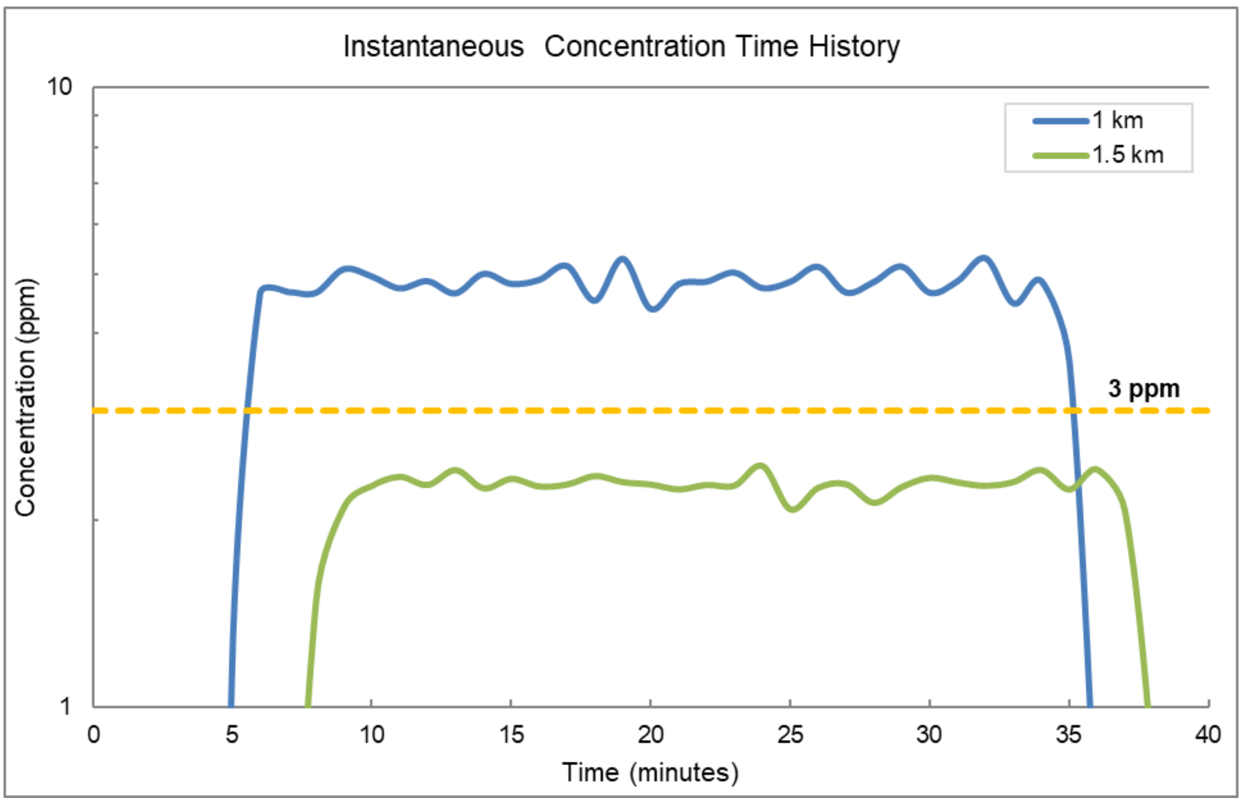


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.83	0.29
Kilometers	1.33	0.46
Maximum Crosswind Width		
Miles	0.093	0.035
Kilometers	0.150	0.056
Area Coverage		
Sq. Miles	0.054	0.008
Sq. Kilometers	0.141	0.021

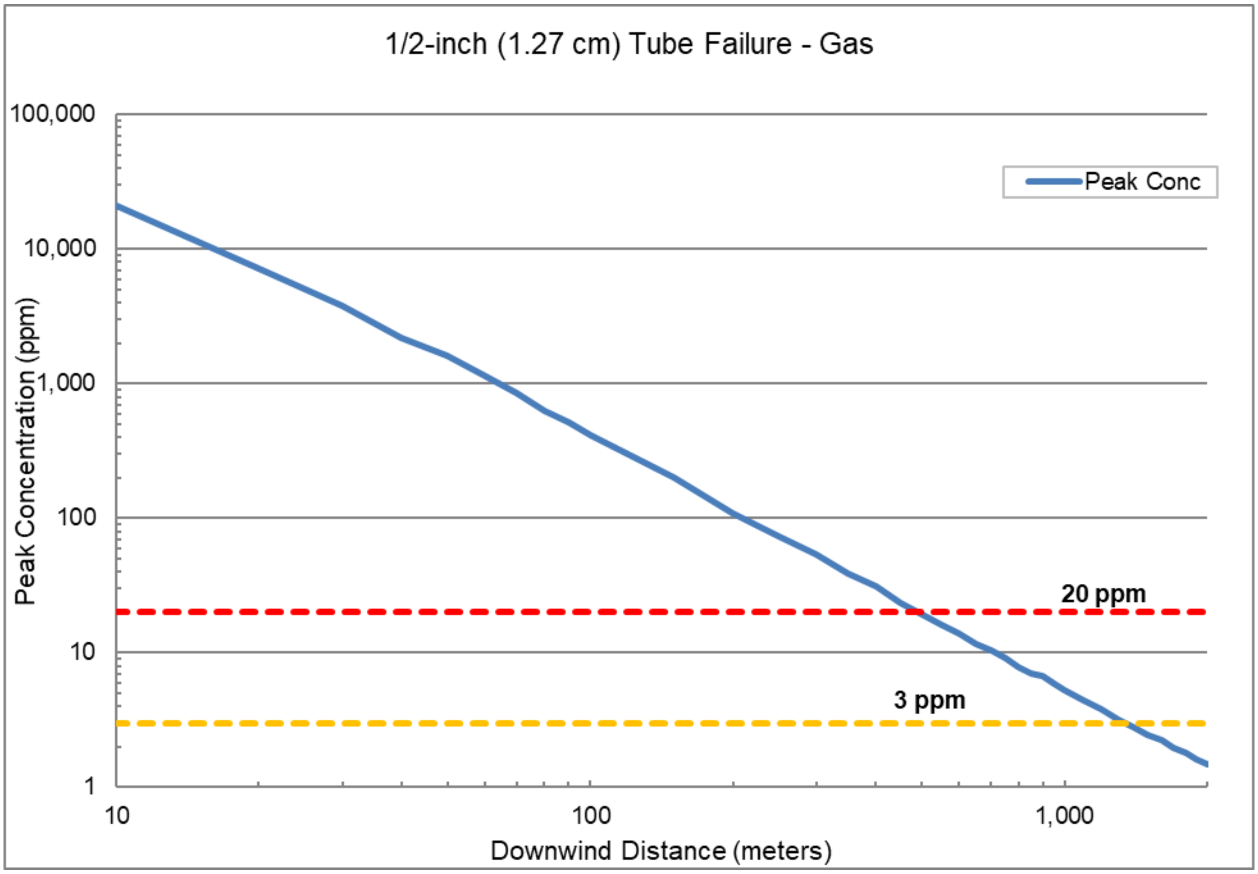
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.11 Alternative-Case ½-Inch (1.27 cm) Tubing Failure (liquid) Scenario – F Stability

A ½ -inch (1.27 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	½ inch	1.27 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	158 lbs./min	71.7 kg/min
Release Duration	30 minutes	
Total Mass Released	4740 lbs.	2150 kg
Gaussian Spread[1]	0.83 inch	2.12 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^oF	-34.04 ^oC
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

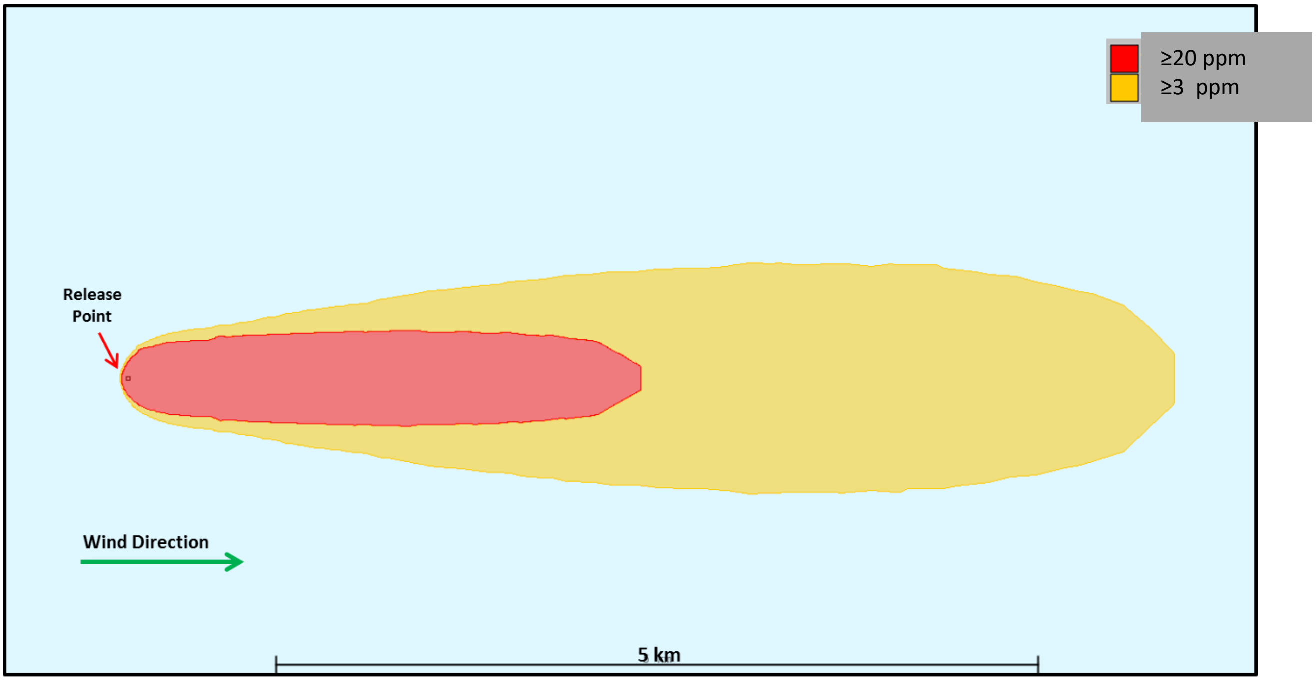
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

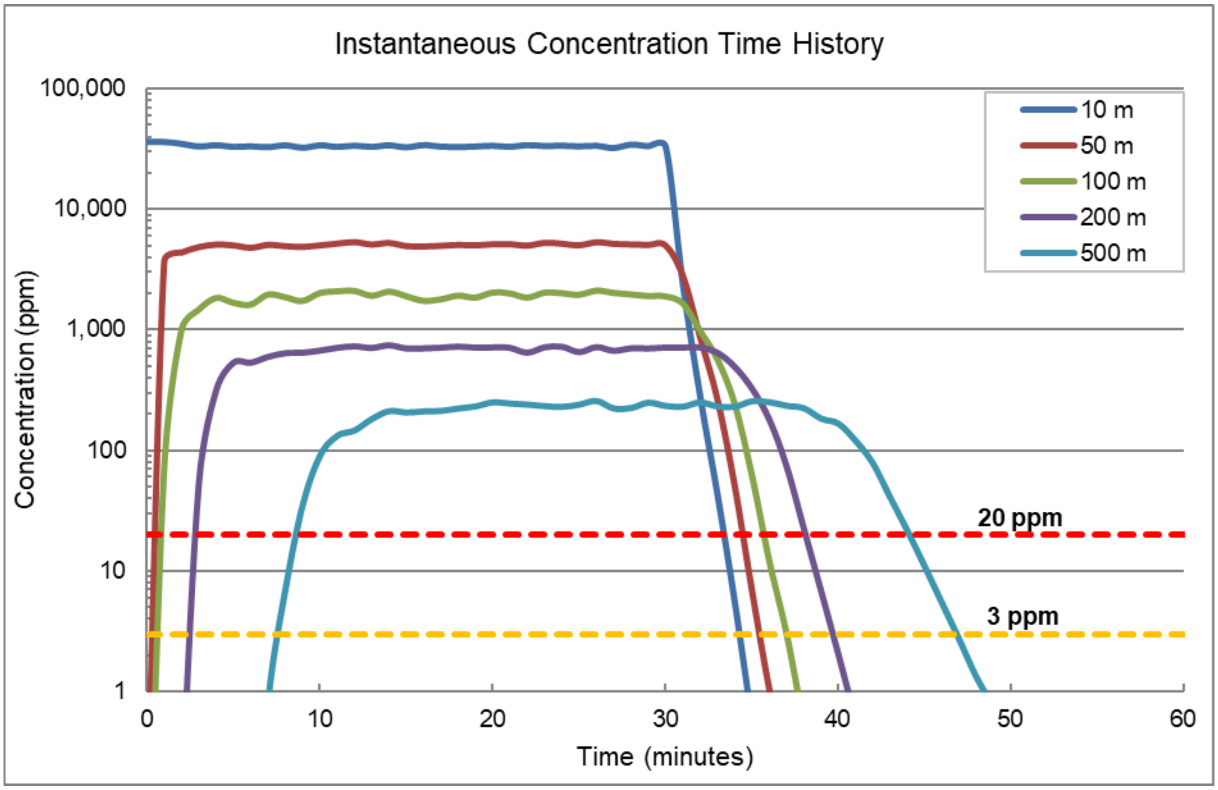
½ -inch (1.27 cm) Tube Failure (Liquid)

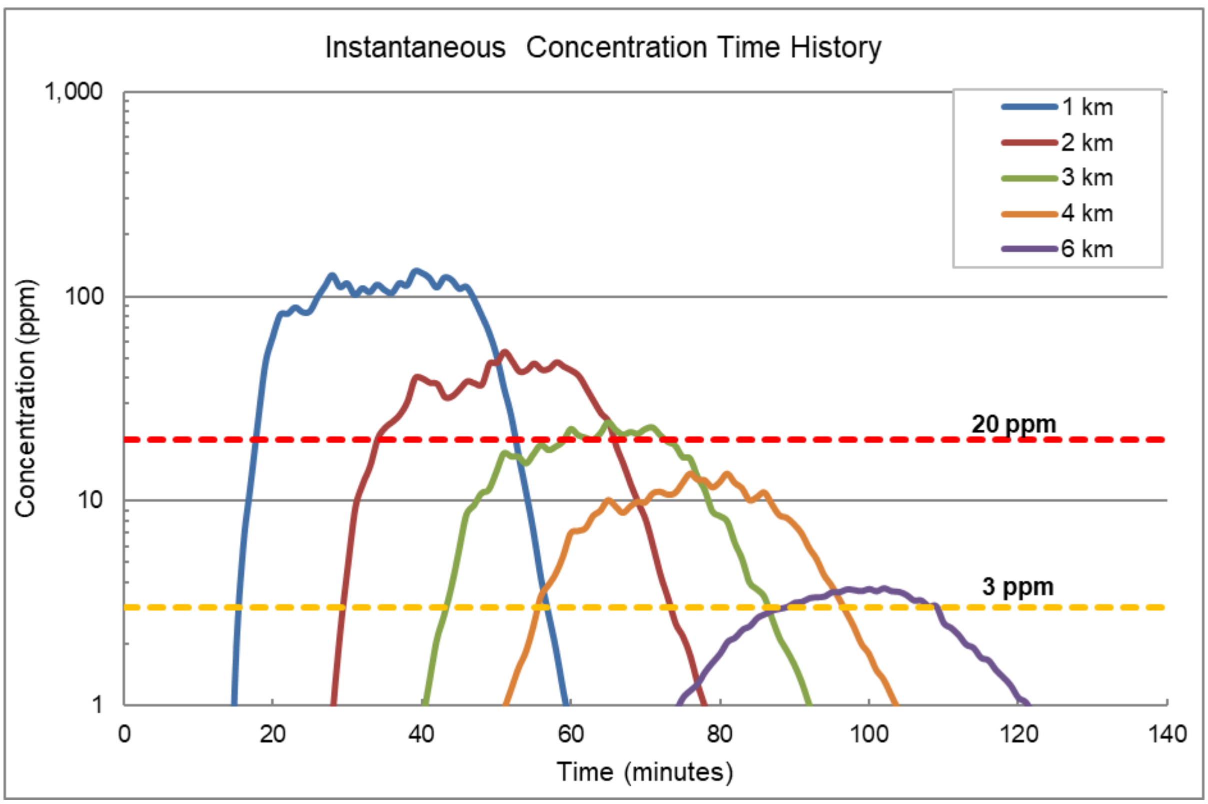


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	4.28	2.10
Kilometers	6.88	3.38
Maximum Crosswind Width		
Miles	0.87	0.36
Kilometers	1.40	0.58
Area Coverage		
Sq. Miles	2.86	0.65
Sq. Kilometers	7.42	1.67

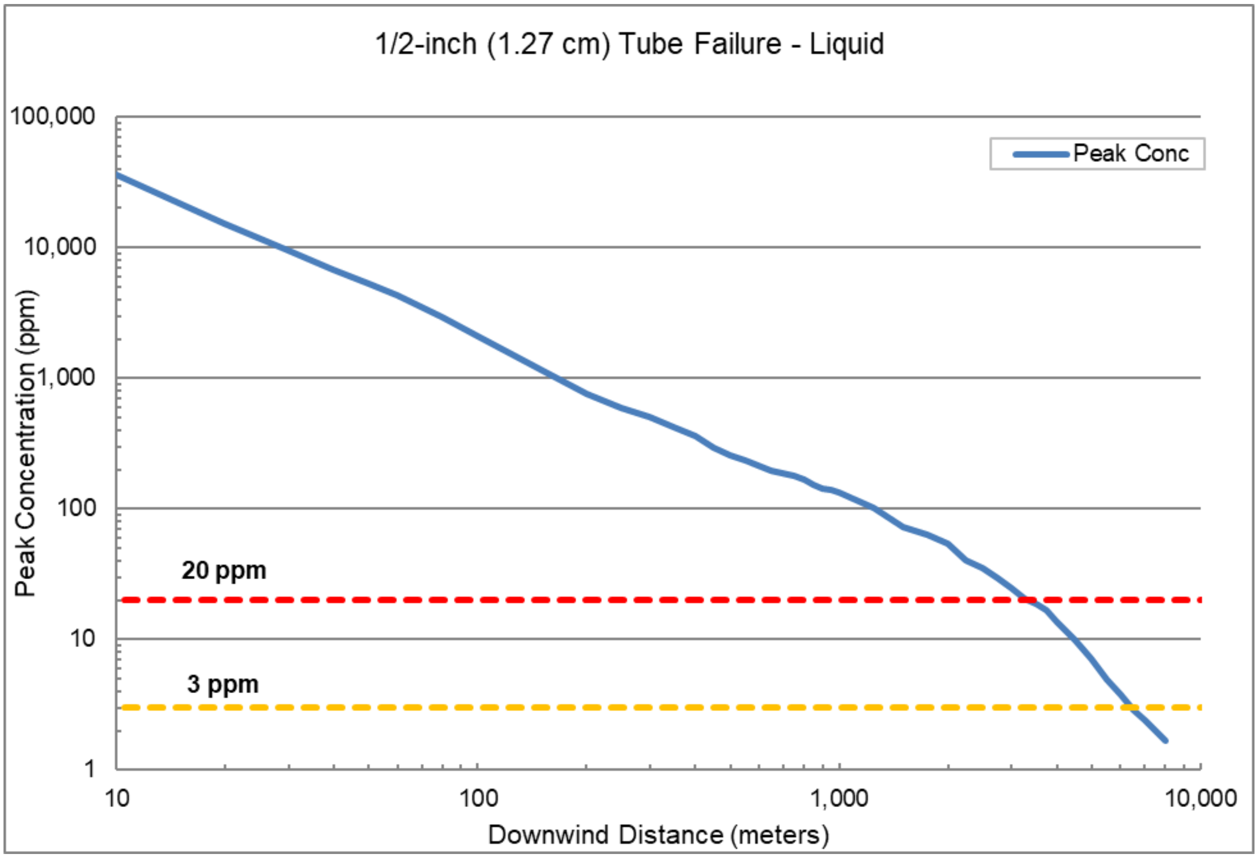
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.5.12 Alternative-Case ½-Inch (1.27 cm) Tubing Failure (liquid) Scenario – D Stability

A ½ -inch (1.27 cm), type K copper tubing is sheared off with an infinite supply of chlorine. Mitigation to stop the release occurs within 30 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Tubing	
Release Mechanism	Failure	
Hole Elevation	3.0 ft.	0.91 m
Opening Diameter	½ inch	1.27 cm
Release State	80% Liquid / 20% Vapor	
Contents Mass	Infinite	
Release Rate	158 lbs./min	71.7 kg/min
Release Duration	30 minutes	
Total Mass Released	4740 lbs.	2150 kg
Gaussian Spread[1]	0.83 inch	2.12 cm
Assumed Chlorine Vapor Temperature (at Release)	-29.27 ^{o}F	-34.04 ^{o}C
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

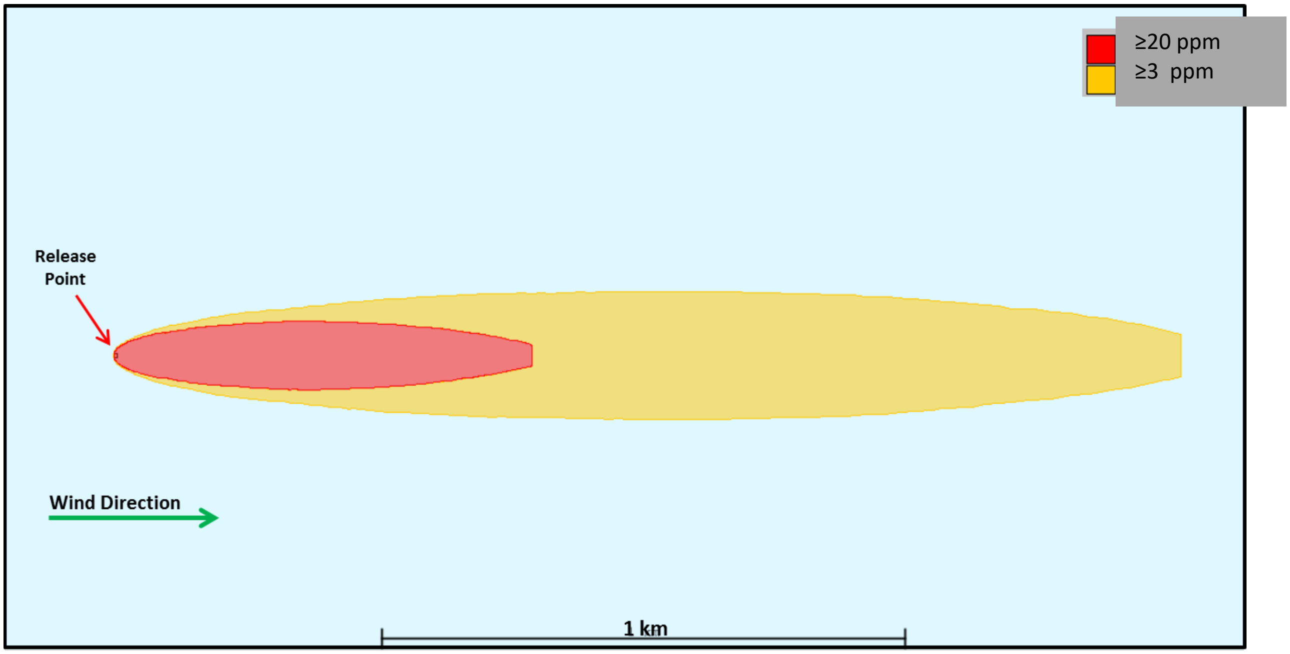
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

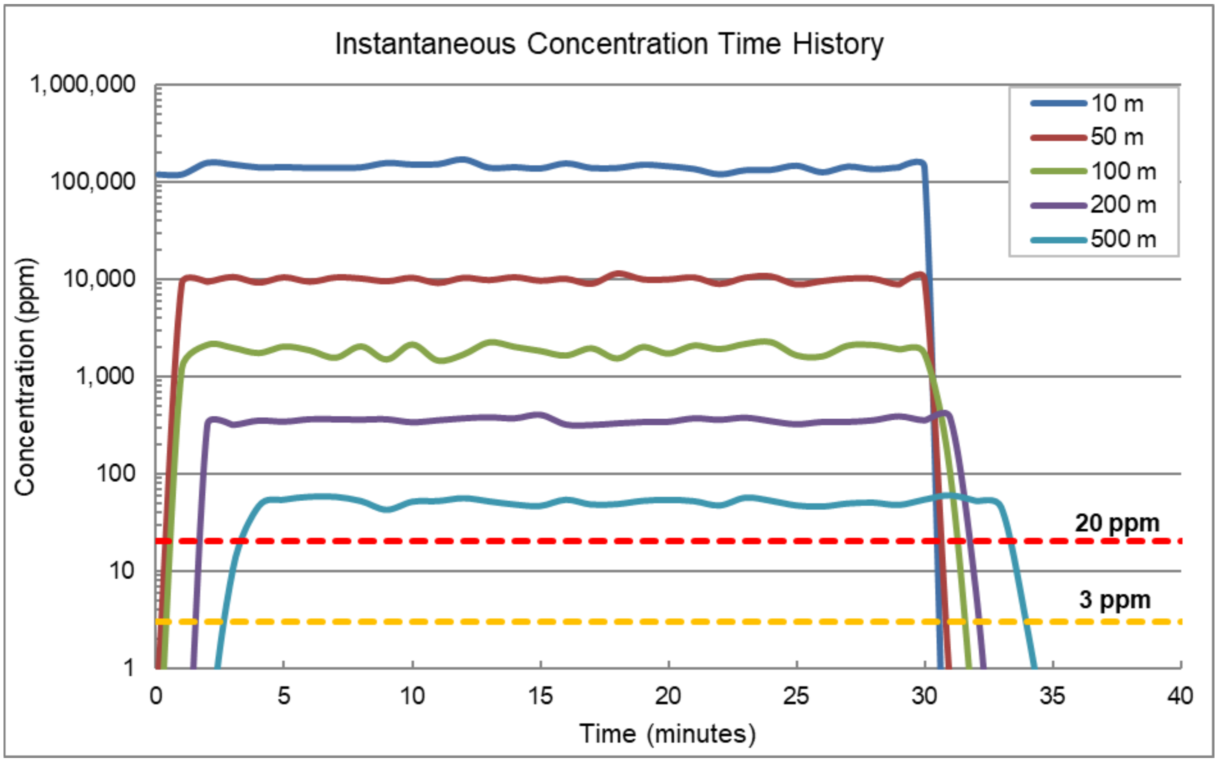
½ -inch (1.27 cm) Tube Failure (Liquid)

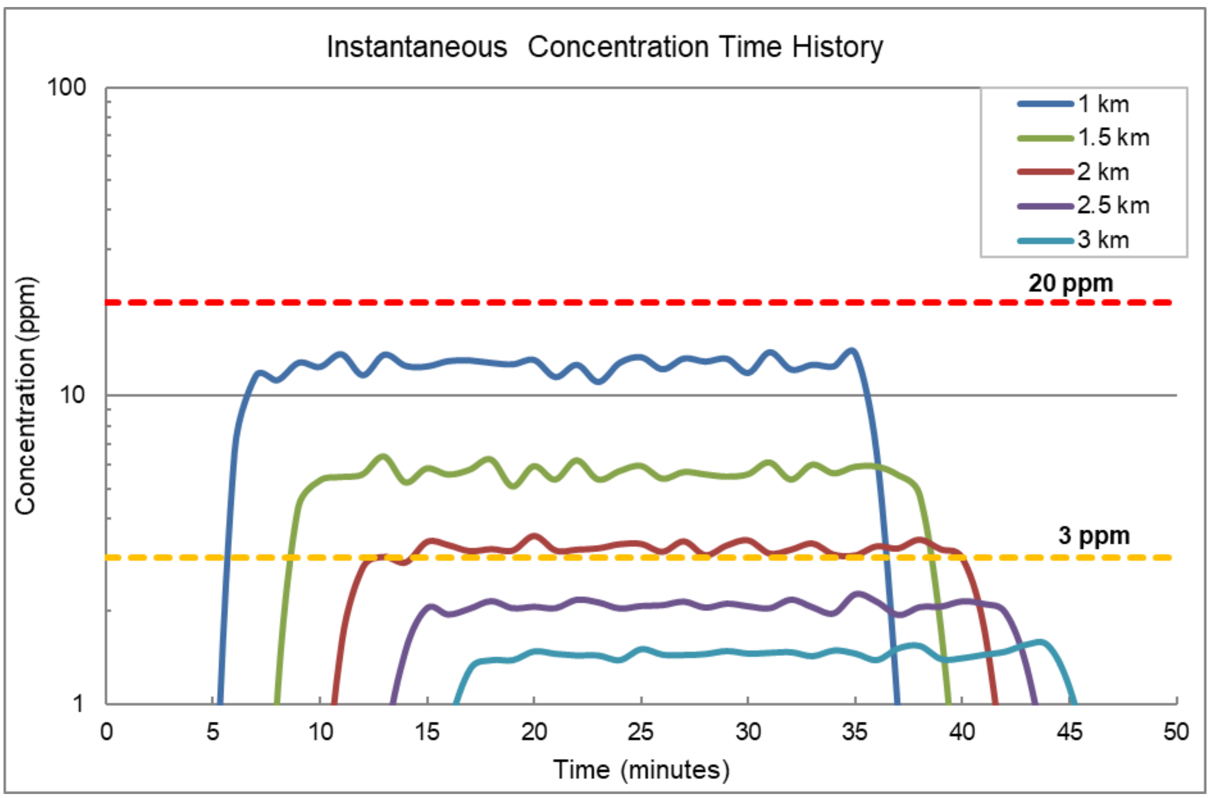


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.27	0.49
Kilometers	2.04	0.79
Maximum Crosswind Width		
Miles	0.141	0.076
Kilometers	0.227	0.123
Area Coverage		
Sq. Miles	0.142	0.029
Sq. Kilometers	0.369	0.075

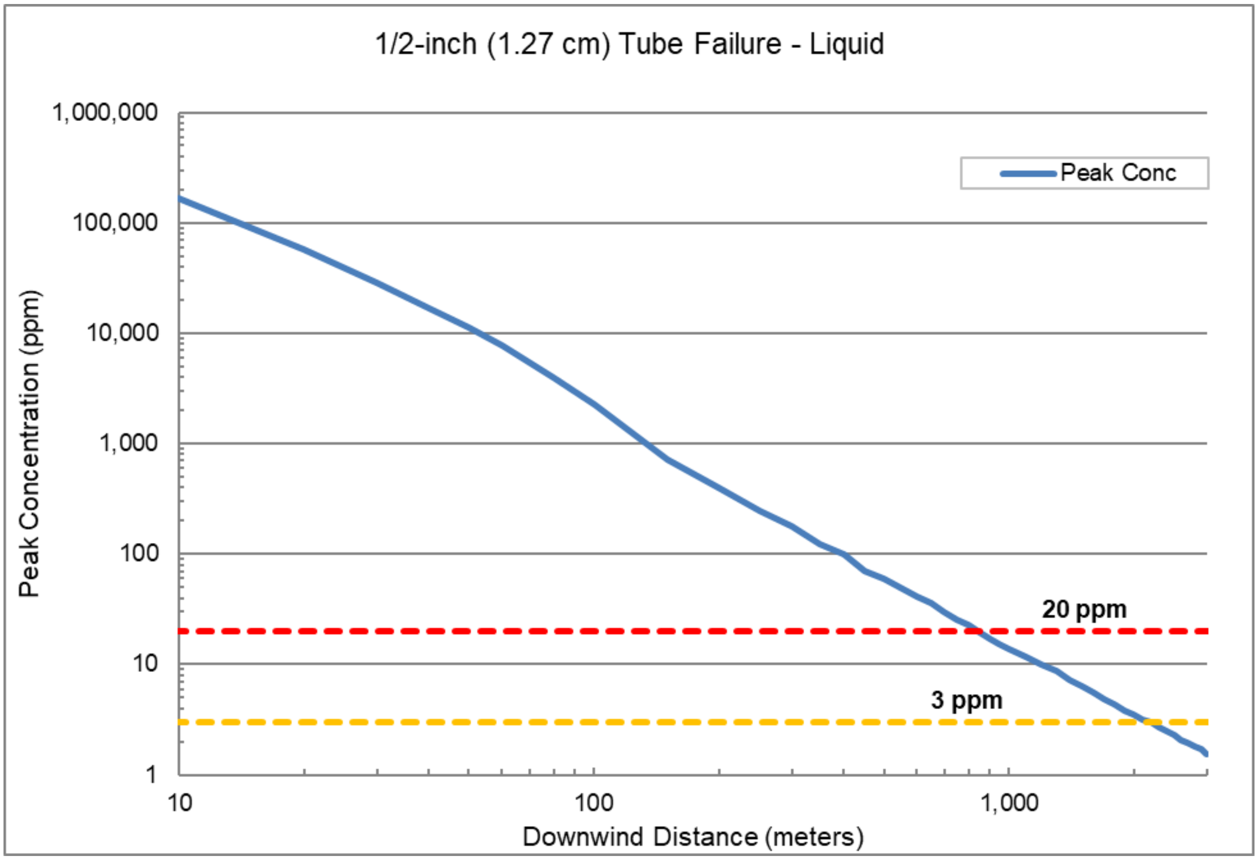
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6 ACCIDENTAL MIXING AND DECOMPOSITION SCENARIO MODELING RESULTS

5.6.1 Alternative-Case Acid Reaction Scenario – F Stability

31.5% Hydrochloric acid is introduced into a 5,000-gallon (18,927 liters) tank of 15% sodium hypochlorite. It is assumed that complete decomposition takes place and releases 6,250 lbs. (2835 kg). of chlorine at a constant rate over 5 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Vessel	
Release Mechanism	Chemical Reaction	
Hole Elevation	0 ft.	0 m
Opening Diameter	NA	NA
Release State	Gas	
Contents Mass	6250 lbs.	2835 kg
Release Rate	1250 lbs./min	567.0 kg/min
Release Duration	5 minutes	
Total Mass Released	6250 lbs.	2835 kg
Gaussian Spread[1]	3.28 ft.	1.0 m
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ºF	25 ºC
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

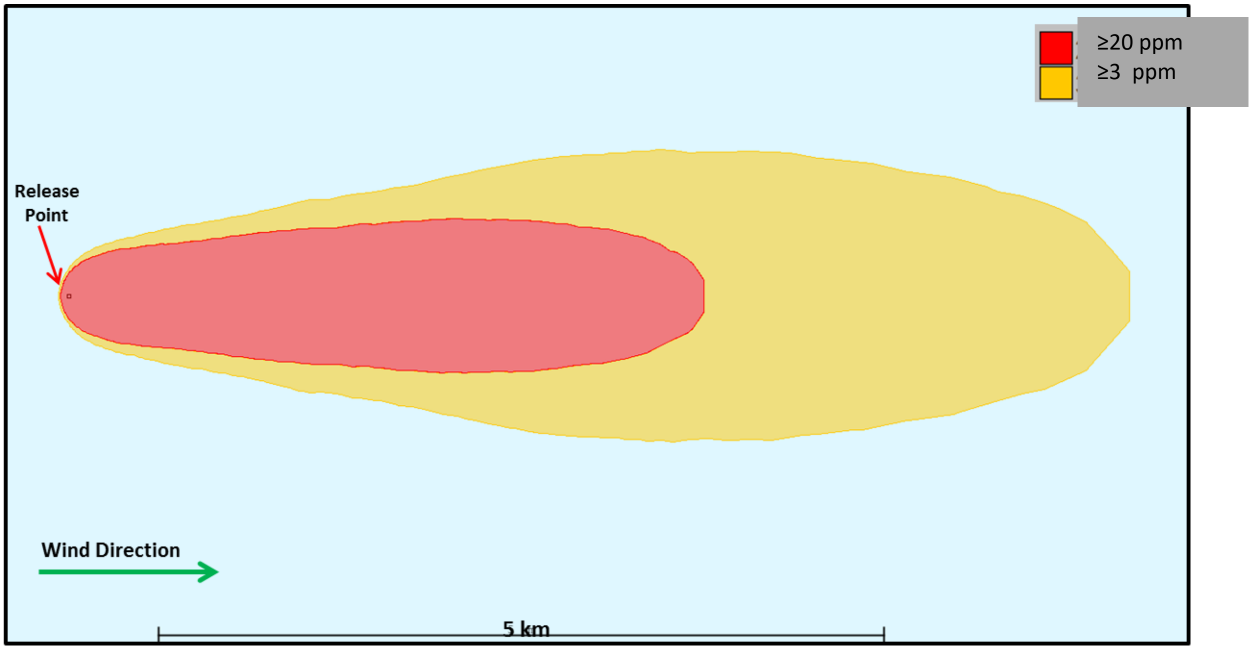
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

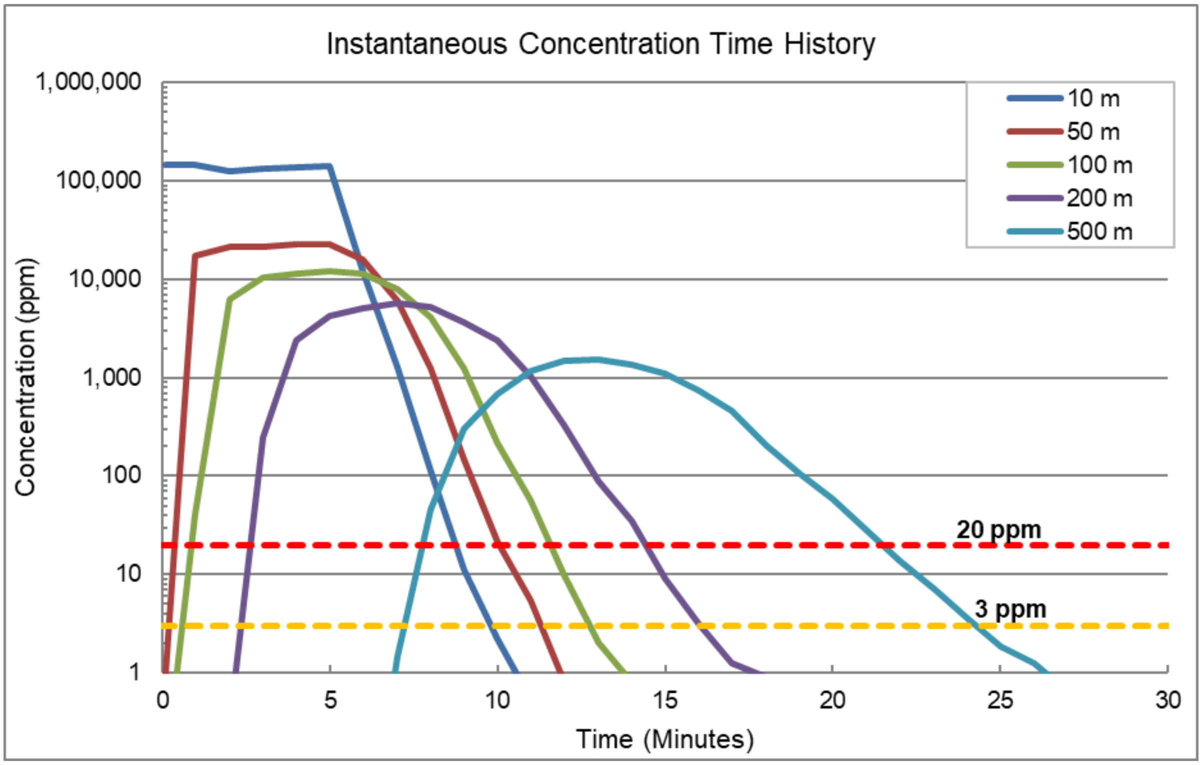
Acid Reaction

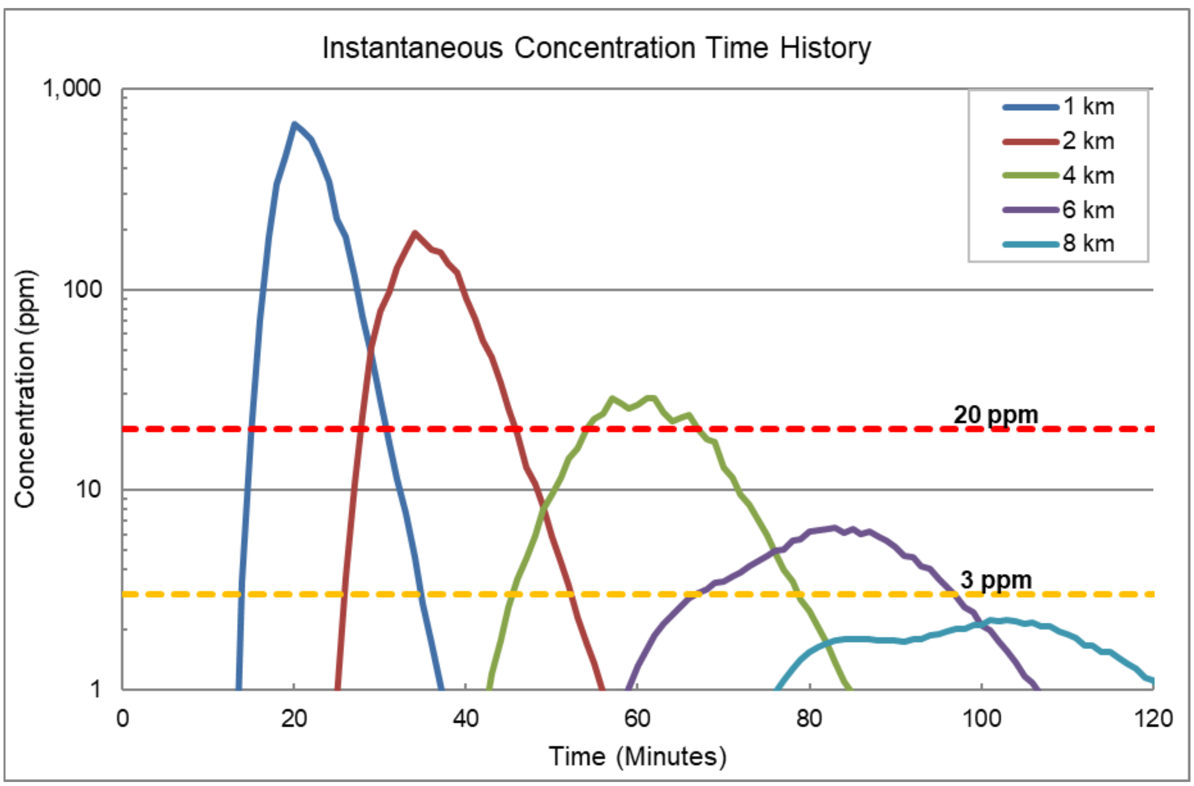


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	4.553	2.724
Kilometers	7.327	4.384
Maximum Crosswind Width		
Miles	1.14	0.60
Kilometers	1.84	0.97
Area Coverage		
Sq. Miles	3.90	1.33
Sq. Kilometers	10.11	3.46

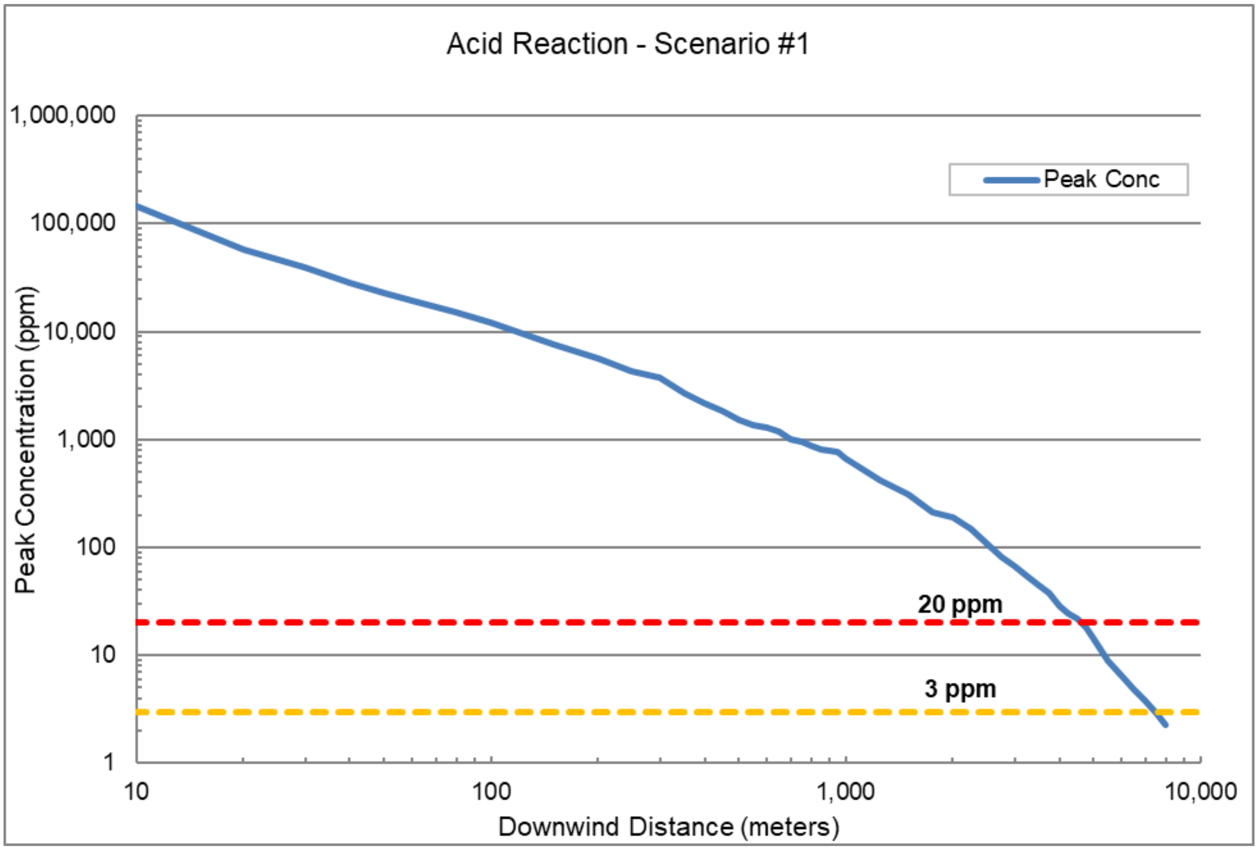
* – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6.2 Alternative-Case Acid Reaction Scenario – D Stability

31.5% Hydrochloric acid is introduced into a 5,000-gallon tank of 15% sodium hypochlorite. It is assumed that complete decomposition takes place and releases 6,250 lbs. (2835 kg) of chlorine at a constant rate over 5 minutes.

Source Description	U.S. Standard Units	Metric Units
Container Type	Vessel	
Release Mechanism	Chemical Reaction	
Hole Elevation	0 ft.	0 m
Opening Diameter	NA	NA
Release State	Gas	
Contents Mass	6250 lbs.	2835 kg
Release Rate	1250 lbs./min	567.0 kg/min
Release Duration	5 minutes	
Total Mass Released	6250 lbs.	2835 kg
Gaussian Spread[1]	3.28 ft.	1.0 m
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

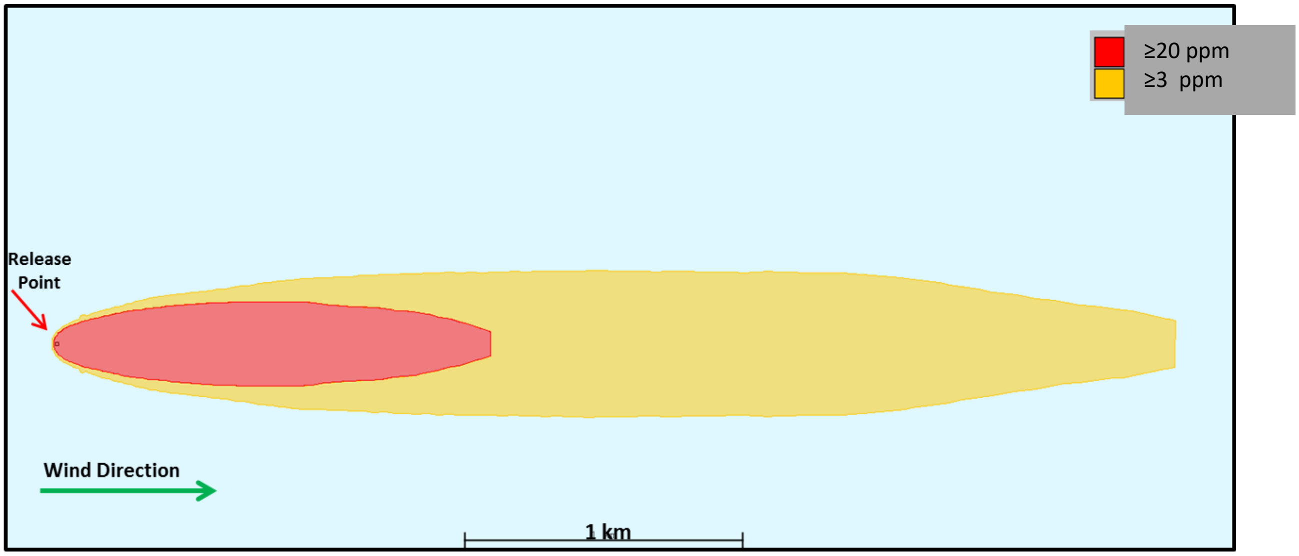
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

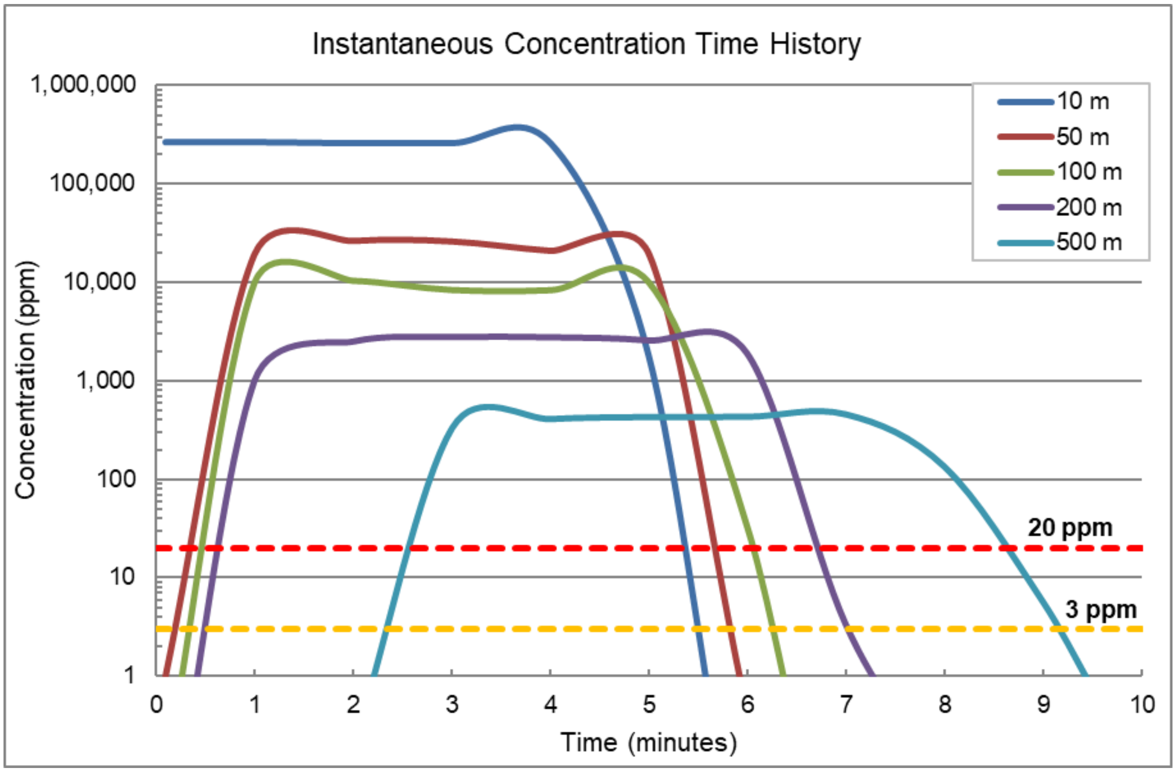
Acid Reaction

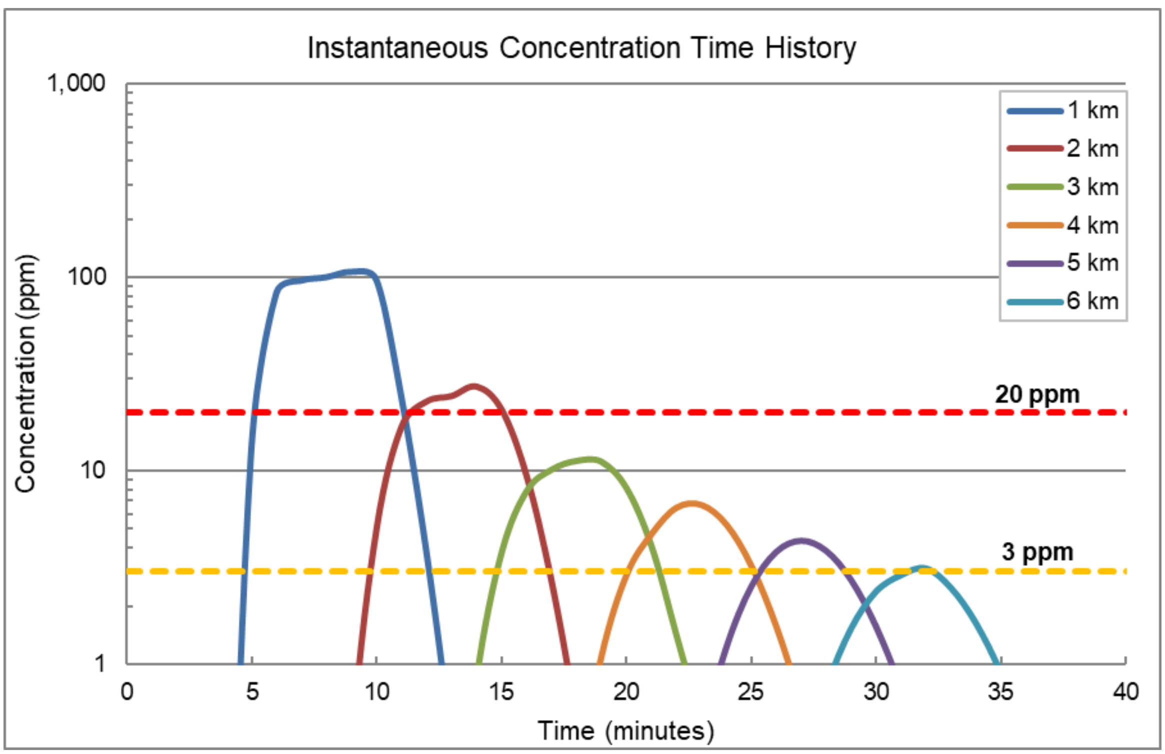


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	2.50	0.97
Kilometers	4.02	1.56
Maximum Crosswind Width		
Miles	0.30	0.17
Kilometers	0.48	0.28
Area Coverage		
Sq. Miles	0.61	0.13
Sq. Kilometers	1.58	0.35

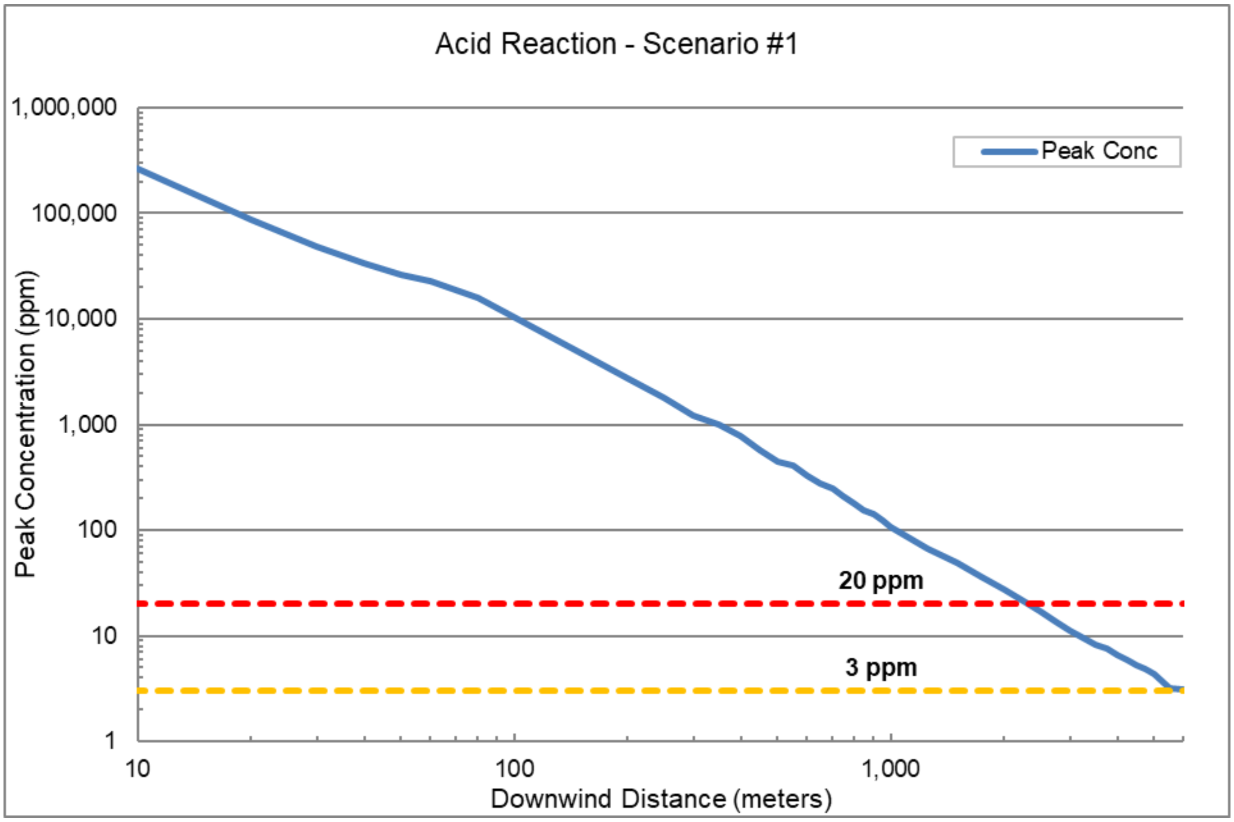
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6.3 Second Alternative-Case Acid Reaction Scenario – F Stability

30% Sulfuric acid is introduced into a 6,500-gallon (26,405 liters) tank of 12.5% sodium hypochlorite. The reaction continues for 45 minutes until the sulfuric acid entering the sodium hypochlorite tank is shut-off. It is assumed that complete decomposition takes place and approximately 3,500 lbs. (1,588 kg). of chlorine is released at a constant rate for one hour. The chlorine gas escapes from a vent and manway lid totaling 21 inches (53.3 cm) in diameter.

Source Description	U.S. Standard Units	Metric Units
Container Type	Storage Tank	
Release Mechanism	Chemical Reaction	
Hole Elevation	17 ft.	5.2 m
Opening Diameter	21 inches	53.3 cm
Release State	Gas	
Contents Mass	3490 lbs.	1583 kg
Release Rate	58.2 lbs./min	26.4 kg/min
Release Duration	60 minutes	
Total Mass Released	3490 lbs.	1583 kg
Gaussian Spread[1]	10.5 inches	26.7 cm
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

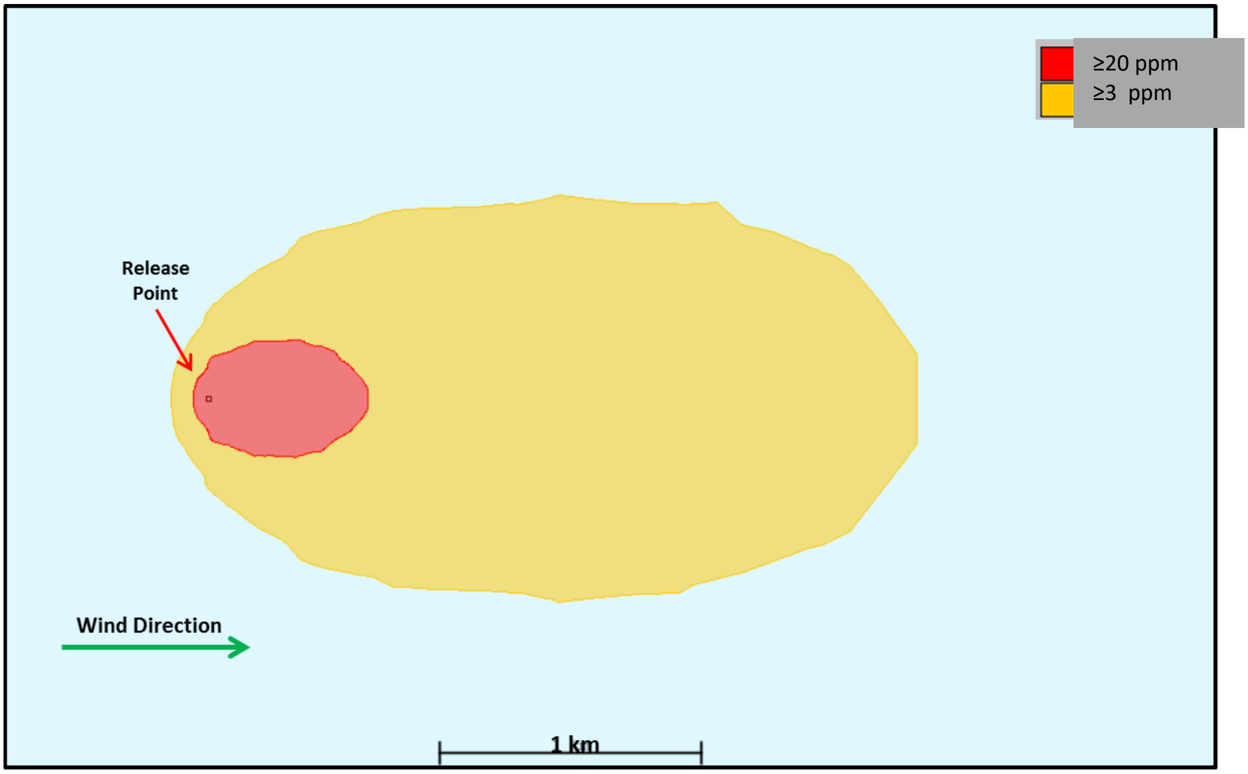
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

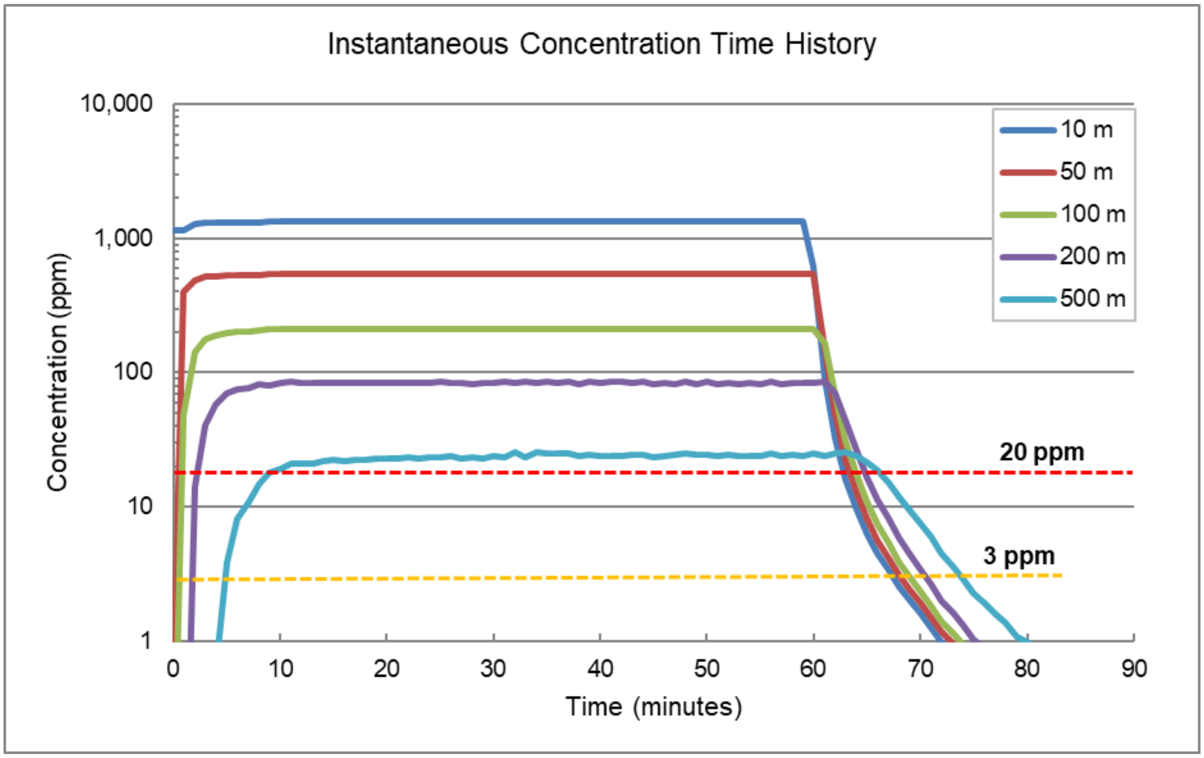
Acid Reaction

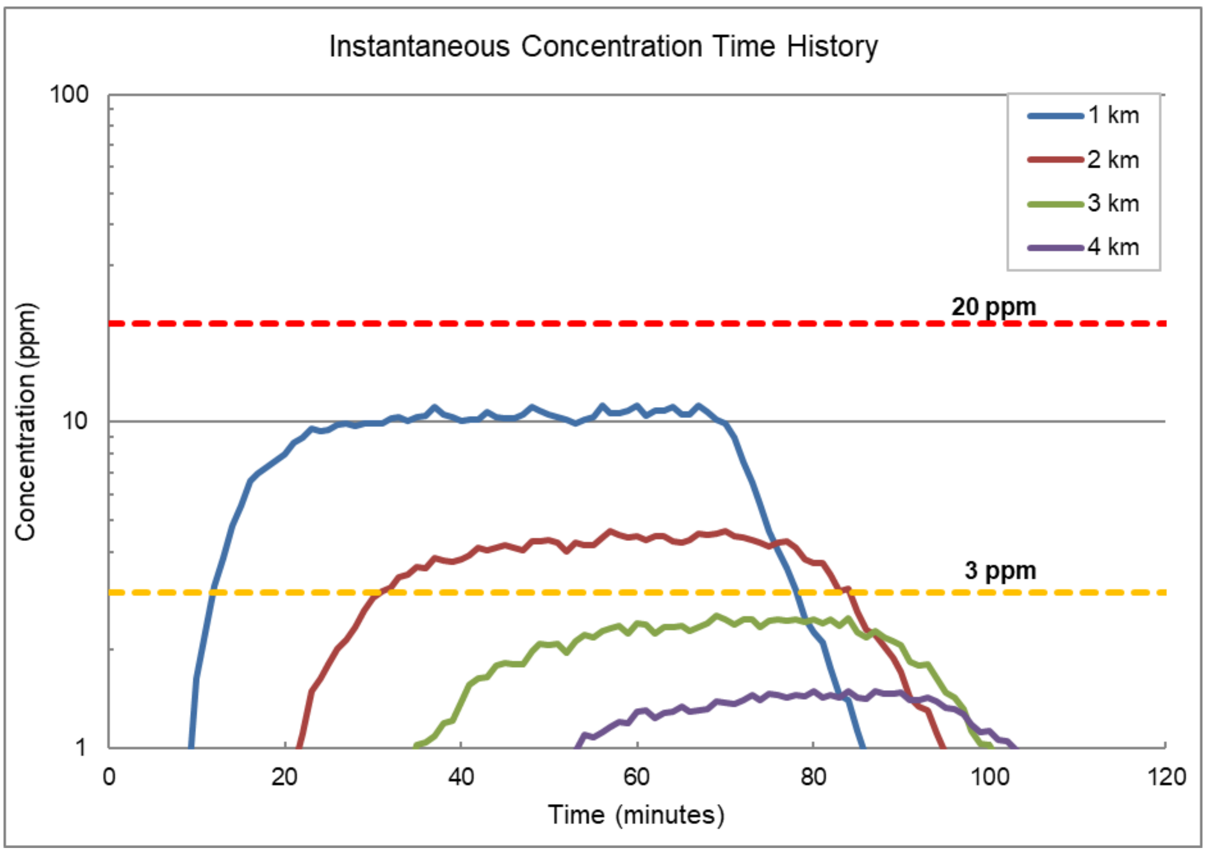


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	1.69	0.38
Kilometers	2.72	0.61
Maximum Crosswind Width		
Miles	0.89	0.26
Kilometers	1.43	0.42
Area Coverage		
Sq. Miles	1.25	0.083
Sq. Kilometers	3.23	0.214

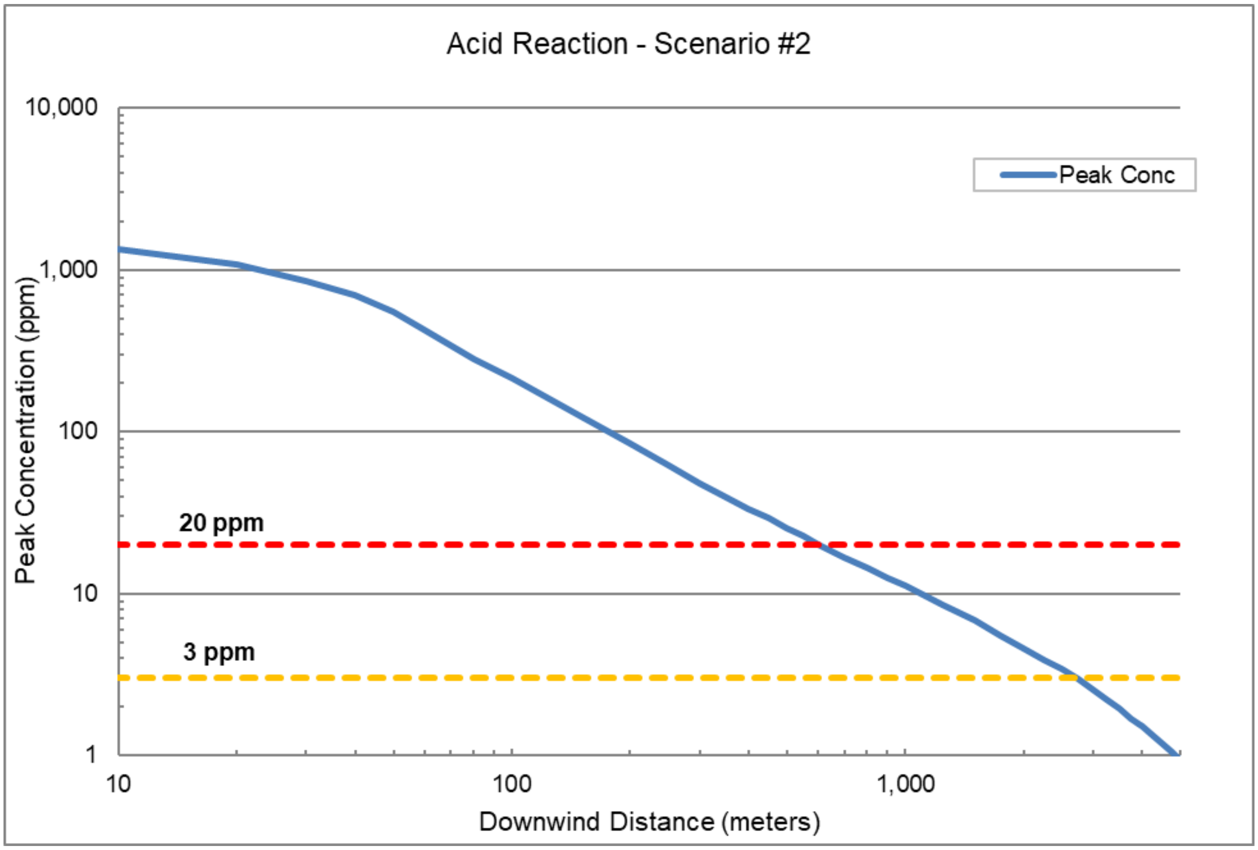
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6.4 Second Alternative-Case Acid Reaction Scenario – D Stability

30% Sulfuric acid is introduced into a 6,500-gallon (24,605 liters) tank of 12.5% sodium hypochlorite. The reaction continues for 45 minutes until the sulfuric acid entering the sodium hypochlorite tank is shut off. It is assumed that complete decomposition takes place and approximately 3,500 lbs. (1,588 kg). of chlorine is released at a constant rate for one hour. The chlorine gas escapes from a vent and manway lid totaling 21 inches (53.3 cm) in diameter.

Source Description	U.S. Standard Units	Metric Units
Container Type	Storage Tank	
Release Mechanism	Chemical Reaction	
Hole Elevation	17 ft.	5.2 m
Opening Diameter	21 inches	53.3 cm
Release State	Gas	
Contents Mass	3490 lbs.	1583 kg
Release Rate	58.2 lbs./min	26.4 kg/min
Release Duration	60 minutes	
Total Mass Released	3490 lbs.	1583 kg
Gaussian Spread[1]	10.5 inches	26.7 cm
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

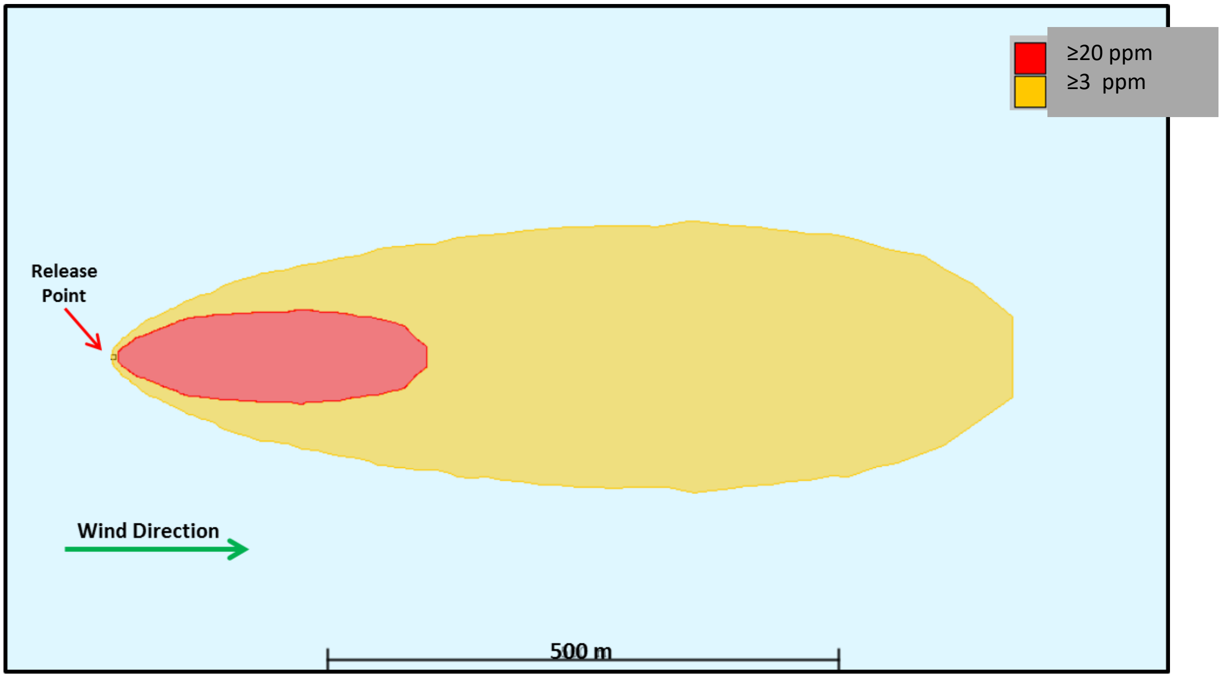
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

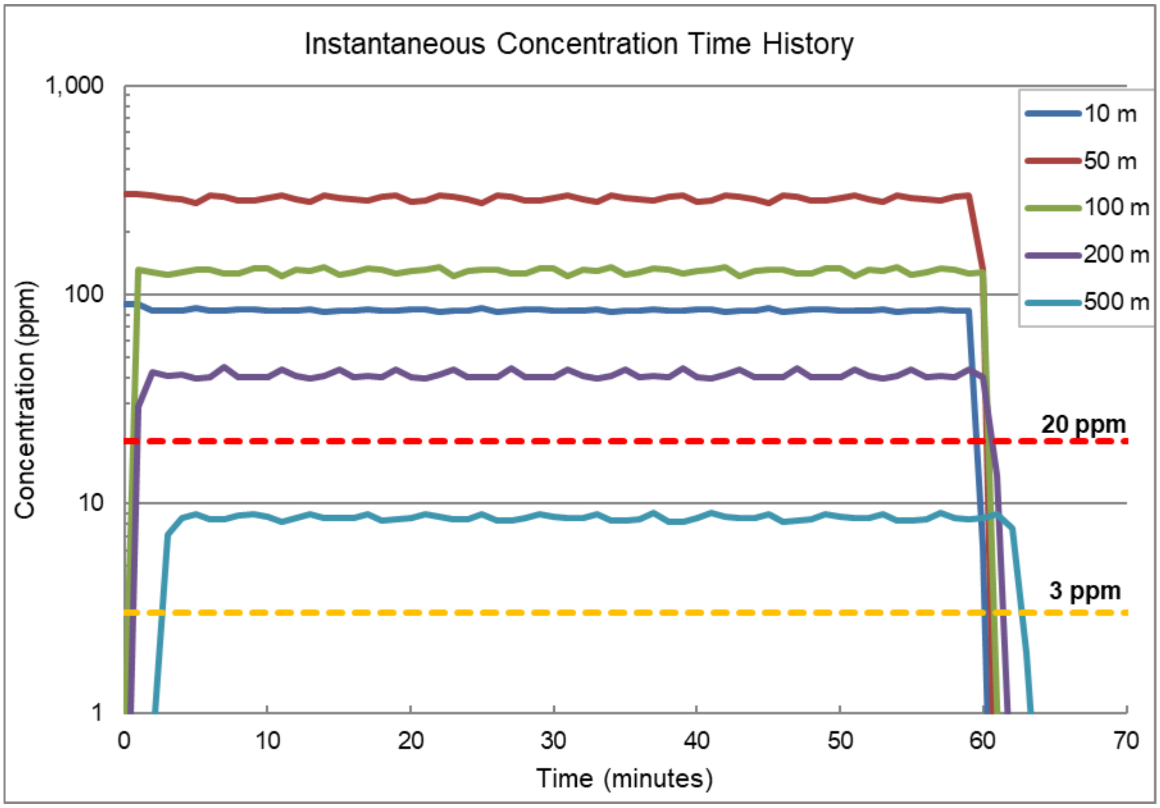
Acid Reaction – Scenario #2

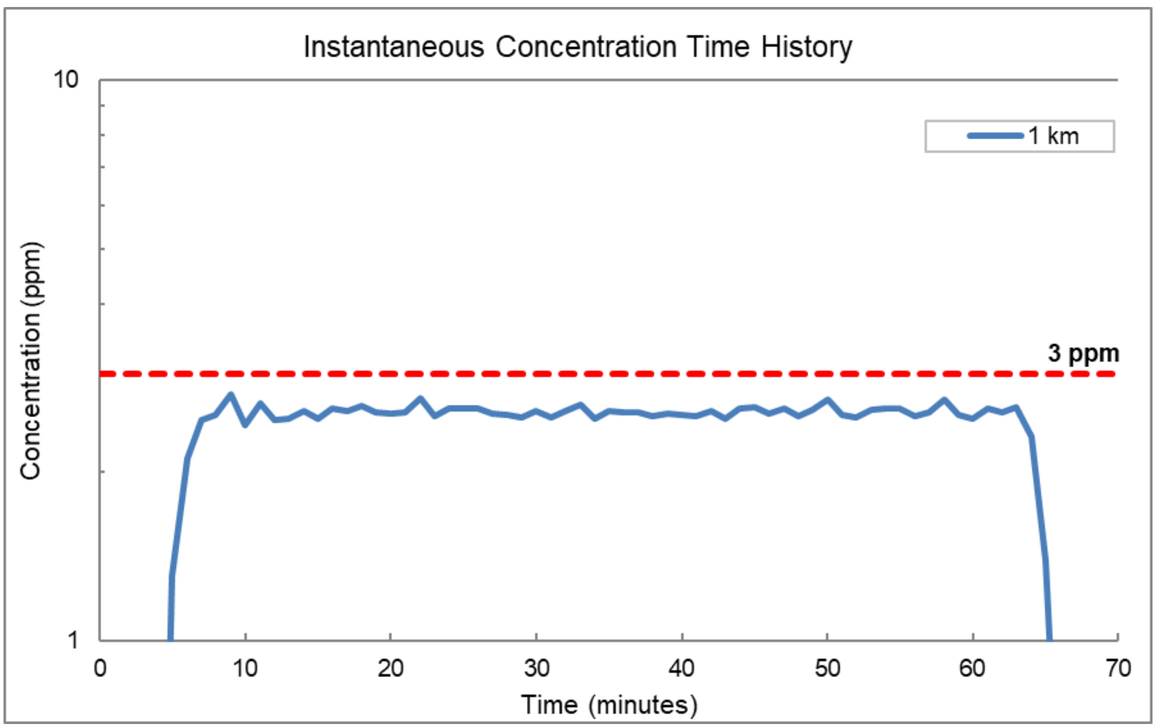


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.55	0.19
Kilometers	0.88	0.31
Maximum Crosswind Width		
Miles	0.30	0.17
Kilometers	0.48	0.28
Area Coverage		
Sq. Miles	0.063	0.008
Sq. Kilometers	0.164	0.020

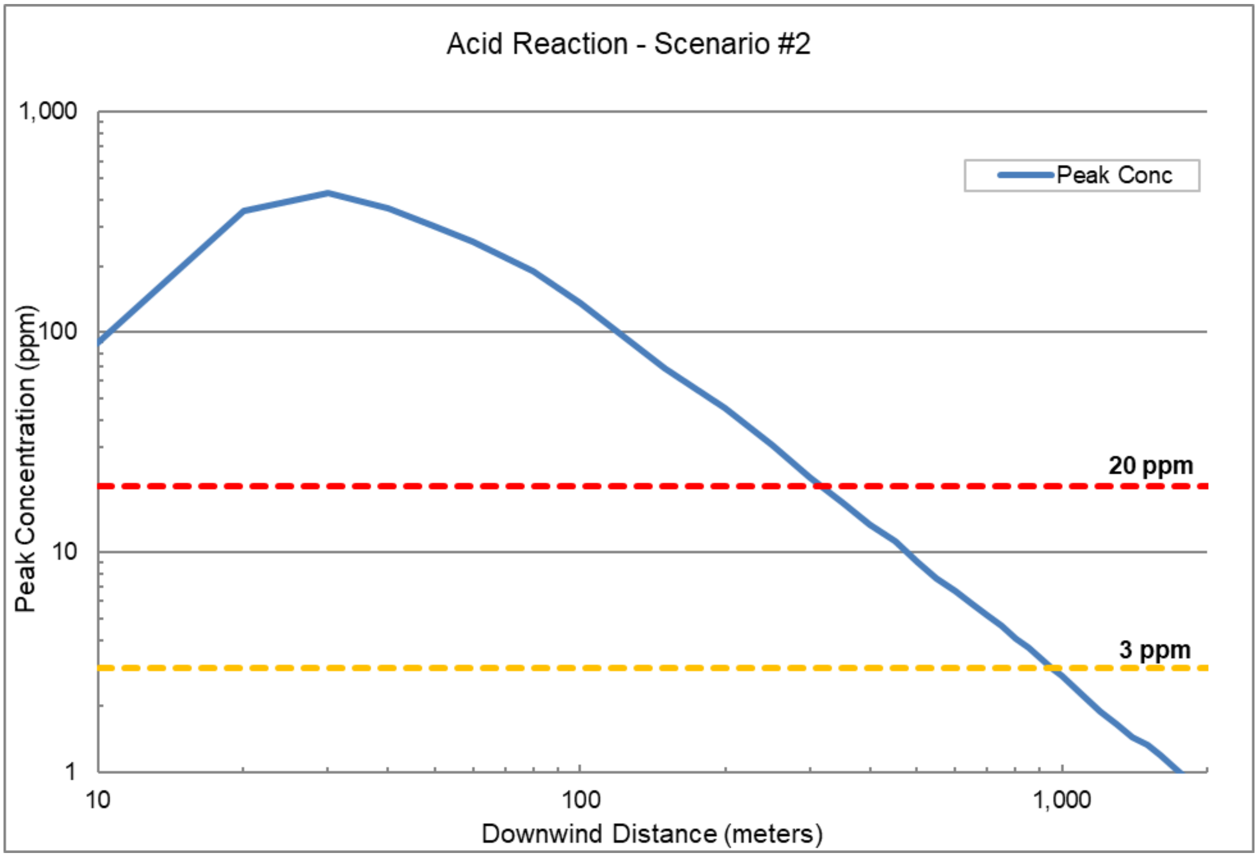
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6.5 Alternative-Case Calcium Hypochlorite - Decomposition Scenario – F Stability

A reaction of 100 lbs. (45 kg) of 65% calcium hypochlorite (65% available chlorine) occurs at a swimming pool. An assumption is made that 25% of the available chlorine or 16.25 lbs (7.37 kg). are released at a constant rate in 1 minute.

Source Description	U.S. Standard Units	Metric Units
Container Type	Vessel	
Release Mechanism	Chemical Reaction	
Hole Elevation	0 ft.	0 m
Opening Diameter	NA	NA
Release State	Gas	
Contents Mass	16.25 lbs.	7.37 kg
Release Rate	16.25 lbs./min	7.37 kg/min
Release Duration	1 minute	
Total Mass Released	16.25 lbs.	7.37 kg
Gaussian Spread[1]	0.82 ft.	0.25 m
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^{o}F	25 ^{o}C
Wind Speed	3.36 mph	1.50 m/sec
Stability Category	F Stability	

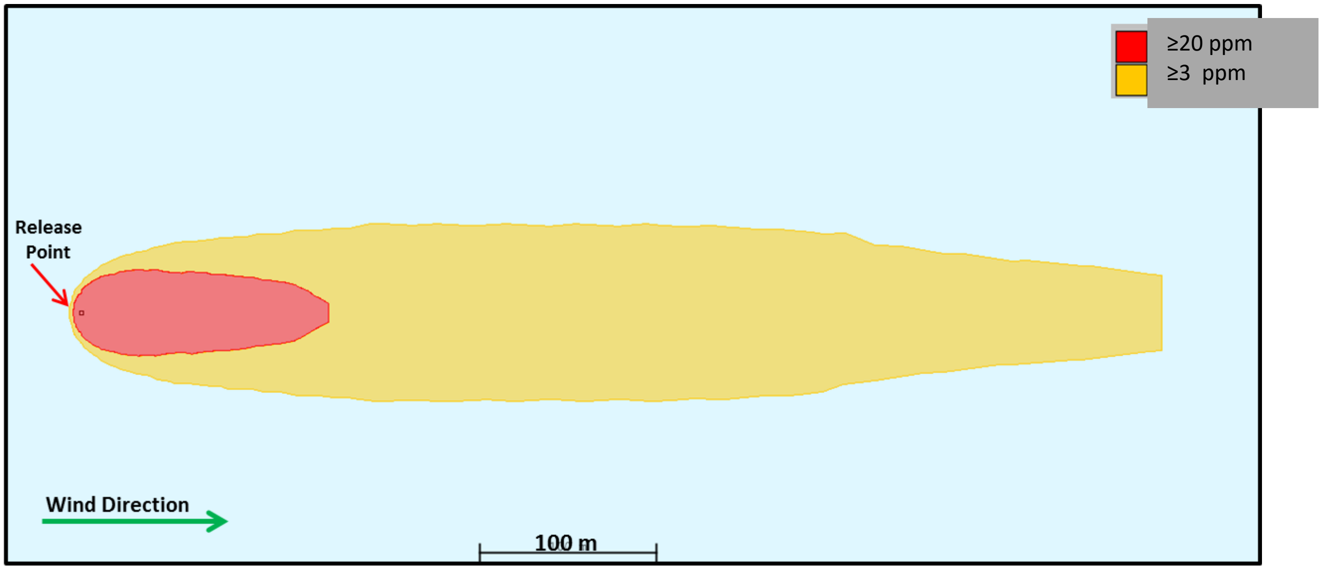
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

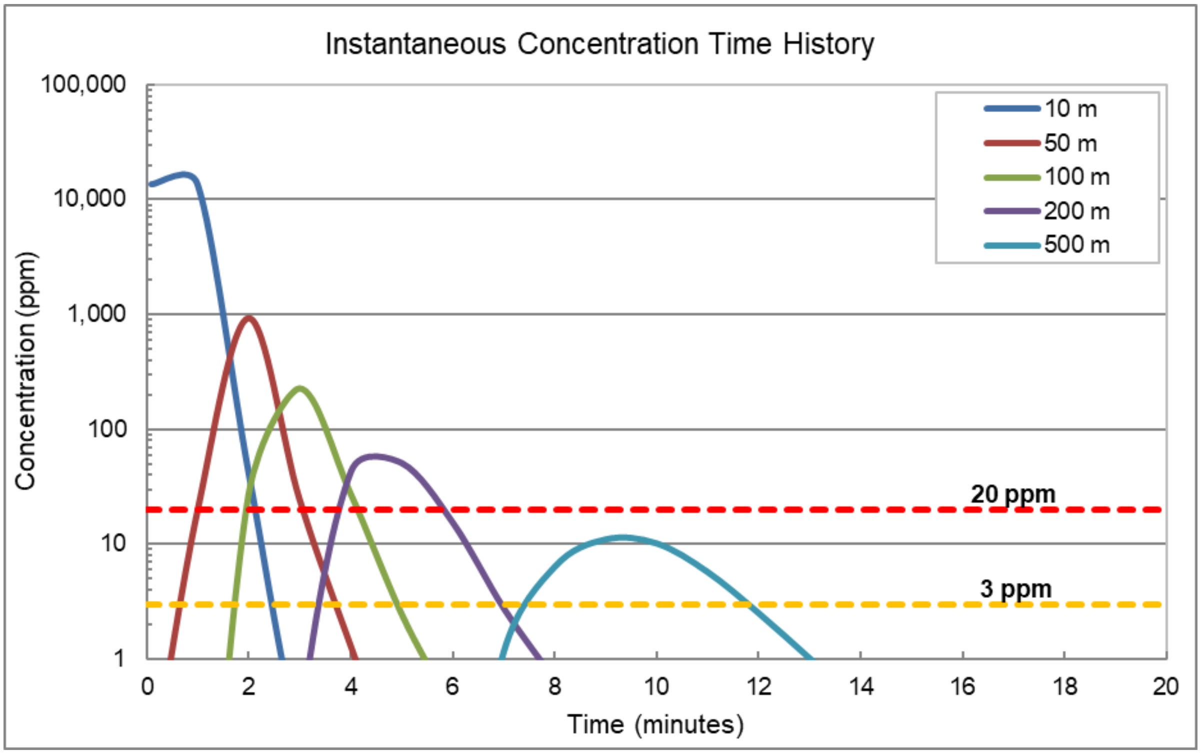
Calcium Hypochlorite - Decomposition

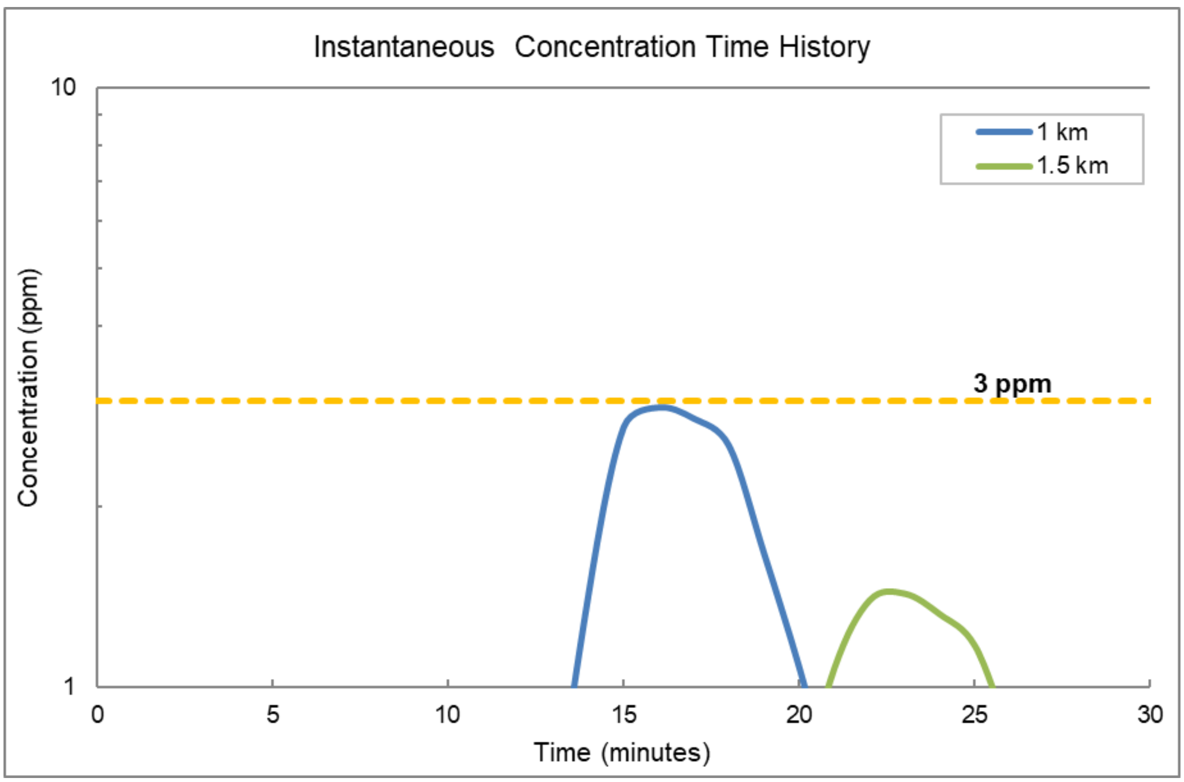


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.38	0.09
Kilometers	0.62	0.14
Maximum Crosswind Width		
Miles	0.057	0.027
Kilometers	0.092	0.044
Area Coverage		
Sq. Miles	0.0181	0.0020
Sq. Kilometers	0.0468	0.0052

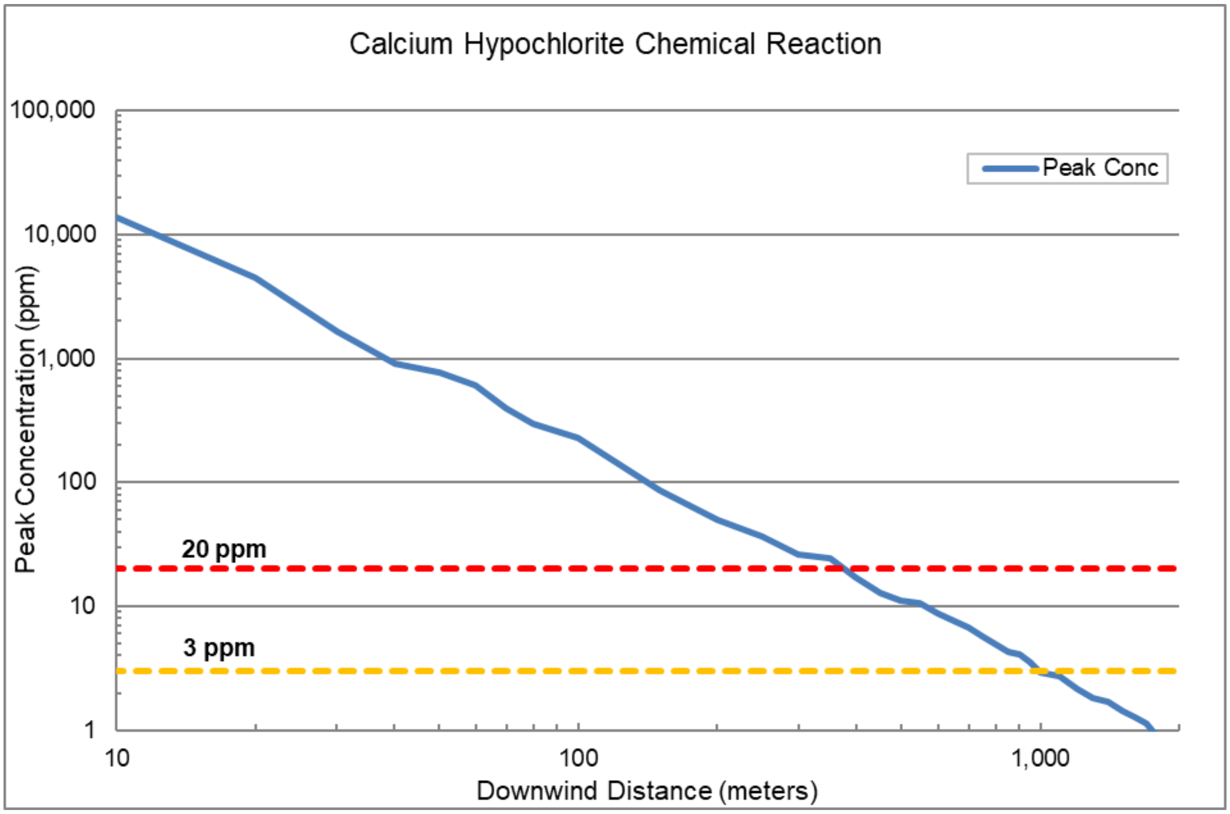
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



5.6.6 Alternative-Case Calcium Hypochlorite - Decomposition Scenario – D Stability

A reaction of 100 lbs. (45 kg) of calcium hypochlorite (65% available chlorine) occurs at a swimming pool. The assumption is 25% of the available chlorine, or 16.25 lbs. (7.37 kg) is released at a constant rate over one minute.

Source Description	U.S. Standard Units	Metric Units
Container Type	Vessel	
Release Mechanism	Chemical Reaction	
Hole Elevation	0 ft.	0 m
Opening Diameter	NA	NA
Release State	Gas	
Contents Mass	16.25 lbs.	7.37 kg
Release Rate	16.25 lbs./min	7.37 kg/min
Release Duration	1 minute	
Total Mass Released	16.25 lbs.	7.37 kg
Gaussian Spread[1]	0.82 ft.	0.25 m
Assumed Chlorine Vapor Temperature (at Release)	Exothermic reaction; buoyant gas initially produced by chemical reaction	
Surface Type (wind profile calculation)	Bare ground / Desert	
Surface Roughness Length	0.04 in.	0.1 cm
Dry Deposition Velocity	0.016 in./sec	0.04 cm/sec
Ground Surface (liquid evaporation calculations)	Impermeable / No secondary evaporation from release	

Meteorology	U.S. Standard Units	Metric Units
Weather Observation Height	32.8 ft.	10.0 m
Temperature	77 ^oF	25 ^oC
Wind Speed	6.7 mph	3.0 m/sec
Stability Category	D Stability	

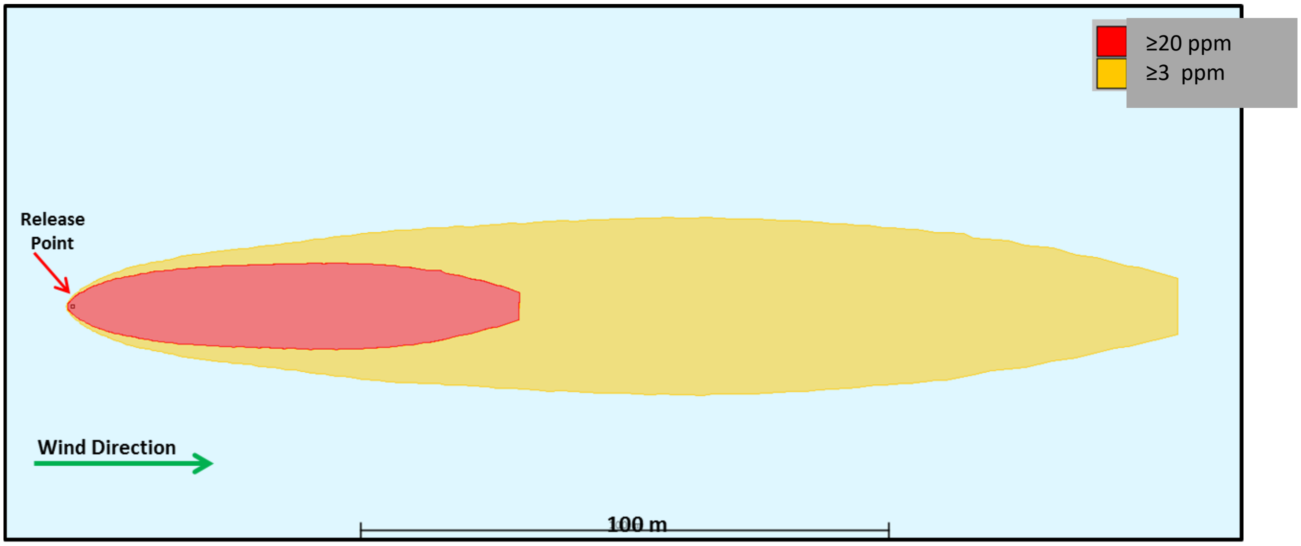
Receptor / Sampler	U.S. Standard Units	Metric Units
Horizontal Position	Along wind direction/plume centerline	
Receptor/Sampling Height	0 ft.	0 m

1 – Gaussian spread indicates the initial radius width (both horizontal and vertical) of the jet/plume where ~95% or greater of the mass exists.

2 – Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint

Hazard Characterization Footprint – Maximum Extent of ppm Level or Greater

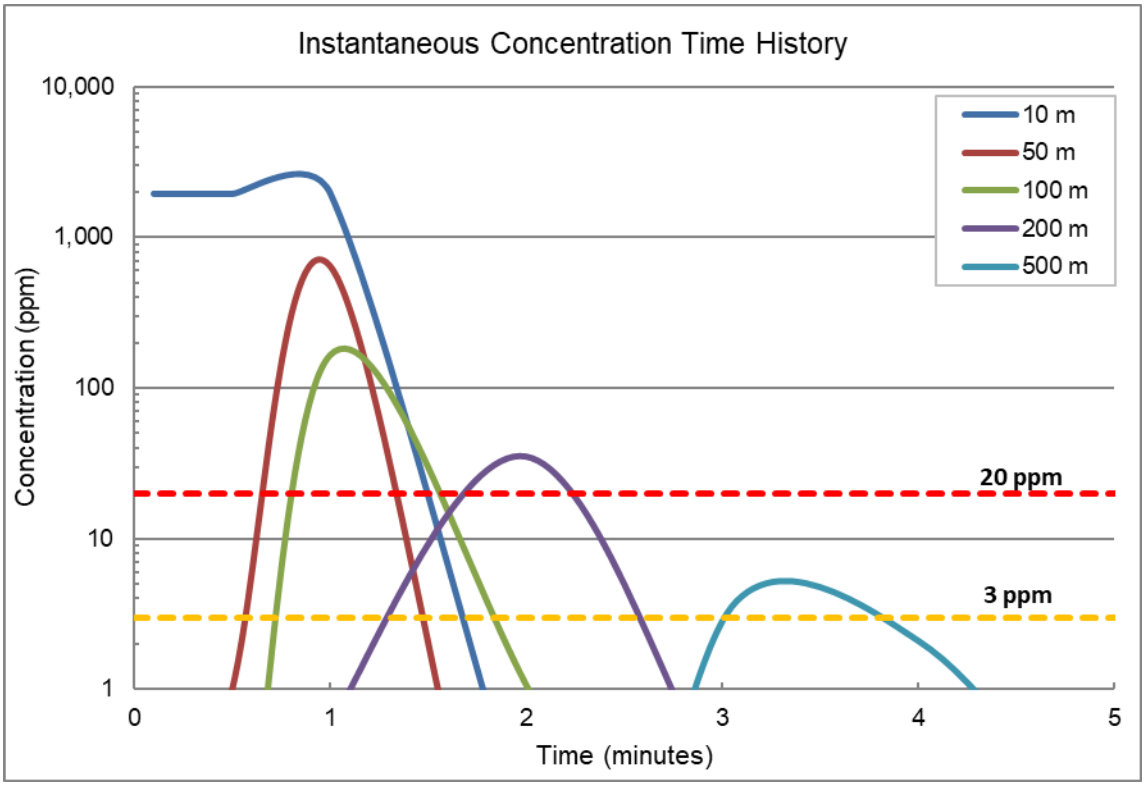
Calcium Hypochlorite – Decomposition

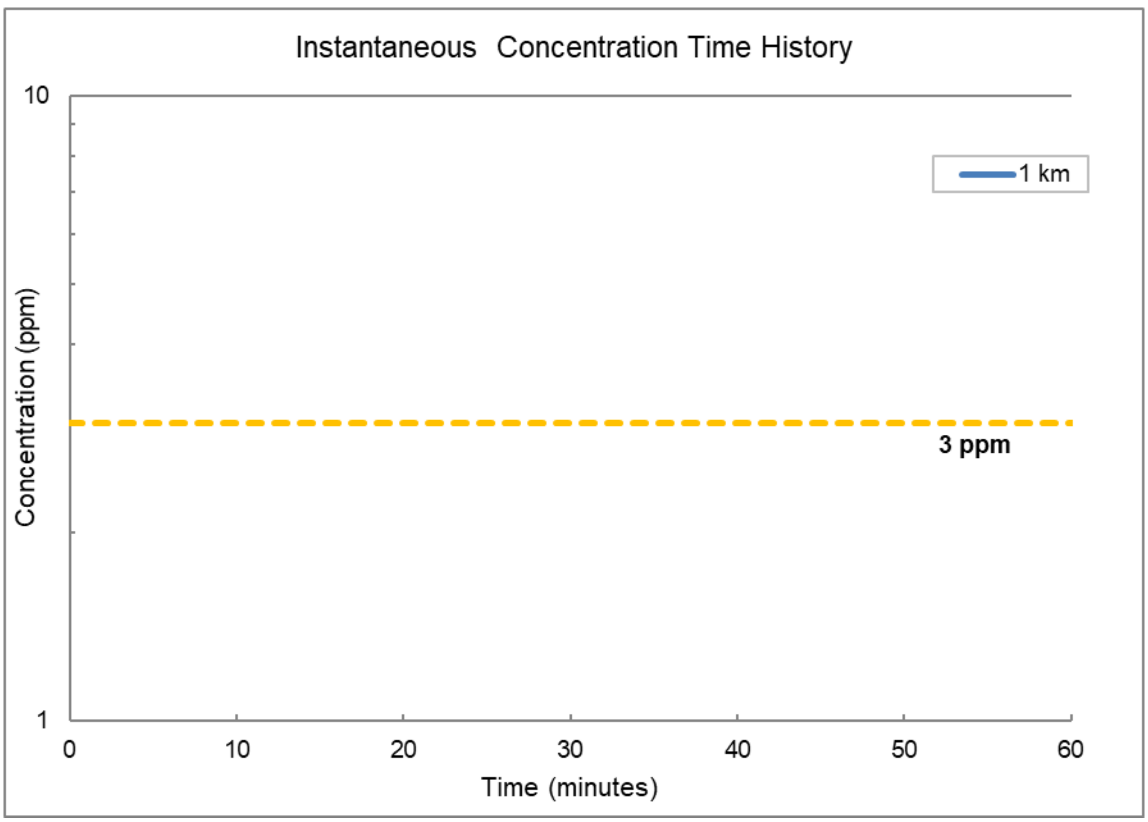


Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.13	0.053
Kilometers	0.21	0.085
Maximum Crosswind Width		
Miles	0.019	0.009
Kilometers	0.031	0.015
Area Coverage		
Sq. Miles	0.0019	0.0004
Sq. Kilometers	0.0050	0.0010

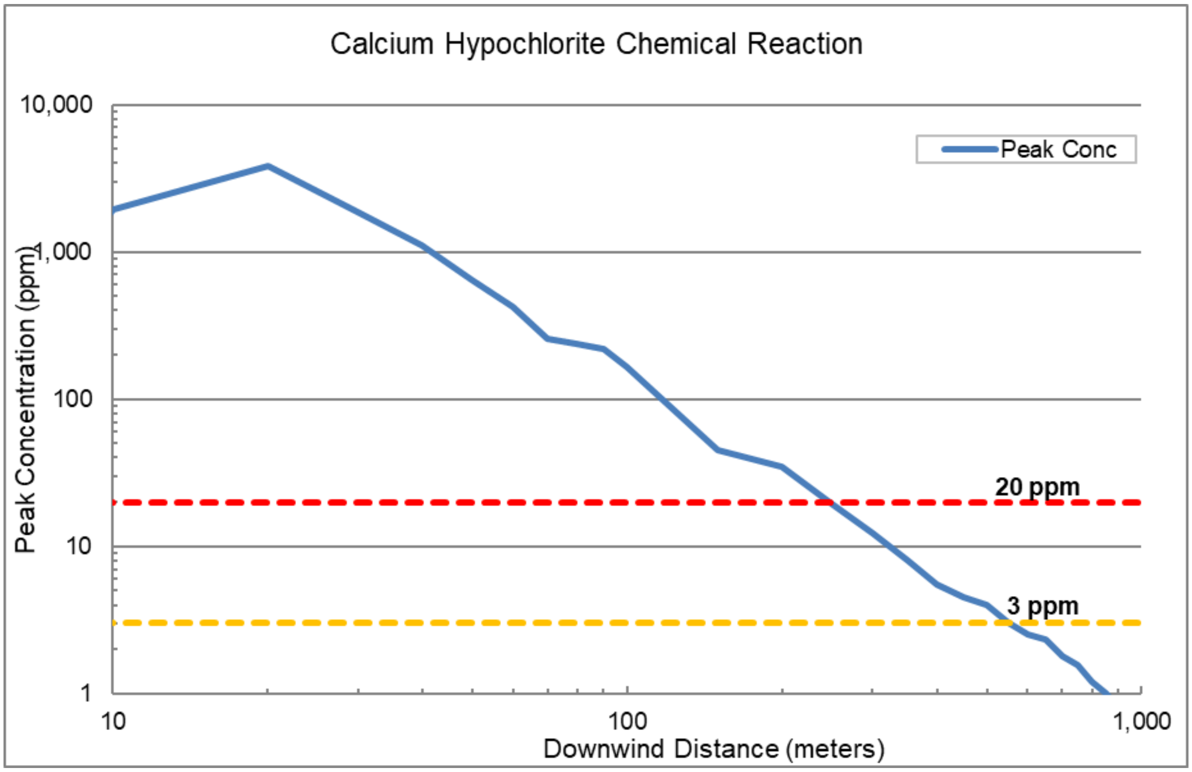
***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

Concentration as a Function of Time at Various Downwind Distances:





Peak Concentration as a Function of Distance:



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APPENDIX A – HPAC MODEL EXPLANATION

The model used to analyze the scenarios in this pamphlet is the Hazard Prediction and Assessment Capability (HPAC), version 6.4. This appendix summarizes some of the key concepts employed in this model. Note, this is not intended to be an exhaustive review of the HPAC model, GUI, or capabilities, but rather an introduction to orient the reader to the model and methodology implemented for these studies.

Basic Concepts:

HPAC 6.4 is a hazard prediction modeling system developed by the U.S. Department of Defense (DOD), Defense Threat Reduction Agency (DTRA), which distributes it freely to U.S. Government agencies and their contractors, but not to commercial interests. HPAC 6.4 contains 20 incident source models related to the release of chemical, biological, radiological, and nuclear (CBRN) materials due to weapon events, facility strikes, industrial accidents, and transportation accidents. For the modeling performed in Pamphlet 74, the HPAC Analytical Incident module was used to define the chlorine release parameters (source term), as the analytic module provides the most flexibility to the modeler in defining release parameters (release rate and timing, release phase partitioning, release angle, droplet size distribution, etc.) and best meets the modeling requirements as outlined by the U.S. Environmental Protection Agency (EPA).

Pertinent physical and chemical properties of the various (200+) hazardous materials are contained within discrete “material files” that HPAC utilizes in various calculations. These files include characteristics such as: molecular weight, density, vapor pressure, surface tension, gas deposition velocity, and toxicity endpoints, as well as other material property choices such as “secondary evaporation” allowing for adsorbed and/or absorbed material to re-enter the atmosphere and continue to transport downwind. HPAC utilizes these material files, along with the source term parameters, meteorological information and transport model, to help calculate the extent and effects of the hazard.

After determining the initial source term (when, where, how much, what physical form, etc.), HPAC employs the Second-order Closure Integrated PUFF (SCIPUFF) model for atmospheric transport and dispersion modeling in order to move the release through the environment. SCIPUFF is an advanced Lagrangian puff dispersion model that uses a collection of Gaussian puffs to represent airborne hazards in an arbitrary three-dimensional concentration field. These puffs are treated as tensors in a Lagrangian numerical framework. The model incorporates an algorithm for splitting and merging puffs and accounts for wind shear effects. Turbulent diffusion is modeled based on second-order turbulence closure theory, which relates the dispersion rate to velocity fluctuation statistics. In addition to calculating average concentration values, the model provides a prediction of the statistical variance in the concentration field resulting from random fluctuations in the wind field. This methodology allows HPAC to stochastically model downwind hazards at very low levels with minimal computer resources. The variance can be used to estimate a probability distribution for the predicted value. The SCIPUFF model calculates dense gas dynamics, which is important and relevant for chlorine releases, and uses an algorithm that computes effects such as settling and spreading of the plume laterally as a result of interaction of the plume with the ground surface. The dense gas model also considers collapse of dense gas clouds (slumping) and suppression of vertical diffusion resulting from stable buoyancy distribution.

A variety of weather inputs can be used with HPAC including: single wind vector or vertical wind profile inputs, time-varying meteorology, imported or user-created weather files, and data imported from the remote Meteorological Data Service (MDS) operated by DTRA. The model can accommodate surface observations (usually made hourly), upper air observations (typically made every 12 hours), and numerical weather predictions. HPAC contains two integrated mass-consistent wind models: Stationary Wind Fit and Turbulence (SWIFT) and Mass-Consistent SCIPUFF (MC-SCIPUFF). The preprocessors calculate a wind field by interpolating the meteorological data while referencing the project terrain file. They support the input of wind observations from multiple meteorological sites during the same scenario. SWIFT is the default wind model but cannot be used when a dimension of the project domain exceeds 1,000 km (621 miles). The models are mass consistent, which ensures there are no mass sources or sinks and that air flows around or over but never through terrain features.

HPAC includes approximately 1-km (0.62 miles) resolution, depending on latitude, terrain elevation, and land cover data that describe three-dimensional topographic variations and account for agent absorption characteristics and surface albedo. Note: HPAC may also utilize the terrain topology embedded in some weather products when using imported MDS weather. Terrain will affect how plumes of hazardous material move through the environment, especially dense gas releases such as what is modeled here for chlorine. In addition, terrain and land cover change the assumed canopy height and surface roughness throughout the entire region of interest, which in-turn affects the transport and dispersion characteristics of the evolving incident. Note that HPAC has a limited capability to explicitly resolve buildings in an urban environment, but generally can be made “building aware” by utilizing the Urban feature within HPAC, an urban transport and dispersion capability, not used here.

Finally, HPAC contains a wide array of options for representing predictions graphically and in text form and supports the output of concentration time histories at a large number of user-defined locations. HPAC is distributed with a 1-km (0.62 miles) resolution population database and can calculate affected populations. It can also output casualty tables with the best estimate, worst-case estimate, and 10% risk estimate of casualties for select chemical and biological warfare agents. Although available, the HPAC output from the scenarios presented in Pamphlet 74 do not include casualty estimates due to sensitivity concerns and because they are site-specific and generic scenarios are given here. However, the expected concentrations, dosages, and ranges predicted for each scenario are presented.

HPAC User GUI:

HPAC has a Graphical User Interface (GUI) that assists in setting up runs and visualizing their output. An example of the HPAC 6.4 GUI is provided in Figure A1. An HPAC project is created by selecting an incident source model and positioning the source, then defining weather and selecting terrain, urban, and other modeling options. Typical run times range from tens of seconds to tens of minutes depending on the fidelity, complexity, and type of model being run.

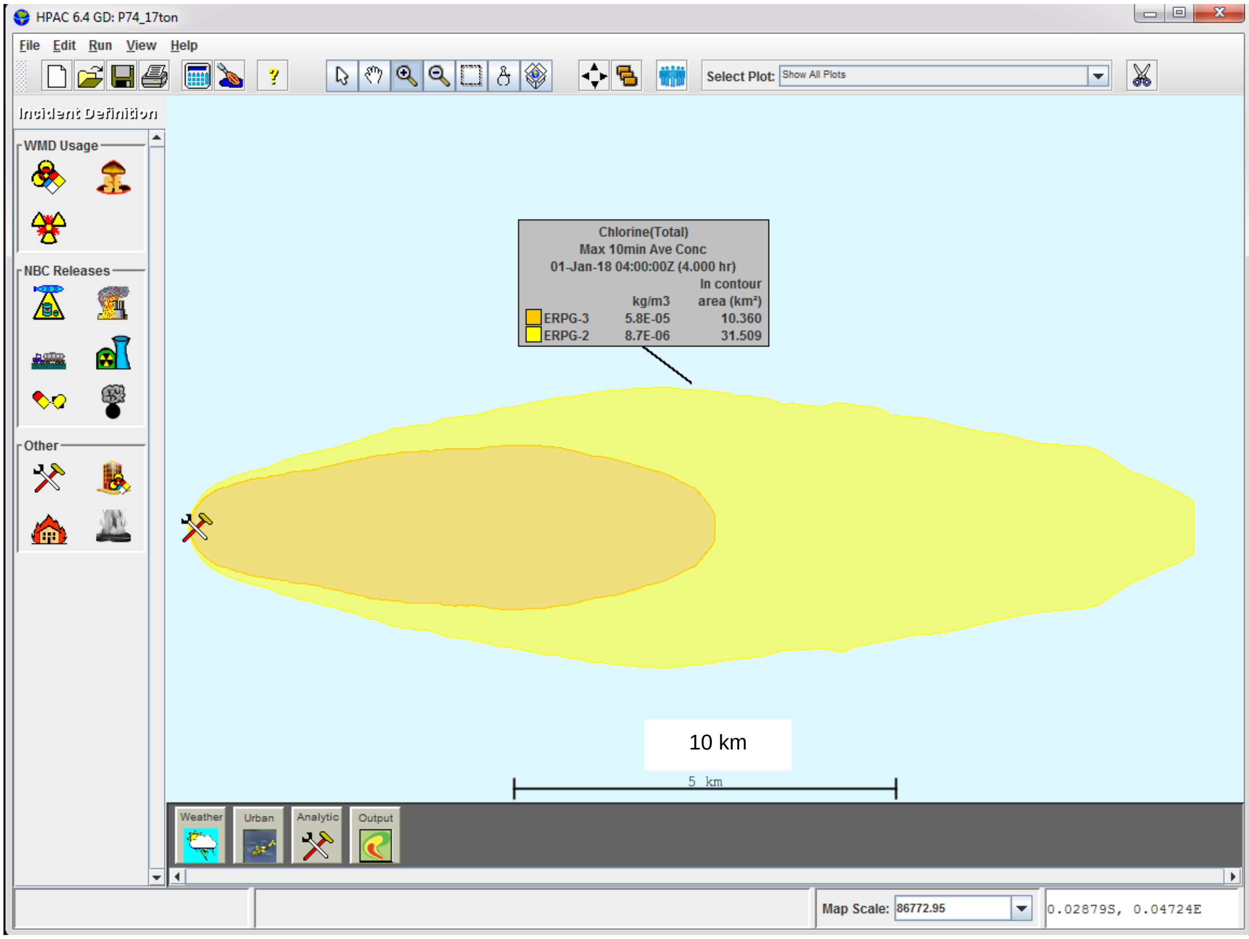

Figure A1 - HPAC Graphical User Interface showing the use of the analytical incident source module.

The incident definition function within HPAC called the Analytical Incident module was used to specify the release conditions in each of the scenarios modeled herein. In Figure A1, an example of the scenario output contour plots is shown. The tools icon at the far left of the filled contours is the icon that the analytical incident source module uses to represent the release location. The analytical incident source module includes the ability to model instantaneous releases, continuous releases at a constant rate, evaporation from liquid pools, emission from moving sources, and stack releases. It also has the ability in some of the sub-models to allow for defining the phase partitioning between liquid and gas for a release event, as well as define a droplet distribution if an aerosol is present. HPAC does not presently account for chemical reactions explicitly, but it can remove material from the plume at a steady rate (gas deposition velocity). New findings from the analysis of chlorine releases in the Jack Rabbit I and II projects were used to define source input parameters and also include the removal of chlorine through reactivity with the soil. *(6.1.12* and *6.1.13).*

Model results will vary based on the inputs and modeling software used. A group of researchers compared modeling results from six different software packages for chlorine releases. Refer to *7.1* for more information.

7. REFERENCES

7.1 APPENDIX A REFERENCES

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APPENDIX B – UNDERSTANDING DISPERSION MODELING RESULTS

The results of dispersion modeling for release scenarios are usually presented in summary tables or graphs (e.g., concentration vs. distance, concentration vs. time, etc.). When there is a chlorine release from a given "source" (e.g., chlorine cylinder, rail tank car, etc.), emergency response personnel need to know the concentration (typically expressed in parts per million or ppm) of chlorine in the atmosphere at various "receptor" sites (e.g., locations of homes, businesses, etc.).

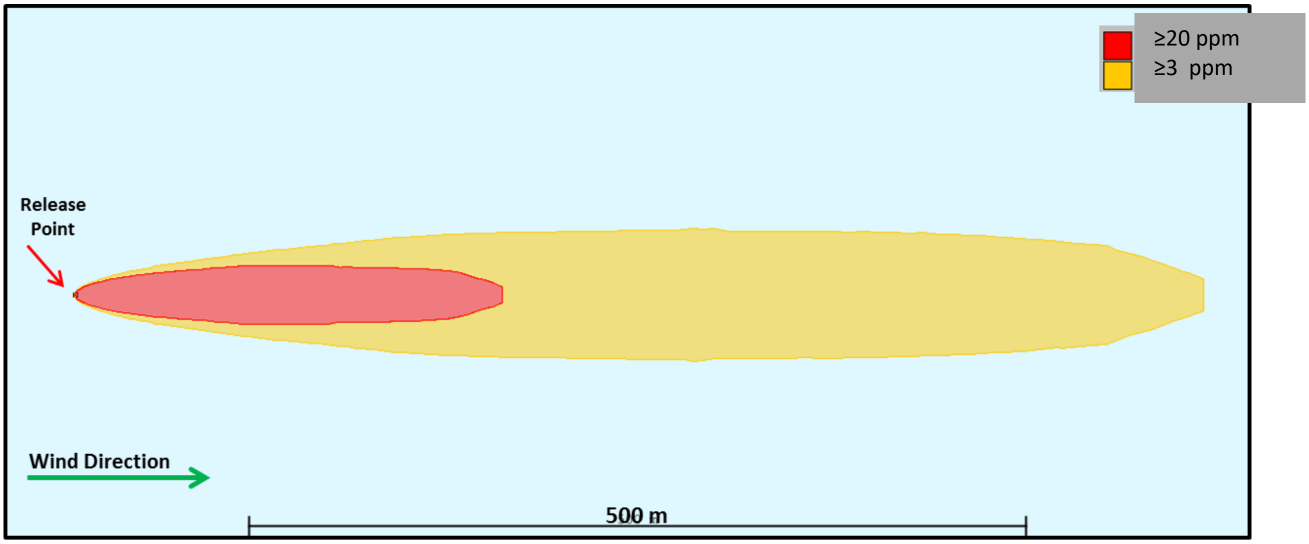
For easier understanding, the results of any given release scenario may be graphically presented, where the particular graphical format(s) selected for use will depend on the questions that need to be answered.

In order to facilitate the user's selection and use of the appropriate information, sample graphical outputs for the HPAC model used in this pamphlet are presented with some explanatory notes.

Representation of toxic endpoint (0.0087mg/L = 3 ppm) is equivalent to 3 ppm shown in hazard footprint.

Note: all the examples described are actual HPAC model outputs for Scenario 5.6. (Alternative-Case 1-Ton Valve Failure (gas) Scenario – D Stability; 1-ton container gas valve remains open. Mitigation to stop the release occurs within 30 minutes)

B.1 FOOTPRINTS



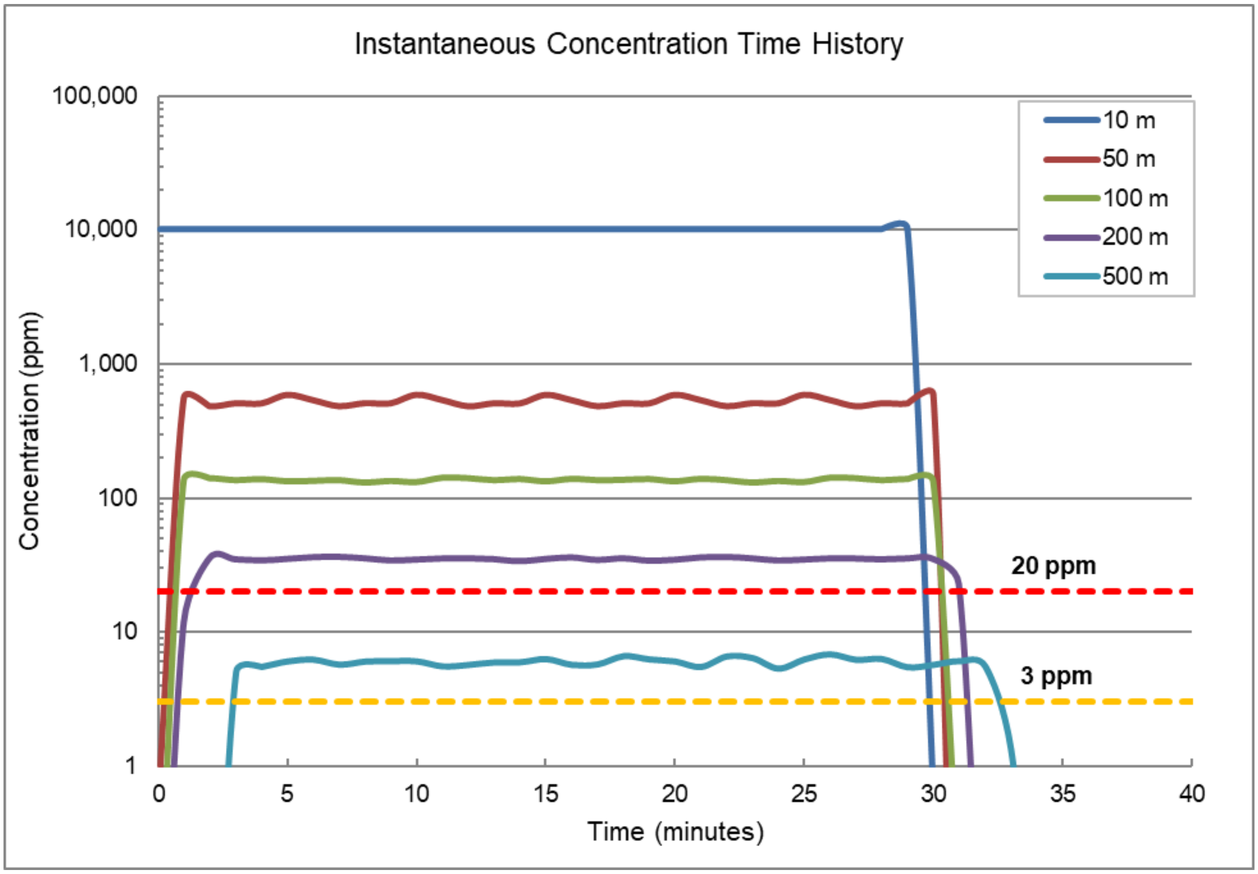
Hazard Footprint	≥3 PPM*	≥20 PPM*
	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 3 ppm or higher)	(For Pamphlet 74, defined as inhalation exposure of 10-minute averaged concentration of 20 ppm or higher)
Maximum Downwind Extent		
Miles	0.45	0.17
Kilometers	0.73	0.28
Maximum Crosswind Width		
Miles	0.049	0.022
Kilometers	0.079	0.035
Area Coverage		
Sq. Miles	0.017	0.003
Sq. Kilometers	0.045	0.008

***** – Although ERPG levels are defined for 60-minute exposure, 10-minute exposure is applied here as a more conservative criteria.

When viewing a footprint, one should think of the plot as the total impact zone resulting from the entire chemical release event, assuming no variation in wind speed or wind direction. This footprint shows the area downwind from the point of release where the chlorine concentration could reach or exceed the ten minute averaged concentration levels of concern (3 ppm and 20 ppm).

This footprint shows the expected maximum downwind distance for such a 20 ppm exposure is 0.17 miles (0.28 kilometers) from the release. Also, the maximum crosswind distance for such exposure 0.022 miles (0.035 kilometers).

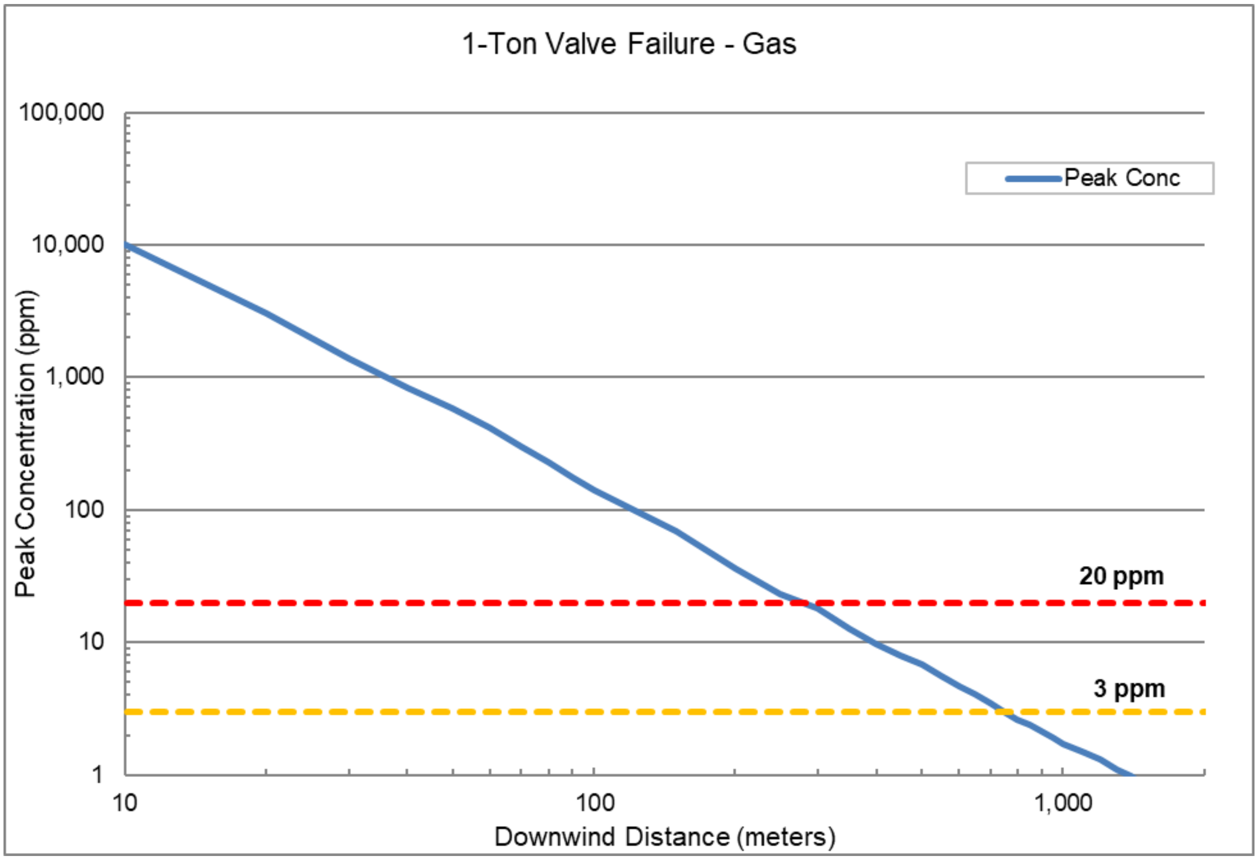
B.2 INSTANTANEOUS CONCENTRATIONS ON THE CLOUD CENTERLINE AS A FUNCTION OF TIME AT VARIOUS DOWNWIND DISTANCES



In looking at the model output depicted above, it can be seen that at 328 feet (100 m) downwind from the source, the instantaneous chlorine concentration is expected to peak at about 140 ppm. At 1,640 feet (500 m) downwind from the source, it is expected to peak at about 6 ppm. This output also provides an estimate of the time after the release that a point downwind will be affected. Note, that the 10-minute average concentration of 20 ppm or above footprint in section B.1 measures 0.17 miles (898 feet or 273 meters) downwind and 0.022 miles (116 feet or 35 meters) crosswind. No crosswind distances are represented on the "Instantaneous Concentration Time History" graphs. These are all on the cloud downwind centerline.

For each scenario, two instantaneous concentration time history graphs are provided for ease of use when presenting various distances downwind.

B.3 PEAK CONCENTRATION AS A FUNCTION OF DISTANCE



This graphical output shows the instantaneous, maximum or peak concentration predicted at a specific distance downwind from the point of release. For example, if one wanted to know the maximum distance that the concentration is expected to reach 10 ppm the graph shows this distance is about 400 meters or 1312 feet. Note: Both axes are shown on a log scale.

It should be noted that real-world concentrations will exhibit more variability. The above HPAC-predicted curves are very smooth and linear. As mentioned earlier, these HPAC runs are assuming constant wind speed and wind direction during the modeling period.

APPENDIX C – JACK RABBIT HISTORY AND INFLUENCE

HISTORY

The Department of Homeland Security (DHS) Science and Technology (S&T) Chemical Security Analysis Center (CSAC), whose mission is to provide analysis and scientific assessment of the chemical threat against the American public, began an analysis in 2008 of toxic chemicals in transportation within the U.S. Based on their research of the toxicity and total volume transported annually of many chemicals in commerce, S&T CSAC initiated Project Jack Rabbit which involved a series of field release experiments with chlorine and anhydrous ammonia to support and inform hazard prediction modeling, emergency response, and mitigation strategies for large-scale toxic inhalation hazard chemical releases.

In 2010, the Jack Rabbit I trials were sponsored by DHS S&T and the Transportation Security Administration (TSA), and led by S&T CSAC with an interagency team of partners. The Chlorine Institute did not participate in Jack Rabbit I. The project involved outdoor release of 1- and 2-ton quantities of chorine and anhydrous ammonia in 10 successful trials at Dugway Proving Ground, a remote U.S. Army facility in Utah. The objectives of the trials were to:

- Execute a reduced-scale test of each of two chemicals (chlorine and anhydrous ammonia) to identify potential vulnerabilities before full test conduct.
- Develop and evaluate a mechanism for the controlled, rapid release of liquefied, pressurized gases from containment to approximate the conditions hypothesized to generate a persistent vapor-aerosol cloud in a 90-ton railcar release.
- Characterize the vapor/aerosol cloud movement, behavior, and physiochemical characteristics and compare those characteristics with known observations and testing of large-scale releases of the testing materials.
- Determine if anhydrous ammonia can potentially act as less expensive and less dangerous dense gas for studying the component phenomena of large scale releases of dense gas TIH materials.
- Field and evaluate instrumentation that can be used for the study of the large-scale release of the testing materials, and develop and evaluate testing methodology for future additional and potentially larger-scale tests.

The data from these experiments was used to support extensive research, studies, and analyses in hazard prediction and dispersion modeling in the years following the tests.

In 2015 and 2016, release trials continued in the Jack Rabbit II (JR II) testing program. JRII was sponsored by the DHS S&T, the Department of Defense (DOD) Defense Threat Reduction Agency (DTRA), Transport Canada and Defence Research and Development Canada (DRDC). JR II was conducted at Dugway Proving Ground, UT, and led by S&T CSAC with an interagency team of partners.

The objectives expanded on the original Jack Rabbit:

- Improved chemical hazard modeling
- Better planning and resilience for release incidents
- More efficient and effective emergency response
- Improved mitigation measures to reduce the impact to affected populations and infrastructure
- Improved HazMat training and safety

In Phase 1 of JR II conducted in 2015, the amount of chlorine release increased per trial, ranging from five to nine tons. The testing site at Dugway Proving Ground was also staged as a mock urban environment, with temporary buildings arranged in a grid. Multiple facets of a release were studied, including downwind chlorine concentrations, building infiltration and shelter-in-place studies, emergency vehicles and equipment exposure testing, and studies of chlorine reactions with environment and surfaces.

Phase II of Jack Rabbit II was conducted the following summer in 2016. During this set of tests, the release sizes again increased to ten and twenty tons. The mock urban environment was removed and all releases occurred on the salt flats at Dugway Proving Ground.

CI's involvement in the Jack Rabbit II, Phases I and II project consisted of donating chlorine and caustic (for scrubbing) to conduct the tests and providing industry volunteers to conduct the safe bulk transfer of material in the desert. The industry volunteers were professionals who regularly use and/or produce chlorine and are experienced in the safe transfer of chlorine from one vessel to another. There were select CI members who were paid for their chlorine-handling services. These CI members worked for emergency response and environmental remediation companies, not chlorine-using or chlorine-producing fixed facilities.

All data collection and analysis of findings were sponsored by DHS, DTRA and Transport Canada and conducted by government laboratories, their contractors, international collaborators and academic partners.

JACK RABBIT'S INFLUENCE ON PAMPHLET 74

Jack Rabbit I demonstrated what had been observed in real-world incidents (such as Macdona, Texas and Graniteville, South Carolina); namely, that the size of a chlorine cloud was predicted to be significantly larger by modeling software than what was actually observed at those locations. This is due to chlorine's high reactivity with organic matter in the environment, such as grasses, trees, shrubbery, carpet, etc. As chlorine is exposed to organic material, it reacts and forms less toxic products, thus reducing the size of the chlorine cloud.

The trials in Jack Rabbit II were expanded to include more ambient air monitors to better measure the chlorine cloud's size and concentration gradient. Plans to measure reactivity on various controlled surfaces were not able to be executed however, and the results only apply to desert playa as found at Dugway. Chlorine is only minimally reactive with the desert playa.

With the data collected from Jack Rabbit, modelers and scientists at CSAC were able to approximate a reactivity term within the modeling software suitable for the desert playa site. This term simulates chlorine's reactive nature to better predict the size and residence of a chlorine cloud. Continuing research sponsored by DHS has the potential to extend such modeling to all other soil or vegetated sites.

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APPENDIX D – SAFER/TRACE™ AND ALOHA FLOWRATE CALCULATIONS

The worse-case release rates used the EPA required source term considerations (i.e. total volume released in gaseous form over 10 minutes). In contrast, SAFER/TRACE™ was used for alternate case scenarios to generate source terms in the previous editions of CI Pamphlet 74. The SAFER/TRACE™ source terms were reviewed for this edition using several methods. In a few cases ALOHA® Version 5.4.7 generated source terms to replace the original source terms used in previous editions. The following discussion from the previous edition references the SAFER/TRACE™ source term modeling approach which is still valid whether the source term was generated using SAFER/TRACE™ or ALOHA®.

The following scenarios used a flow rate from ALOHA®:

- 1-inch liquid piping failure
- 150-lb valve failure
- Ton liquid valve failure

All other scenarios used a flow rate calculated from SAFER/TRACE.

Estimation of Leak Rates

The first stage in the development of many chemical accidents, which leads to hazardous situations, is the generation of a vapor cloud (toxic or flammable in nature). This cloud may consist of vapor from a pool or liquid droplets suspended in the vapor. The crucial variables at this stage are the amount (or rate) of discharge and the thermodynamic properties (temperature, pressure, state, etc.) of the stream.

In the case of a tank rupture, SAFER/TRACE™ algorithms take into account the chemical properties, environmental variables (atmospheric pressure and ambient temperature), tank specifications (length, width, height, or diameter), rupture geometry (circular, rectangular, smooth, or jagged edges), pipe length, and the containment variables (pressure, temperature).

SAFER scenarios are categorized into four distinct groups:

a. Gas flow through a rupture

This module has capabilities to model sonic and subsonic flows. The critical pressure ratios are determined as a function of tank dimensions, rupture size, and chemical properties. If the critical pressure ratio exceeds P(atm)/P(tank), sonic flow occurs or otherwise exists. Depending upon each region (sonic or subsonic), the SAFER/TRACE™ calculates an appropriate release rate. For the subsonic region, isentropic flow is assumed to occur. The SAFER/TRACE™ algorithm carries out an iterative process by which a sonic flow is reduced to subsonic (as the pressure decreases) and subsequently is reduced to atmospheric pressure.

b. Two-phase flow-through rupture

In two-phase flows, the volumetric void fraction of vapor in the liquid is first calculated. Subsequently, the model estimates whether two-phase subsonic or two-phase sonic flow occurs. The critical pressure ratio in this case is determined as a function of the stagnation quality.

c. Liquid flow-through rupture

For chemicals whose boiling point is above ambient temperature, the flow is assumed to be incompressible. The flow rate is dependent upon the area of the hole, discharge coefficients, and height of liquid above the hole. The program calculates the flow rate in increments until the liquid level reaches to the top of the hole or until the hole pressure approaches atmospheric pressure and air is ingested.

d. Liquid flow through sheared pipe

The chemical mass in the tank is divided into several increments so that each increment is equal or greater than the pipe holdup. During the discharge of each element, the tank thermodynamic variables are assumed constant. A two phase flow model uses a “trial and error” procedure to find the correct initial pressure into the pipe until the maximum discharge or choked flow is obtained.

If the pressure differential approaches zero, the SAFER/TRACE™ algorithm has an air ingestion formulation. The volumetric flow of ingested air is set to equal the equivalent volume of out-flowing chemical until the liquid level reaches the bottom of the hole, and subsequently, the flow stops.

When the pressure in the vapor space falls below the vapor pressure of the chemical at the tank temperature, evaporation of the liquid occurs. This process results in cooling the contents of the tank.

Heat transfer considerations account for the above-described evaporation process and by the heat exchange with the ambient atmosphere. The balance of these processes determines the temperature of the contained chemical and, consequently, the chemical and physical properties.

The above formulations are used to develop a time history for the release rate, temperature, pressure, void fraction and pressure of the tank. These functions are then used by other SAFER/TRACE™ algorithms (described subsequently) to set up the source term for dispersion.

APPENDIX E – DRY DEPOSTION

Chemical species suspended in the atmosphere (e.g., gases, vapor, particulates) are known to be deposited on materials on the earth's surface including water, vegetation, and buildings or structures, and this removal process is typically modeled as dry deposition. The rate of dry deposition is modeled as being directly proportional to the chemical concentration in air where the proportionality constant is determined by the chemical species and the surface on which the dry deposition occurs; this proportionality constant is termed the deposition velocity. All other things equal, the deposition rate increases for higher deposition velocities. Early work on dry deposition typically considered only low concentrations of airborne chemicals typical of air pollution, so these assumptions were reasonable and effective. Dry deposition can model many different phenomenon (e.g., adsorption and chemical reaction), but once deposited, chemical species that react irreversibly will not re-enter the atmospheric flow which will reduce the impact of a hazardous chemical. Chlorine and nitric acid have similar behavior when reacting with environmental materials, but more experimental investigation of nitric acid has been conducted because of its role in the atmosphere's nitrogen cycle.

Table E.1

Measured Nitric Acid Deposition Velocities (cm/sec) for Various Terrains	
Dry savanna (Sahel)	0.34 – 0.61
Grass (Japan)	0.3 - 3.2
Forrest, grass (Canada)	0.61 - 2.1
Prairie (Illinois)	1.0 - 4.7
Forest (Japan)	1.2 - 11.7

The available data for nitric acid illustrates the wide range of deposition velocity that can be observed for different surfaces (Table E.1). In general, as the amount of vegetation increases, the deposition velocity will also be higher. The table values also show that the rate of dry deposition of nitric acid on grass could vary by over an order of magnitude (for a constant airborne concentration of nitric acid) because the deposition velocity can range from 0.3 to 3.2 cm/s. Put another way, the table values show that the rate nitric acid can be removed from the atmosphere (and react with surfaces) could vary by over an order of magnitude.

It is worth noting that all of the known data for nitric acid were taken under conditions of low airborne concentrations typical of air pollution. It is also worth noting that dry deposition velocities for nitric acid are considered to be generally much lower during nighttime conditions predominately due to the reduction in atmospheric turbulence.

As discussed above, chlorine behaves in a similar manner when it encounters various surfaces (*6.1.2*), but less experimental work has been conducted using chlorine in comparison to nitric acid. Chlorine will react irreversibly with many environmental materials but can be re-emitted in low concentrations under some conditions for some surfaces (such as glass or water). All currently available chlorine data has been collected for concentrations of 50 ppm or less. (As a reference, the default deposition velocity used in HPAC is 0.3 cm/s for chlorine.)

Although the traditional approach of modeling surface reactivity as dry deposition was effective for modeling the impact of air pollution, issues can be encountered when using a simple dry deposition model to assess the hazards of a chlorine release. In simple dry deposition models, the rate of deposition (or reaction) does not depend on the amount of chlorine already reacted with a surface. For deposition onto a water surface, there is a well-documented limit to the amount of chlorine which can react with a fixed volume of water. There is preliminary evidence that such a limit exists for other solid surfaces as well. In the hazard assessment process for a chlorine release, it could be possible to predict an unreasonably large amount of chlorine removal (reaction with surfaces) using a simple dry deposition model which does not include a limit on the amount of chlorine that can react with a material. Current experimental work is ongoing to improve the understanding of chlorine reactivity with environmental materials to quantify the maximum amount of chlorine selected materials can remove from the atmosphere.

Consistent with observations of low chlorine reactivity from the Jack Rabbit II testing on bare salt playa at Dugway Proving Ground, Utah, a deposition velocity of 0.04 cm/s was used in this work to represent those conditions. This is a conservative assumption because it leads to a minimum removal of chlorine from the cloud. More deposition and hence lower chlorine concentrations will occur when there is more vegetation or soil with organic content present.

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