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Shelter-In-Place: Indoor Exposure Assessment During an Airborne Chemical, Biological, Radiological, and Nuclear (CBRN) Event

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SHELTER-IN-PLACE: INDOOR EXPOSURE ASSESSMENT DURING AN AIRBORNE CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR (CBRN) EVENT

THESIS

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AFIT/GIH/ENV/09-M02

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Wright-Patterson Air Force Base, Ohio

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AIRBORNE CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR
(CBRN) EVENT

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Industrial Hygiene

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March 2009

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Abstract

The goal of Shelter-In-Place (SIP) is to reduce human exposure to chemical, biological, radiological, and nuclear (CBRN) agents in the event of an accidental or intentional airborne release into the outdoor environment. The Air Force Bioenvironmental Engineering (BE) career field is responsible for providing hazard identification, evaluation, and control capabilities as well as executing health risk assessments to recommend appropriate courses of action to commanders pre-, trans-, and post-incident. Specifically, BE is responsible for providing sampling, identification, and quantification input to hazard prediction models and supporting evacuation plan development to provide risk-based control recommendations. This also includes providing exposure and contamination control recommendations for sheltered populations. A Gaussian plume model combined with indoor box model was used to test the consequences associated with the delay of implementing SIP procedures. It is imperative that emergency planners pre-plan the installation SIP protocol for likely scenarios identified during the various vulnerability surveys conducted for both on- and off-installation. The decision to shelter-in-place must be made immediately in order to reduce the exposure and depending on scenario, a delay greater than one minute can significantly increase the exposure resulting in additional casualties presenting at the local medical treatment facility.

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Acknowledgments

I would like to thank my wife for her support and understanding during the graduate school process. I would also like to thank my thesis advisor for his support and guidance throughout the course of this thesis effort.

Robert D. Schmidtgoessling

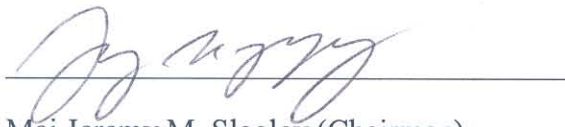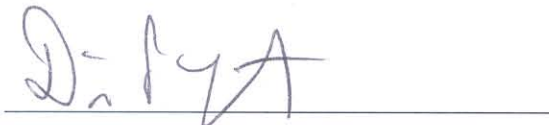# Table of Contents

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SHELTER-IN-PLACE: INDOOR EXPOSURE ASSESSMENT DURING AN AIRBORNE CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR (CBRN) EVENT

I. Introduction

Background

The goal of Shelter-In-Place (SIP) is to reduce human exposure to chemical, biological, radiological, and nuclear (CBRN) agents in the event of an accidental or intentional airborne release into the outdoor environment. In the event of an airborne release of a CBRN agent, the U.S. Department of Homeland Security (DHS) recommends expedient SIP when evacuation is not immediately possible. [1] Expedient SIP is the process used to seal a chosen room to create a temporary barrier between individuals and the contaminated air outside. The process involves using plastic and duct tape to help seal windows, doors, and air vents to reduce air infiltration into room. SIP also involves turning off fans, forced air conditioning and heating systems.

Recent studies have shown that sheltering-in-place in residential districts can provide adequate protection against hazardous material during short-term accidental and intentional releases [2] [3]. But, it may not always be possible to properly SIP on an Air Force installation, which consists of industrial, administrative, and residential districts. In the event of an accidental or intentional airborne release, Air Force personnel may

receive excessive exposures due to inadequate implementation of sheltering or improper evacuation resulting in increased expected casualty rates.

The Air Force Bioenvironmental Engineering (BE) career field is responsible for providing hazard identification, evaluation, and control capabilities as well as executing health risk assessments to recommend appropriate courses of action to commanders pre-, trans-, and post-incident. [4] Specifically, BE is responsible for providing sampling, identification, and quantification input to hazard prediction models and supporting evacuation plan development to provide risk-based control recommendations. This also includes providing exposure and contamination control recommendations for sheltered populations. [5] There are a few shortfalls associated with execution of this capability, but the impact severity is extensive to major because failure to control hazards may lead to unacceptable potential for impact to personnel health. [6]

SIP is a relevant topic, because recent history has shown the need for sheltering-in-place due to accidental release of hazardous materials in residential districts. On 11 April 2003, an explosion at the D.D. Williamson & Co., Inc plant in Louisville, Kentucky, where food-grade caramel was manufactured, damaged the western end of the facility and released 26,000 pounds of ammonia killing one worker and forcing the evacuation of 26 residents with 1,500 people required to SIP. [7] Similarly, On 28 June 2004, a Union Pacific Railroad train collided with another train in San Antonio, Texas, resulting in approximately 9,400 gallons of liquefied chlorine being released. Three fatalities and sixty-six casualties resulted from the accident. [8]

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With society's dependence on the chemical industry to provide goods, history has shown that both intentional and accidental releases happen. The needs for tools that allow incident commanders predict consequences associated with evacuation and sheltering decisions.

Problem Statement

Thesis Topic

This research attempts to evaluate the effectiveness of SIP on an Air Force installation by looking at the feasibility of combining outdoor dispersion models with modified industrial hygiene exposure models to estimate indoor airborne exposures to test the consequences associated with the delay of implementing SIP procedures.

Hypothesis

This research hopes to show that the models developed for this thesis are consistent with those produced by commercial modeling software, such as in ALOHA dispersion software by the U.S. EPA. The null hypothesis is that the thesis model peak concentration is not within 15% of the results reported by ALOHA. A comparison of the time at which the concentrations peaks between the thesis model and ALOHA is not valid test, because results of the peak time must be read off an ALOHA plot, which is insufficiently accurate.

Equation 1-Hypothesis Test No. 1

$$H_O = Thesis\ model\ does\ not\ match\ ALOHA\ \ peak\ concentrations\ within\ 15\%$$

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Equation 2-Alternative Hypothesis Test No. 1

$$H_A = Thesis\ model\ does\ match\ ALOHA\ peak\ concentrations\ within\ 15\%$$

Thesis Goal

The goal is to provide a tool to base level BE personnel for use in fulfilling their emergency response roles, in support of evacuation plan development and to provide risk-based control recommendations to the Incident Commander. An effective risk-based control recommendation must consider the consequences, in order to assign relative risk and to choose the best option.

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II.   Literature Review

The Department of Transportation (DOT) states that SIP should be used when evacuating the public would cause greater risk than staying in place, or when an evacuation cannot be performed. The DOT further states that in-place protection may not be the best option for the following situations: (1) when the gas or vapors are flammable; (2) if it will take a long time for the contaminant to clear the area; or (3) if buildings cannot be closed tightly. [9]

A key aspect of SIP risk assessment is the time delay to SIP implementation. A review of nine experiments was conducted to look at the performance of men and women of different occupations constructing shelters in a residential test house. Participants were allowed up to 60 minutes to construct a shelter with provided plastic sheeting, duct tape, and DHS guidance. Participants' ages ranged from 22 to 64, with occupations ranging from homemaker to chemist. The approximate time to construct the shelters ranged from 20 minutes to 60 minutes, with 35 minutes being the mean time. Depending on the temperature differences between the indoors and outdoors, the protection factors for the facility ranged from 1.3 to 539. [10] The protection factors were a determined as the ratio of outdoor concentration to indoor concentration as a measure of infiltration into the shelter.

The starting point for estimating the interior contaminant concentration modeling is the estimation of contaminant concentrations at the building exterior via atmospheric modeling of the contaminant plume.

Atmospheric Modeling

To understand how to model the fate and transport of CBRN agents within the environment, first the atmospheric conditions and meteorology must be understood.

Meteorological and Atmospheric Effects

The atmospheric conditions and meteorological effects play an important role in contaminant transport in the atmosphere. The air motion in the lowest layers of the troposphere, which is adjacent to the earth crust, is a solid boundary of variable temperature and roughness, resulting in turbulence. This turbulence is responsible for the transport of heat, water vapor, and agents from the surface to the atmosphere. Turbulent flows are defined as irregular and random which cause the velocity components (profiles) of the air at any given location to vary randomly with respect to time.

The stratum near the surface of the earth can be divided into three layers: the surface layer, Ekman layer, and free atmosphere. The surface layer is immediately adjacent to the surface and typically extending up to 30 to 50 meters above the surface. The vertical turbulent fluxes of momentum and heat are assumed constant with respect to height. The Ekman layer is defined as the transition layer between the surface boundary layer of the atmosphere, where the shearing stress is constant, and the free atmosphere.

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The free atmosphere is then defined as the portion of the earth's atmosphere, in which the effect of the earth's surface friction on the air motion is negligible and is treated as an ideal fluid [11]

In meteorological applications, the surface elements causing roughness is usually so closely distributed (i.e. grass, crops, bushes, etc.) that only the height of the roughness elements and not their spacing is important. This is why the roughness is characterized by a single length parameter. The surface is considered smooth if the roughness elements are sufficiently small to allow the establishment of a laminar sublayer in which they are submerged. A rough surface is one where the elements are high enough to prevent laminar flow. Table 1 shows common surfaces and the associated roughness length.

Table 1-Roughness Lengths for Surfaces

Type of Surface	Roughness Length (z_o), meters
Lawn or Grassland	0.01
Fully Grown Root Crops	0.1
Tree Covered or Light Residential	1.0
Cities	3.0

The temperature difference between a parcel of air and the air surrounding it determines the degree of stability of the atmosphere. This temperature difference causes the parcel to move up or down vertically. Four conditions are used to describe this movement and the general stability of the atmosphere. In stable conditions, this vertical movement is discouraged, whereas in unstable conditions the air parcel tends to move upward or downward and to continue that movement. When conditions neither encourage nor discourage air movement beyond the rate of adiabatic heating or cooling, they are

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considered neutral. An inversion occurs when conditions are extremely stable and cooler air near the surface is trapped by a layer of warmer air above it. [12]

In 1961 Pasquill developed the concept of stability classes to define the atmospheric stabilities based on routine observations. Table 2 below is a reproduction of the Pasquill stabilities. [13]

Table 2-Estimation of Pasquill Stability Classes

Surface Wind Speed at 10 m (m/sec)	Solar Radiation			Night Time Cloud Cover Fraction	
	Strong	Moderate	Slight	$\geq 4/8$	$\leq 3/8$
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

As represented in stability class table above, classes A, B, and C refer to daytime hours with unstable conditions. Class D is representative of overcast days or nights with neutral conditions. Finally classes E and F refer to nighttime, stable conditions and are based on the amount of cloud cover. Once an understanding of how the atmospheric processes such as the movement of air and the exchange of heat dictate the fate of pollutants as they go through the stages of transport, dispersion, transformation and removal, then the proper dispersion model can be chosen.

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Dispersion Models

Models are approximate representations of real environmental systems. There are several types of atmospheric contaminant dispersion models. These models are a set of mathematical equations that predict concentrations due to plume dispersal and impaction. These models can incorporate dispersion estimates and various meteorological conditions including temperatures, wind speeds, stabilities, and topography.

There are four generic types of dispersion models: Gaussian, numerical, statistical, and physical. [14] The Gaussian models use the Gaussian distribution equation of the plume in the vertical and horizontal directions under steady state conditions.

Numerical models are generally used for urban locations that involve reactive pollutants, but require extremely detailed source and pollutant information. An example of a numerical method of is the box model. The box model assumes that the atmosphere is one large homogenous volume with releases entering the box uniformly and instantaneously mixed throughout.

Statistical models are used when scientific information about the chemical and physical processes of a source is incomplete or vague. The statistical models can be mathematically described in the spatial and temporal distribution by the Eulerian and Lagrangian approaches. The Eulerian approach is the common way of treating the heat and mass transfer and the Lagrangian approach is used to describe changes in concentration relative to the moving fluid. [11]

The Lagrangian particle model divides the release into thousands of tiny masses that are individually tracked as these masses are stochastically transported downwind.

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The Eulerian grid model divides the atmosphere into a three-dimensional array of rectangular grids within which mixing are uniform and instantaneous.

Physical models may also be known as computational fluid dynamic (CFD) models. The CFD models provide complex analysis of fluid flow and are based on conservation of mass and energy and Newton's laws of physics. The Navier-Stokes equations are used as the governing equations for Newtonian fluid dynamics. [15]

Over recent years, numerous software packages based on the four generic types have been developed to address a variety of applications. Though, not all packages are useful for emergency response. Several software packages suitable for use in emergency response are listed below.

Atmospheric Modeling Software

Atmospheric modeling software has been developed by federal and state agencies utilizing the four basic model types to assess risk to populations. The Hotspot Health Physics codes were created to provide emergency response personnel and emergency planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. The model software is also used for safety analysis of facilities handling nuclear material. [16]

The Area Locations of Hazardous Atmospheres (ALOHA) software is an atmospheric dispersion model used for evaluating releases of hazardous chemical vapors. ALOHA allows the user to estimate the downwind dispersion of a chemical cloud based on the toxicological and physical characteristics of the released chemical, atmospheric conditions, and specific circumstances of the release. ALOHA is a part of the Computer-

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Aided Management of Emergency Operations (CAMEO) suite developed by EPA's

Office of Emergency Management (OEM) and the National Oceanic and Atmospheric

Administration (NOAA) Office of Response and Restoration, to assist front-line chemical

emergency planners and responders. [17]

The Hazard Prediction and Assessment Capability (HPAC) software, developed

by the Defense Threat Reduction Agency (DTRA), is an atmospheric dispersion model to

quickly predict the effects of hazardous material released into the atmosphere and its

impact on civilian and military populations. [18] HPAC uses an advanced Lagrangian,

Gaussian puff model that uses second-order turbulence closure techniques to relate the

dispersion rates to measurable turbulent velocity statistics called SCIPUFF. [19]

The U.S. Naval Surface Warfare Center (NSWC) developed the Chemical and

Biological Agent Vapor, Liquid, and Solid Tracking (VLSTRACK) computer model to

predict atmospheric dispersion. VLSTRACK is a Lagrangian transport and dispersion

model employing the Gaussian puff method, in which a collection of three-dimensional

puffs represents an arbitrary concentration field. [20]

As numerous dispersion models have been developed to address a variety of

atmospheric applications, there has been an equal amount of effort spent toward

modeling the exposures of indoor settings.

Indoor Exposure Modeling

Industrial hygienists use physical-chemical models to predict current and future

exposures as well as historical exposures that cannot otherwise be reconstructed.

Typically a tiered approach is used starting with very simple models moving to more and

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more complicated models. Such models include simple saturation models, the box model and then dispersion models. [21]

There are four common complex models that attempt to model the contaminant in air within a room. These models are the Well-Mixed Room (WMR), Near Field/Far Field (NF/FF), Turbulent Eddy Diffusion without Advection, and Turbulent Eddy Diffusion with Advection. The WMR model assumes the chemical instantaneously and perfectly mixes throughout the room, such that the concentration is uniform throughout the volume of air. The NF/FF model assumes that the total volume comprises two zones. The near field zone contains the emission source and the breathing zone of the worker of concern and the far field contains the remaining room volume. The turbulent eddy diffusion involves the random motion of parcels of air which carry molecules or particles away from the source with or without an advective air flow along one of the room axes. [22]

Indoor Modeling Software

The Indoor Environment Management Branch of the U.S. EPA has developed an Indoor Air Quality (IAQ) model called RISK computer model. It was designed to allow for the calculation of individual exposure to indoor air pollutants from sources. The RISK is designed to calculate exposure due to individuals, activity patterns, and source use. The model also provides the capability to calculate risk due to the calculated exposure. [23]

The Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) has developed a software package for multizone indoor air

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quality and ventilation analysis called CONTAM. [24] CONTAM is designed to help

determine: 1) Airflows with respect to infiltration, exfiltration, and room-to-room

airflows in building systems driven by mechanical means, wind pressures acting on the

exterior of the building, and buoyancy effects induced by the indoor and outdoor air

temperature difference; 2) the dispersal of airborne contaminants transported by these

airflows; transformed by a variety of processes including chemical and radio-chemical

transformation, adsorption and desorption to building materials, filtration, and deposition

to building surfaces, etc.; and generated by a variety of source mechanisms; and/or 3) the

predictions of exposure of occupants to airborne contaminants for eventual risk

assessment. [25]

The essential piece of information need to effectively within the interior

concentration modeling is the estimation of infiltration and air exchange rates. These

values will ultimately determine the amount of contaminate present indoors.

Infiltration

Infiltration is the term used to describe the natural air exchange that occurs

between a building and its environment when windows and doors are closed. Infiltration

is driven by pressure differences between the inside of the building and the outside air.

The differences in pressure can be caused by wind or temperature differentials. The

infiltration may come from such places as cracks, openings in the building envelope,

plumbing, ducts, and electrical wiring.

The infiltration can also be thought of as "airtightness" of a building. A review

conducted by the National Institute of Standards and Technology (NIST) on airtightness

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of commercial buildings in the U.S. found an average airtightness of 28.4 m^3/h-m^2 at 75 Pa for 201 commercial buildings. This means that there is 28.4 m^3/h of air flow per square meter of above-grade surface area of building envelope. [26]

Office facilities have forced ventilation systems using mechanical air handling systems to induce air circulation by way of fans or blowers. Though less common, office facilities may still use natural ventilation, which involves using open windows and doors to increase circulation.   As SIP may require very quick implementation, other measures of airtightness already published, such as air exchange rates, offer a ready piece of data for use in modeling the transfer of the atmospheric contaminant release to the building interior.

Air Exchange Rates

Air exchange rates in office buildings

The U.S. Environmental Protection Agency (EPA) conducted the Building Assessment Survey and Evaluation (BASE) study. The BASE study was conducted over a five-year period from 1994-1998, to characterize determinants of indoor air quality (IAQ) and occupant perceptions in representative public and commercial office buildings. The study used a standardized protocol to collect extensive indoor air quality data from 100 randomly selected public and commercial office buildings in 37 cities and 25 states. Information collected included the building age, construction features, use, furnishings, renovations, local pollutant sources, and general maintenance. The HVAC systems were characterized regarding maintenance, design features, and the amount and quality of fresh

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air being introduced into the building and indoor occupied area. Environmental measurements included parameters such as light, sound, temperature, and relative humidity as well as pollutant concentrations such as particulate matter, volatile organic compounds (VOCs), biological contaminants, and radon. [27]

A review of the data from the 100 buildings in the BASE study for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) Journal states the mean design supply airflow capacity for all systems was 1.19 cubic feet per minute per square foot of floor area (cfm/ft^2). The mean design minimum outdoor intake was 0.18 cfm/ft^2. The mean ratio of minimum outdoor intake to supply airflow was 0.19 and the mean ratio of supply air to return air was 1.14. The mean air changes per hour (ACH) were 2.00 inverse hours (h^{-1}). [28] The significance of this study is that the mean design criteria can then be used to estimate the air exchanges within a building.

Air exchange rates in residential buildings

Residential buildings are different than commercial buildings, because they are generally much smaller and typically do not have heating and cooling systems that bring in fresh outside air. Residential buildings rely on natural ventilation and individuals opening doors to bring in fresh outside air. Depending upon the building characteristics and environmental conditions, typical exchange rates in residences with normal activities vary from 0.07 to 4.0 ACH. [29] Under ideal conditions, a well-constructed energy efficient home may have an air exchange rate of 0.1 ACH and with strong winds or high temperature differential; the air exchange might be as high as 2.4 ACH. [30]

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Natural Air Exchange Rates

When there is no forced ventilation and the facility or residence is not pressurized by internal events, such as an internal fire, the ventilation will occur by natural effects, such as wind pressure on the building and temperature differences between indoors and outdoors. Two equations can be used to estimate the volumetric flow rate and are listed below. [31]

Equation 3-Wind Pressure Driven Ventilation Rates

$$Q = 88(C_v)(A)(v)$$

where

$$Q = volumetric\ flow\ (ft^3/min)$$
$$C_v = effectiveness\ of\ openings\ (unitless)$$
$$= 0.55\ for\ perpendicular\ winds$$
$$= 0.30\ for\ diagonal\ winds$$
$$A = free\ area\ of\ inlet\ openings\ (ft^2)$$
$$v = wind\ velocity\ (ft/sec)$$

Equation 4-Temperature Driven Ventilation Rates

$$Q = 60(C_D)(A)\left[2(g)(\Delta H_{NPL})\left(\frac{T_i - T_o}{T}\right)\right]^{1/2}$$

where

$$C_D = discharge\ coeficient\ of\ opening$$

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$$= 0.40 + 0.0025(T_i - T_o)$$

$$g = gravitational\ acceleration\ (32\ ft/sec^2)$$

$$A = free\ area\ of\ inlet\ openings\ (ft^2)$$

$$\Delta H_{NPL} = height\ from\ midpoint\ of\ lower\ opening\ to\ neutral\ pressure\ level\ (ft)$$

$$T_i = Indoor\ Temperature\ (R)$$

$$T_o = Outdoor\ Temperature\ (R)$$

$$T = Largest\ of\ T_i\ and\ T_o\ (R)$$

Exposure Limits

Essential to the risk assessment is the selection of an appropriate exposure limit to compare with the estimated contaminant concentration output from the various models. These exposure limits can also be used to forecast the expected casualties. There are many exposure limit sources with varied application intent and underlying assumptions.

Occupational Exposure Limits

Hazardous substance exposure limits can be derived for the general public or for workers exposed to the hazardous substance. The American Conference of Governmental Industrial Hygienists (ACGIH) annually publishes guidelines known as Threshold Limit Values (TLVs®) for use in determining safe levels of exposure to chemicals found in the workplace. TLVs® refer to airborne exposures to chemical substances and represent conditions under which it is believed that nearly all workers

may be repeatedly exposed, day after day, over a working lifetime, without adverse health effects for the conventional 8-hour workday and 40-hour workweek. [32]

The National Institute for Occupational Safety and Health (NIOSH) publishes their Recommended Exposure Limits (RELs).   RELs have been developed for up to a 10 hour workday and 40-hour workweek.   RELs are recommended for workplace exposure limits and appropriate preventive measures to reduce or eliminate adverse health effects and accidental injuries. [33] NIOSH is the federal agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness and is part of the Centers for Disease Control and Prevention (CDC) under the Department of Health and Human Services (DHHS). [34]

The Occupational Safety and Health Administration (OSHA) set enforceable Permissible Exposure Limits (PELs) to protect workers against the health effects of exposure to hazardous substances. PELs are regulatory limits on the amount or concentration of a substance in the air and have been developed for the conventional 8-hour workday and 40-hour workweek. [35] The OSHA mission is to prevent work-related injuries, illnesses, and deaths, and it is part of the Department of Labor. [36]

Military Guidelines

The U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) provides Military Exposure Guidelines (MEGs) for chemicals in air, water, and soil for use during deployments. USACHPPM provides application guidance describing how the MEGs can be used to characterize the level of health and mission risks associated with

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identified or anticipated exposures in the deployment environment. The MEGs are designed by USACHPPM to address a variety of scenarios such as a single catastrophic release of a chemical, temporary exposure conditions lasting hours to days, or for continuous ambient environmental conditions that might be present in a deployed location. Such environmental conditions may include regional pollution, use of a contaminated water supply, or persistent soil contamination where there is regular contact. [37]

Emergency Response Guidelines

The U.S. EPA has published Acute Exposure Guideline Levels (AEGLs) intended to represent threshold exposure limits for the general public to use in emergency exposure periods ranging from 10 minutes to 8 hours. The three levels of severity for AEGLs have been defined as AEGL-1 and AEGL-2, and AEGL-3 and have values for five exposure periods (10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours). AEGL-3 is defined as the airborne concentration above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death. AEGL-2 is then defined as the airborne concentration 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.   Lastly, AEGL-1 is defined as the airborne concentration above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. [38]

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The American Industrial Hygiene Association (AIHA) produces the Emergency Response Planning Guideline (ERPG) values intended to provide estimates of concentration ranges where one reasonably might anticipate observing adverse effects. Three ERPGs have been defined as ERPG-1 and ERPG-2, and ERPG-3 for a one hour exposure period. The ERPG-1 is the maximum concentration below which it is believed that nearly all individuals could be exposed without experiencing other than mild transient adverse health effects or perceiving a clearly defined, objectionable odor. The ERPG-2 is the maximum concentration below which it is believed that nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. The ERPG-3 is the maximum concentration below which it is believed that nearly all individuals could be exposed without experiencing or developing life-threatening health effects. [39] [40]

The Subcommittee on Consequence Assessment and Protective Actions (SCAPA) provides the U.S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) with technical information and recommendations for emergency preparedness. SCAPA has developed Temporary Emergency Exposure Limit (TEEL) values so that DOE facilities could conduct appropriate hazard analyses and conduct consequence assessments for chemicals not covered by AEGLs or ERPGs. SCAPA has defined four TEEL limits. TEEL-0 is defined as the threshold concentration below which most people will experience no appreciable risk of health effects. TEEL-1 is defined as the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing other than mild transient adverse health effects or

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perceiving a clearly defined objectionable odor. TEEL-2 is defined as the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action. Lastly TEEL-3 is defined as the maximum air concentration below which it is believed nearly all individuals could be exposed without experiencing or developing life-threatening health effects. [40]

With an understanding of how the outdoor and indoor environment affects the transport of a CBRN agent and how to apply the appropriate exposure limit, an accurate health risk assessment can be conducted to evaluate the consequences of improperly sheltering.

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It is important to shelter-in-place in a timely manner, in that it is most beneficial when people enter and construct the shelter before the arrival of a plume of hazardous agent and exit soon after the cloud passes.

To assess the effectiveness of SIP on an Air Force installation against a hazardous release of a chemical, a well mixed box model was used to assess the indoor exposure. The Palazzi et al. modified continuous Gaussian dispersion model was used to predict the outdoor concentration, and emergency exposure guidelines were used to assess the associated health effects. The Gaussian dispersion model and indoor box model were chosen over the more complicated models, because these models can be solved quicker and allow the ability to test and react on SIP decisions quickly.

The Gaussian distribution equation was used because it involves relatively simple calculations requiring only dispersion parameters to identify the variation of pollutant concentrations away from the center of the plume. This distribution equation estimates the ground level pollutant concentrations based on time-averaged atmospheric variables such as temperature and wind speed.

Atmospheric Modeling

Under ideal conditions the mean concentration of an agent released from a point source has a Gaussian distribution. Even beyond the case of stationary, homogeneous

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turbulence, the Gaussian distribution serves as the basis for a large class of atmospheric diffusion formulas that are commonly used today. Rarely does an accidental or incidental release of a toxic agent fall into the situation of an instantaneous release or continuous release. Gaussian puff models have been adapted to deal with these short-term releases [41].

The equation describing the continuous release from a point source that follows the Gaussian distribution is listed below.

Equation 5-Gaussian distribution for a continuous point source

$$C_G = \frac{q}{2\pi\bar{u}\sigma_y\sigma_z} exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left[exp\left(-\frac{(z-h)^2}{2\sigma_z{}^2}\right) + exp\left(-\frac{(z+h)^2}{2\sigma_z{}^2}\right)\right]$$

where

$$q = Source\ emission\ rate\ (mg/sec)$$

$$h = Height\ of\ plume\ centerline\ (m)$$

$$\bar{u} = Mean\ wind\ velocity\ (m/sec)$$

$$y = Horizontal\ distance\ from\ point\ of\ release\ (m)$$

$$z = Vertical\ distance\ from\ point\ of\ release\ (m)$$

$$\sigma_y = dispersion\ coefficient\ in\ y\ direction\ (m)$$

$$\sigma_z = dispersion\ coefficient\ in\ z\ direction\ (m)$$

For any time during the release of chemical at any coordinate (x,y,z), the equation below is used to calculate to un-averaged outdoor exposure.

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Equation 6-Palazzi et al. (t≤tr)

$$C(x, y, z, t) = C_G \frac{1}{2}\left[erf\left(\frac{x}{\sigma_x\sqrt{2}}\right) - erf\left(\frac{x - \overline{ut}}{\sigma_x\sqrt{2}}\right)\right]$$

where

$$C(x, y, z, t) = Unaveraged\ Outdoor\ Concentration\ (mg/m^3)$$

$$C_G = Continuous\ Point\ Source\ Outdoor\ Concentration\ (mg/m^3)$$

$$x = Downwind\ distance\ from\ point\ of\ release\ (m)$$

$$y = Horizontal\ distance\ from\ point\ of\ release\ (m)$$

$$z = Vertical\ distance\ from\ point\ of\ release\ (m)$$

$$t = Time\ (sec)$$

$$t_r = Duration\ of\ release\ (sec)$$

$$\sigma_x = dispersion\ coefficient\ in\ x\ direction\ (m)$$

$$\bar{u} = Mean\ wind\ velocity\ (m/sec)$$

$$\mathrm{erf}(x) = error\ function\ of\ x$$

For any time after the release of chemical at any coordinate (x,y,z), the equation below is used to calculate the un-averaged outdoor exposure.

Equation 7-Palazzi et al. (t≥tr)

$$C(x, y, z, t) = C_G \frac{1}{2}\left[erf\left(\frac{x - \bar{u}(t - t_r)}{\sigma_x\sqrt{2}}\right) - erf\left(\frac{x - \overline{ut}}{\sigma_x\sqrt{2}}\right)\right]$$

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where

$$C(x, y, z, t) = Unaveraged\ Outdoor\ Concentration\ (mg/m^3)$$

$$C_G = Continuous\ Point\ Source\ Outdoor\ Concentration\ (mg/m^3)$$

$$x = Downwind\ distance\ from\ point\ of\ release\ (m)$$

$$y = Horizontal\ distance\ from\ point\ of\ release\ (m)$$

$$z = Vertical\ distance\ from\ point\ of\ release\ (m)$$

$$t = Time\ (sec)$$

$$t_r = Duration\ of\ release\ (sec)$$

$$\sigma_x = dispersion\ coefficient\ in\ x\ direction\ (m)$$

$$\bar{u} = Mean\ wind\ velocity\ (m/sec)$$

$$\mathrm{erf}(x) = error\ function\ of\ x$$

The dispersion coefficients are based on curves fit to the Pasquill-Gifford curves and depend on the downwind distance and stability class. [42] [43] [44]

Indoor Modeling

Mass Balance on Commercial Buildings with HVAC Systems

A simple box model can be used to represent the building and heating, ventilation, and air conditioning (HVAC) system to develop the mass balance. The purpose of the HVAC system is to provide heating, cooling and humidity control within the building. The primary purpose of the plenum and air control is to mix fresh outside air and return

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air in proper ratio to allow efficient use of energy while attempting to keep contaminant levels down. The mass balance assumes conservation of mass and good mixing within the building. To overcome some of the limitations of the box model the variables for non-ventilatory loss rate and the mixing efficiency can be added to the mass balance equations.
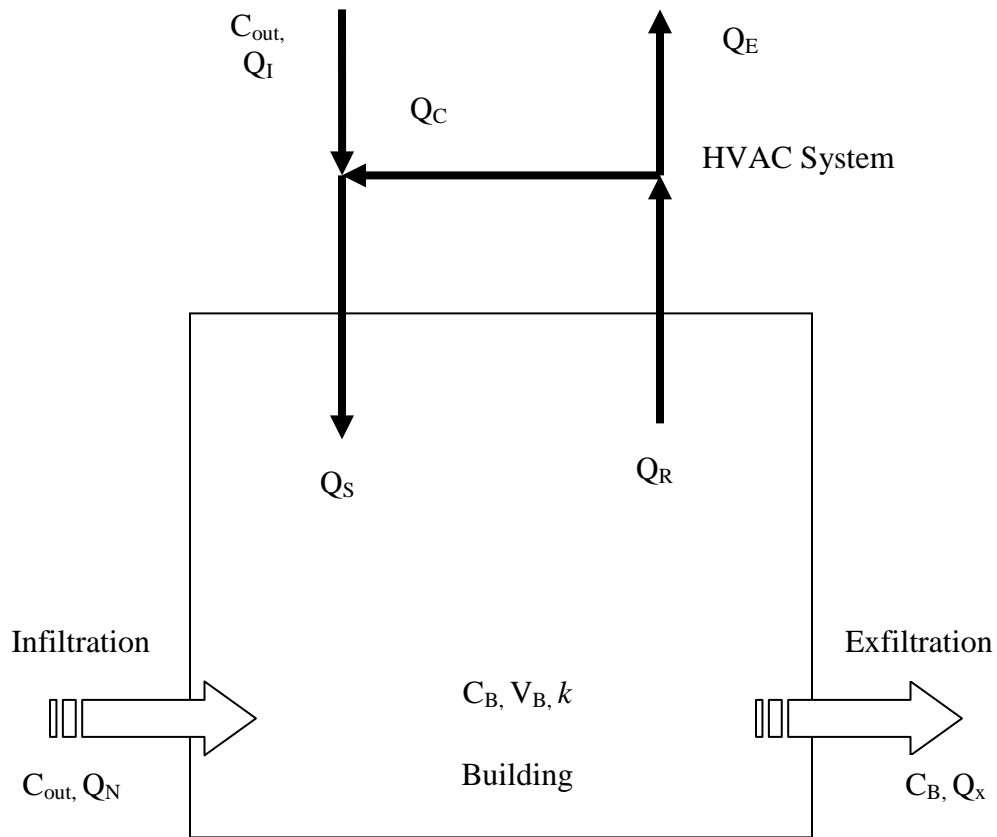
Figure 1-Box model for Commercial Building with HVAC system

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where

$$C_S = Concentration\ supplied\ to\ the\ building\ by\ HVAC\ (mg/m^3)$$

$$C_R = Concentration\ returned\ to\ HVAC\ from\ building\ (mg/m^3)$$

$$C_B = Concentration\ within\ the\ building\ (mg/m^3)$$

$$Q_S = Volumetric\ Flow\ rate\ of\ Supplied\ Air\ (m^3/sec)$$

$$Q_R = Volumetric\ Flow\ rate\ of\ Return\ Air = C_B(m^3/sec)$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration(m^3/sec)$$

$$\hslash = Non-ventilatory\ loss\ rate(m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

The basic mass balance equation for the toxic substance in a building with filtration included is provided below. The indoor generation of contaminant is assumed to be zero, because the contaminant source is exterior to the building

Equation 8-Mass Balance on Commercial Building

$$Accumulation$$
$$= Generation + (Supply + Infiltration) - (Return + Exfiltration)$$
$$- Nonventilatory\ Loss$$

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Equation 9-Mass Differential on Building

$$V_B \frac{dC_B}{dt} = 0 + [(Q_s)(m)(C_s) + (Q_N)(m)(C_{out})] - [(Q_R)(m)(C_R) + (Q_X)(m)(C_B)] - k(C_B)$$

where

$$C_S = Concentration\ supplied\ to\ the\ building\ by\ HVAC\ (mg/m^3)$$

$$C_R = Concentration\ returned\ to\ HVAC\ from\ building\ (mg/m^3)$$

$$C_B = Concentration\ within\ the\ building\ (mg/m^3)$$

$$Q_S = Volumetric\ Flow\ rate\ of\ Supplied\ Air\ (m^3/sec)$$

$$Q_R = Volumetric\ Flow\ rate\ of\ Return\ Air (m^3/sec)$$

$$= C_B\ when\ well\ mixed\ building\ is\ assumed$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration (m^3/sec)$$

$$k = Non-ventilatory\ loss\ rate (m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

$$t = time\ (sec)$$

$$m = mixing\ factor$$

The mixing factor (m) is a dimensionless number that is used as an uncertainty factor to describe hot spot concentrations associated with poor mixing within rooms. The

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non-ventilatory loss rate (k) is an attempt to describe how organic compounds may deposit onto the environmental surfaces where they can accumulate, degrade, or reenter the air. The mixing factor and non-ventilatory loss coefficients must be experimentally derived. Experimental work on characterization of ventilation systems in buildings suggests mixing factor values of 0.30 to 0.68. The values vary depending on location within the building. [45]

The mass balances for both the supply and return air are then substituted into the derived mass balance for the building. The differential mass balance on the building then resembles equation 12 below.

Equation 10-Mass Balance on Supply Air
$$Q_S C_S = Q_I C_{out} + Q_C C_C$$

Equation 11-Mass Balance on Return Air
$$Q_R C_B = Q_E C_E + Q_C C_C$$

where

$$C_{out} = Concentration\ from\ outdoors\ (mg/m^3)$$

$$C_E = Concentration\ exhausted\ to\ outdoors\ (mg/m^3)$$

$$C_C = Concentration\ of\ recycled\ (mg/m^3)$$

$$Q_I = Volumetric\ Flow\ rate\ of\ Intake\ Air\ (m^3/sec)$$

$$Q_E = Volumetric\ Flow\ rate\ of\ Exhaust\ Air\ (m^3/sec)$$

$$Q_C = Volumetric\ Flow\ rate\ of\ Recycled\ Air\ (m^3/sec)$$

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Equation 12-Complete Differential Mass Balance on Building

$$V_B \frac{dC_B}{dt} = 0 + [m[(Q_I)(C_{out}) + (Q_C)(C_C)] + (Q_N)(m)(C_{out})]$$

$$- [m[(Q_E)(C_B) + (Q_C)(C_C)] + (Q_X)(m)(C_B)] - k(C_B)$$

The differential equation is rearranged in the form below to resemble the general form of partial differential equations.

Equation 13-General Form and Solution for Partial Differential Equation

$$\frac{dC}{dt} + P(t)C = R(t)$$

$$Ce^{\int P(t)dt} = \int R(t)e^{\int P(t)dt}dt + Constant$$

The general solution to the mass balance of the building is given in equation 14 below. Rearranging the general solution reveals that it mirrors the WMR model from the AIHA Exposure Assessment Strategy, given in equation 15. [22]

Equation 14-General Solution to Building Concentration

$$C_B = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right) + \left(C_o - \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right)\right) e^{-\left(\frac{m(Q_E + Q_X) + k}{V_B}\right)t}$$

Equation 15-WMR Model for Building Concentration

$$C_B = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right)\left(1 - e^{-\left(\frac{m(Q_E + Q_X) + k}{V_B}\right)t}\right) + C_o\, e^{-\left(\frac{m(Q_E + Q_X) + k}{V_B}\right)t}$$

Since the outside concentration is dynamic, the solution to equation 13 was solved numerically at the time interval of one second. During that one second, it was assumed

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that the outside concentration was constant and the initial concentration becomes the
building concentration from the prior second. The numerical solution is listed in equation
16 below.

Equation 16-Numerical WMR Model for Building Concentration

$$C_{B_{i+1}} = \left(\frac{m(Q_I + Q_N)C_{out_{i+1}}}{m(Q_E + Q_X) + k} \right) \left(1 - e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)(t_{i+1}-t_i)} \right)$$
$$+ C_{B_i}\, e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)(t_{i+1}-t_i)}$$

Mass Balance on Residential Buildings
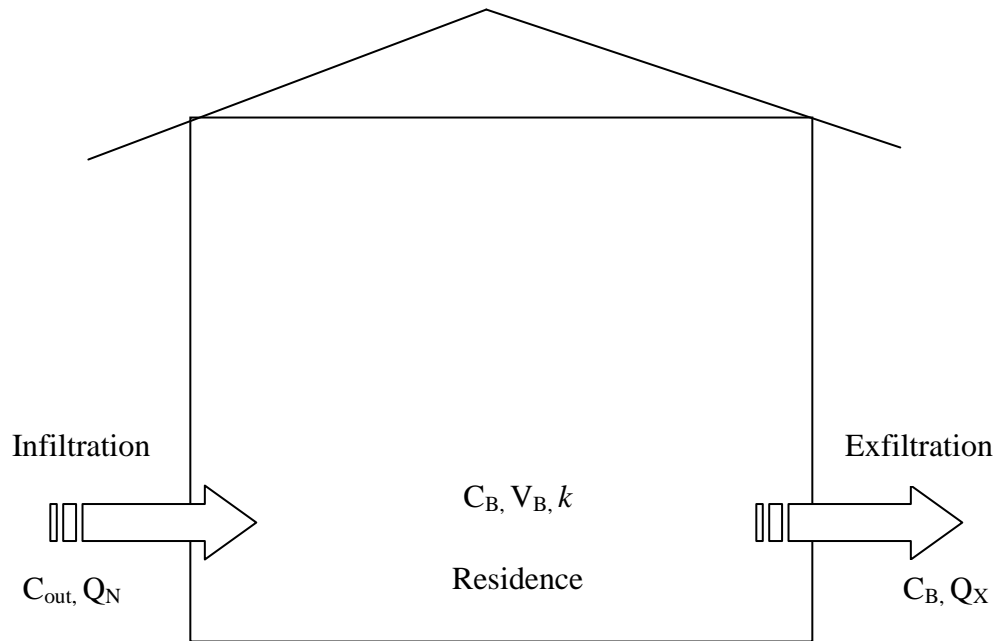
Figure 2- Box model for Residential Buildings without HVAC systems

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where

$$C_B = Concentration\ within\ the\ building\ (mg/m^3)$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration(m^3/sec)$$

$$\hbar = Non-ventilatory\ loss\ rate(m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

A simple box model can be used to represent a residential home to develop the mass balance. The mass balance assumes conservation of mass and good mixing within the residency. To overcome some of the limitations of the box model the variables for non-ventilatory loss rate and the mixing efficiency can be added to the mass balance equations.

Equation 17-Mass Balance on Residential Building

$$Accumulation$$
$$= Generation + Infiltration - Exfiltration - Nonventilatory\ Loss$$

Equation 18-Mass Differential on Residential Building

$$V_B \frac{dC_B}{dt} = 0 + (Q_N)(m)(C_{out}) - (Q_X)(m)(C_B) - \hbar(C_B)$$

where

$$C_B = Concentration\ within\ the\ building\ \left(\frac{mg}{m^3}\right)$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration(m^3/sec)$$

$$\hbar = Non-ventilatory\ loss\ rate(m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

$$t = time\ (min)$$

$$m = mixing\ factor$$

The mass balances for infiltration and exfiltration were then substituted into a derived mass balance for the building.

Equation 19-Mass Balance on Infiltration
$$Q_X = Q_N$$

The differential mass balance on the building then resembles the equation 20.

Equation 20-Complete Differential Mass Balance on Building
$$V_B \frac{dC_B}{dt} = 0 + (Q_N)(m)(C_{out}) - (Q_N)(m)(C_B) - \hbar(C_B)$$

The differential equation is rearranged in the form below to resemble the general form of partial differential equations. Applying the general solution for a partial differential equation takes the form shown below. The general solution to the mass balance of the building is given in the equation 21 and simplified to equation 22.

Equation 21-General Solution to Building Concentration
$$C_B = \left(\frac{m(Q_N)C_{out}}{m(Q_N) + \hbar}\right) + \left(C_o - \left(\frac{m(Q_N)C_{out}}{m(Q_N) + \hbar}\right)\right) e^{-\left(\frac{m(Q_N)+\hbar}{V_B}\right)t}$$

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Equation 22-WMR Model for Building Concentration

$$C_B = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right)\left(1 - e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}\right) + C_o\, e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}$$

Once again, since the outside concentration is dynamic, the solution to equation 22 above was solved numerically at the time interval of one second. During that one second, it was assumed that the outside concentration was constant and the initial concentration becomes the building concentration from the prior second. The numerical solution is listed in equation 23 below.

Equation 23-Numerical WMR Model for Building Concentration

$$C_{B_{i+1}} = \left(\frac{m(Q_N)C_{out_{i+1}}}{m(Q_N)+k}\right)\left(1 - e^{-\left(\frac{m(Q_N)+k}{V_B}\right)(t_{i+1}-t_i)}\right) + C_{B_i}\, e^{-\left(\frac{m(Q_N)+k}{V_B}\right)(t_{i+1}-t_i)}$$

Method Parameters

Two scenarios were chosen to test the model and the effectiveness of the different SIP strategies. The first scenario involved the accidental or intentional release of chlorine into the environment. The second scenario involved the intentional release of sarin gas by a terrorist.

Three key parameters of the release event play a role in determining the effectiveness of SIP strategies. They include the release characteristics, exposure limits, and the strategy itself.

Chlorine Release Characteristics

The release duration and quantities were selected to represent realistic scenarios. Chlorine is often transported by 150-lb cylinders, one-ton cylinders, 17-ton tanker trucks, or 90-ton railcars. The associated release times would be durations of 10 minutes, 1 hour, and 4 hours, with the worst case scenario using 10 minute duration. [46] If an Air Force installation treats their drinking water, swimming pools, or is located near or has a Wastewater Treatment Plant (WWTP), these quantities are realistic.

The dispersion of chlorine was modeled under six stability classes: Extremely Unstable (Class A), Moderately Unstable (Class B), Slightly Unstable (Class C), Neutral (Class D), Slightly Stable (Class E), and Moderately Stable (Class F), and two wind speeds of 1.5 meters per second (mps) and 3 mps. These wind speeds are moderate and are assumed in U.S. EPA Risk Management Guidance in their worst case scenarios. [46] Atmospheric mixing height (h) was given a value of zero to simulate a ground release.

Chlorine Exposure Limits

The Department of Energy Protective Action Criteria (PAC) for emergency planning of chemical release events was used to define the exposure limits. The PACs are based on the following chemical exposure limit values: Acute Exposure Guideline Level (AEGL), Emergency Response Planning Guideline (ERPG), and the Temporary Emergency Exposure Limit (TEEL). The PAC values are based on 60-minute chlorine AEGL values published by the U.S. EPA. The values for chlorine are listed in the table below.

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Table 3-Chlorine PAC Values

	TEEL-0	PAC-1	PAC-2	PAC-3
Units of PPM	0.5	0.5	2	20
Units of mg/m³	1.45	1.45	5.8	58

Chlorine Shelter-In-Place Strategy

The decision to shelter should be made as soon as possible to limit the delay in time that it takes to shelter, thereby reducing infiltration during the passing ambient plume. The optimal time to terminate SIP should be when the tail of the hazardous plume has passed the shelter. [47] Often there is a time lag between the time the order to shelter is given and the time that the shelter is constructed and the HVAC system is shutdown. The values of 1 minute, 30 minutes, 1 hour, 2 hours, and infinity were used for the implementation delay.

The building air change rates of 0.5, 1, and 2 ACH were adopted for the model and were chosen at one-quarter, one-half, and one times the average identified in the U.S. EPA BASE study. [28] Infiltration rates of 0.1 and 0.7 ACH when the building HVAC systems were shutdown and are consistent with those identified in DOE literature. [29] The values of 0.4 and 1 were used to describe the mixing factor (m) and the uncertainty of hotspot concentrations associated with poor mixing within rooms. The mixing factor of 0.4 is a useful starting point in industrial hygiene modeling indoor exposures. [21] The table below is a summary of parameters tested by the model for chlorine.

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Table 4-Chlorine Summary Parameters

Release Characteristics	
Release Duration, T_r (min)	10, 60, 240
Release Amount (ton)	0.075,1, 17, 90
Stability Class and Mixing Height	Class A, B,C,D,E,F H=0
Mean Wind Velocity (m/s)	1.5, 3
Building Characteristics	
Air Exchange Rates	0.5, 1, 2
Infiltration Rates	0.1, 0.7
Mixing Factor	0.4, 1
Downwind Distance (m)	100, 1000, 3000
Shelter-In-Place Strategy	
Implementation Delay (hr)	0.017, 0.5, 1,2,∞

Sarin Release Characteristics

The sarin release duration and quantities were selected to represent realistic
scenarios. Quantities of sarin chosen were 150-lb cylinders, one half-ton cylinders, and
one-ton cylinders with the release durations of 1 minute, 10 minutes, and 1 hour.
Because the likelihood that a terrorist could be capable of releasing large quantities of
sarin gas is small, lower quantities and release times were chosen.

The dispersion of chlorine was modeled under six stability classes: Extremely
Unstable (Class A), Moderately Unstable (Class B), Slightly Unstable (Class C), Neutral
(Class D), Slightly Stable (Class E), and Moderately Stable (Class F), and two wind
speeds of 1.5 meters per second (mps) and 3 mps. These wind speeds are moderate and

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are assumed in U.S. EPA Risk Management Guidance in their worst case scenarios. [46] Atmospheric mixing height (h) was given a value of zero to simulate a ground release.

Sarin Exposure Limits

The exposure limit values for sarin are listed in the table below. PAC values 1-3 for sarin refer to the 60-minute AEGL values.

Table 5-Sarin PAC Values

	TEEL-0	PAC-1	PAC-2	PAC-3
Units of PPM	0.00015	0.00048	0.006	0.022
Units of mg/m^3	0.00075	0.00275	0.0344	0.126

Sarin Shelter-In-Place Strategy

The values of 1 minute, 30 minutes, 1 hour, 2 hours, and infinity were used for the implementation delay. The building air change rates of 0.5, 1, and 2 ACH, with infiltration rates of 0.1 and 0.7 ACH when the building HVAC systems were shutdown. The values of 0.4 and 1 were used to describe the mixing factor (m) and the uncertainty of hot spot concentrations associated with poor mixing within rooms. These parameters were selected for the same reason as the chlorine scenario. The table below is a summary of parameters tested by the model for sarin.

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Table 6-Sarin Summary Parameters

Release Characteristics	
Release Duration, Tr (min)	1, 10, 60
Release Amount (ton)	0.075, 0.5, 1
Stability Class and Mixing Height	Class A, B,C,D,E,F H=0
Mean Wind Velocity (m/s)	1.5, 3
Building Characteristics	
Air Exchange Rates	0.5, 1, 2
Infiltration Rates	0.1, 0.7
Mixing Factor	0.4, 1
Downwind Distance (m)	100, 1000, 3000
Shelter-In-Place Strategy	
Implementation Delay (hr)	0.017, 0.5, 1,2,∞

Model Software

Since one goal was to provide a tool to base level BE personnel, a Microsoft
Office Excel$^®$ 2007 spreadsheet was used to numerically solve the transport equations
developed above and to evaluate the SIP decisions.

Model Validation

The model results were validated against the scenario presented in the W.R. Chan
et al. study and against two scenarios in ALOHA dispersion software to generate the
concentration at downwind points plot. The purpose of the validation process is to show
that the outputs of the transport models used in the thesis are consistent with results
published and produced by commercially available products.

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The W.R. Chan et al. study predicted normalized outdoor and indoor concentrations for a release under stability class D and with wind speed of 3 mps. The indoor concentrations were modeled for a 0.2 ACH and 2 ACH at 1 kilometer downwind of the release. [2]

The two scenarios used in ALOHA involved one release of chlorine and one release of sarin. The specific details of these two simulations can be found in Appendix D and E.

SIP Strategy Validation

The methodology for evaluating whether or not a particular strategy is effective or not at protecting the population will consist of comparing the predicted concentration to the appropriate exposure limits. The risk assessment will use the tiered PAC values for chemical release events were used to define the effectiveness and expected physiological responses.

IV. Results and Analysis

Validation Results

The model results were validated against the scenario presented in the W.R. Chan et al. study and against two scenarios in ALOHA dispersion software to generate the concentration at downwind points plot to ensure that the thesis model was as accurate in producing results.

W.R. Chan et al. Validation

The outdoor and indoor concentrations for a 6 minute release of hazardous chemical were predicted under a stability class D and wind speed of 3 mps. The concentrations were then normalized to the peak outdoor concentration and plotted in figure 3 below for both 0.2 ACH and 2 ACH at 1 kilometer downwind of the release predicted by the model outlined in the methodology section.

41
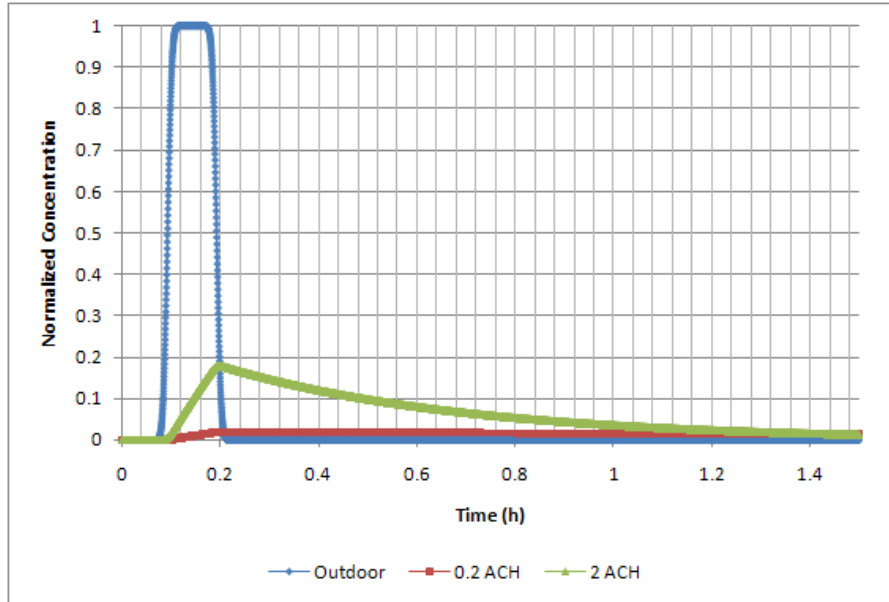
Figure 3-Chan-6 min Release

The outdoor and indoor concentrations for a 60 minute release of hazardous chemical was predicted under a stability class D and wind speed of 3 mps.   The concentrations were then normalized to the peak outdoor concentration and plotted in figure 4 below for both 0.2 ACH and 2 ACH at 1 kilometer downwind of the release.

42
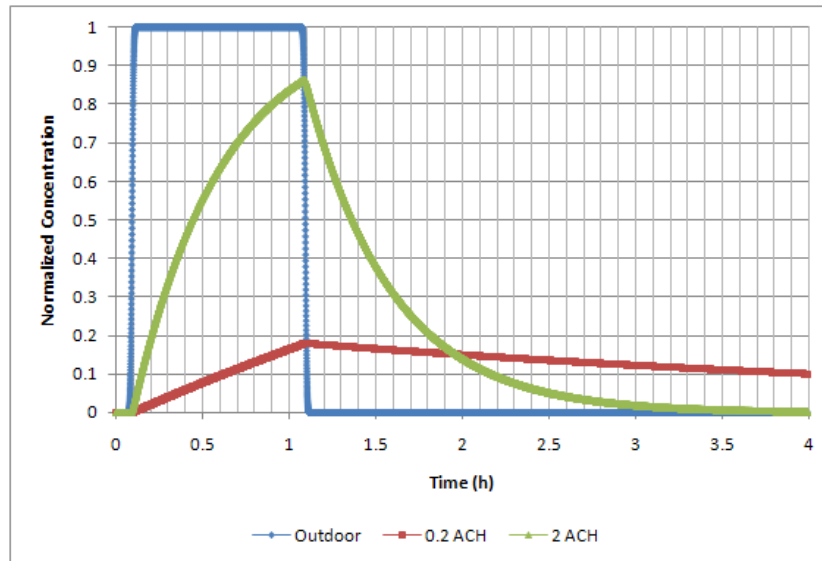
Figure 4-Chan 1-hour Release

The outdoor and indoor concentrations for a 5 hour release of hazardous chemical was predicted under a stability class D and wind speed of 3 mps. The concentrations were then normalized to the peak outdoor concentration and plotted in figure 5 below for both 0.2 ACH and 2 ACH at 1 kilometer downwind of the release.

43
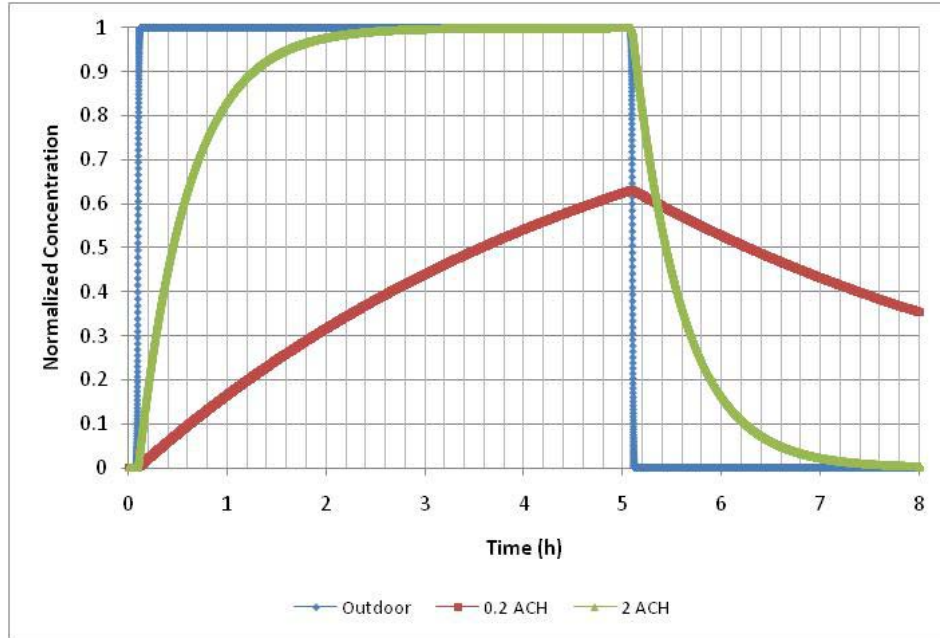
Figure 5-Chan 5-hour Release

The normalized predicted indoor and outdoor results matched the results
published in figure 1 of Chan et al. for a release of hazardous material. [2]

ALOHA Validation

Chlorine Scenario

The outdoor and indoor concentration for a 10 minute release of a 1-ton chlorine
cylinder was predicted under a stability class D and wind speed of 3 mps.   The
concentrations were then plotted below for both 0.32 ACH and 2 ACH at 1 kilometer
downwind of the release.

44
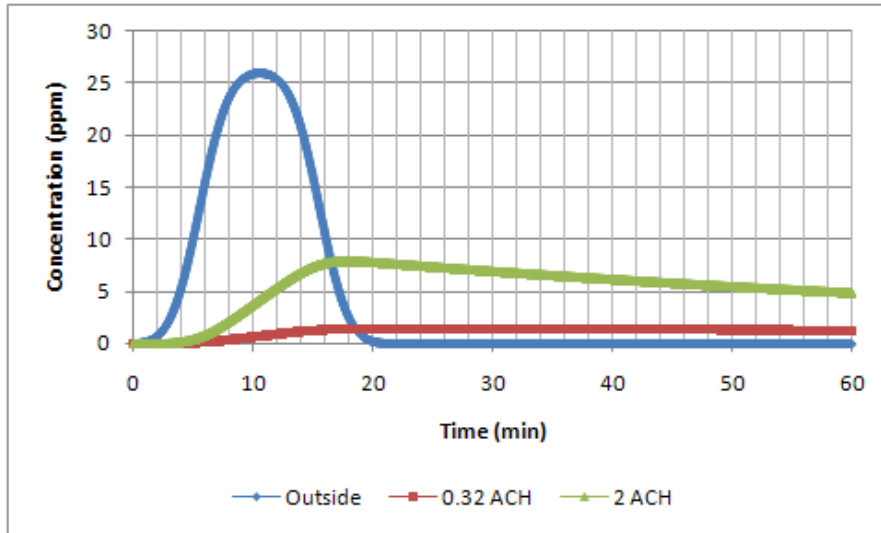
Figure 6-Chlorine Validation Scenario

The trends of the predicted indoor and outdoor results matched the results in the figures located in Appendix D under a stability class D and wind speed of 3 mps at 1 kilometer. The results of the thesis model were slightly higher than the ALOHA reported values, but are likely due to the differences in the dispersion coefficients used by ALOHA. The difference between ALOHA and thesis model is like due to the use of a set of Briggs dispersion coefficients describe the vertical and crosswind dispersion and the parameters used to develop the dispersion coefficient in the along-wind direction caused by wind shear. [48]

Sarin Scenario

The outdoor and indoor concentration for a 1 minute release of 1000 pounds of sarin gas was predicted under a stability class D, wind speed of 3 mps, and roughness of 3 m.   The concentrations were then plotted below for both 0.32 ACH and 2 ACH at 1 kilometer downwind of the release.

45
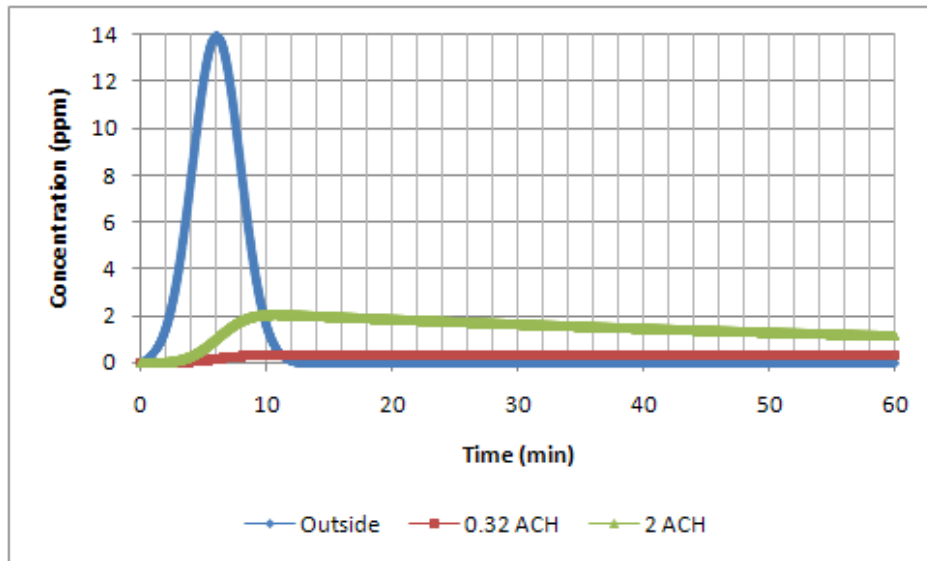
Figure 7-Sarin Validation Scenario

The trends of the predicted indoor and outdoor results matched the results in the figures located in appendix E under a stability class D and wind speed of 3 mps at 1 kilometer. The results of the thesis model were slightly higher than the ALOHA reported values, but again are likely due to the differences in the dispersion coefficients used by ALOHA.

Hypothesis

The hypothesis test results are listed in the table below. The specific details of these simulations can be found in Appendix D and E.

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Table 7-Hypothesis Test Results

Scenario	ALOHA Results (ppm)		Thesis Model (ppm)		Outdoor Within 15%	Indoor Within 15%
	Outdoor	Indoor	Outdoor	Indoor		
Chlorine #1 (0.32 ACH)	23	1.19	26.1	1.37	**Y**	**Y**
Chlorine #1 (2 ACH)	23	6.29	26.1	7.94	**Y**	**Y**
Chlorine #3 (0.32 ACH)	4.33	0.223	8.60	0.44	N	N
Chlorine #3 (2 ACH)	4.33	1.18	8.60	2.326	N	N
Sarin #1 (0.32 ACH)	8.97	0.0789	13.91	0.35	N	N
Sarin #1 (2 ACH)	8.97	0.459	13.91	2.08	N	N
Sarin #2 (0.32 ACH)	4.89	0.0575	5.13	0.1129	**Y**	N
Sarin #2 (2 ACH)	4.89	0.334	5.13	0.6323	**Y**	N
Sarin #3 (0.32 ACH)	4.89	.0575	7.18	0.1137	N	N
Sarin #3 (2 ACH)	4.89	0.334	7.18	0.6544	N	N

The trends of the predicted indoor and outdoor results matched the results in the figures located in appendix D and E, however the results of the thesis model were 14 to 50 percent higher than the ALOHA reported values. The differences were beyond 15%, but were within an order of magnitude in concentration, which may be acceptably accurate for this type of estimating. This is likely due to the differences in the dispersion coefficients used by ALOHA.

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V.   Discussion

This thesis attempted to evaluate the effectiveness of SIP on an Air Force installation by looking at the feasibility of combining outdoor dispersion models with modified industrial hygiene exposure models to estimate indoor airborne exposures to test the consequences associated with the delay of implementation of SIP procedures.

Scenario Results

The two scenarios outlined in Tables 4 and 6 were used to test the model and the effectiveness of the different SIP strategies. The trends are discussed below.

Stability Class

The outdoor concentration for a 1 minute release of 150 pounds of sarin gas was predicted under the A, B, C, D, E, and F stability classes and wind speed of 1.5 mps. The concentrations were then plotted below for at a 1 kilometer downwind of the release.
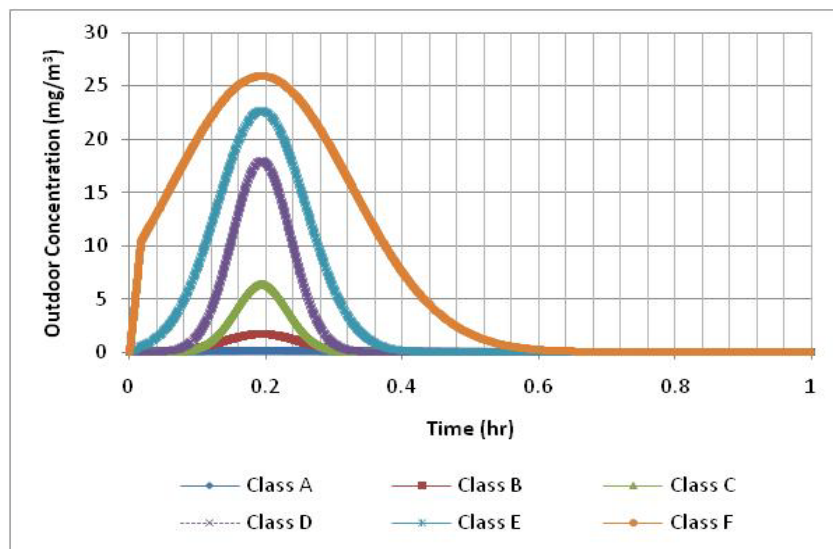
Figure 8-Stabiltiy Class Comparison

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It can be noted that as the atmosphere becomes more stable, the observed peak downwind concentration will increase. This reconfirms that a release at night will result in a higher exposure to the population.

Wind Speed

The outdoor concentration for a 10 minute release of 150 pounds of chlorine was predicted under stability class D and wind speeds of 1.5 mps and 3.0 mps. The concentrations were then plotted below for at a 1 kilometer downwind of the release.
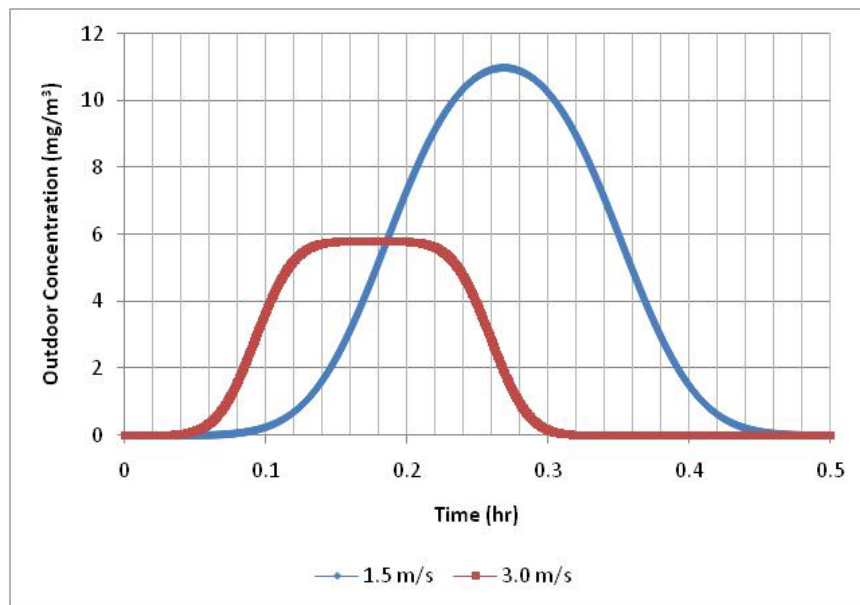
Figure 9-Wind Speed Comparison

As expected, the outdoor concentration arrives quicker as wind speed increases, as well as the peak outdoor concentration decreases as wind speed increases.

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Air Exchange Rates

To illustrate the effects of air exchange rates on indoor exposure, the outdoor and indoor concentrations for a 10 minute release of a 1-ton chlorine cylinder were predicted under a stability class E and wind speed of 3 mps.   The concentrations were then plotted below for both 0.5 ACH and 2 ACH at 1 kilometer downwind of the release.
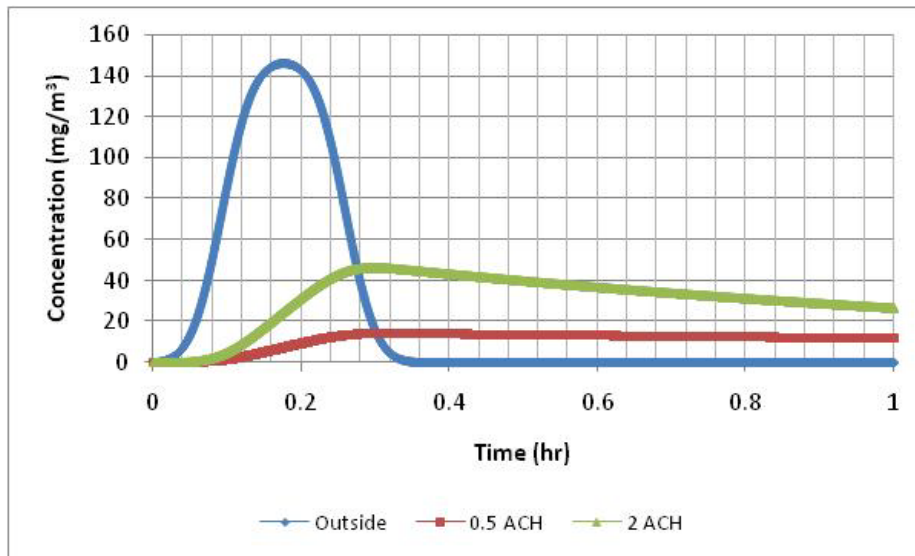
**Figure 10-Air Exchange Rate Comparison**

As seen in figure 10 above, the exposure received by indoor occupants is substantially higher in a facility that has a large air exchange rate than that which has a lower air exchange rate.

Distance

To illustrate the effects of distance, the outdoor and indoor concentration for a 10 minute release of a 1-ton chlorine cylinder was predicted under a stability class E and

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wind speed of 3 mps.   The concentrations were then plotted below for a 1 km and 3 km

downwind distance of release.
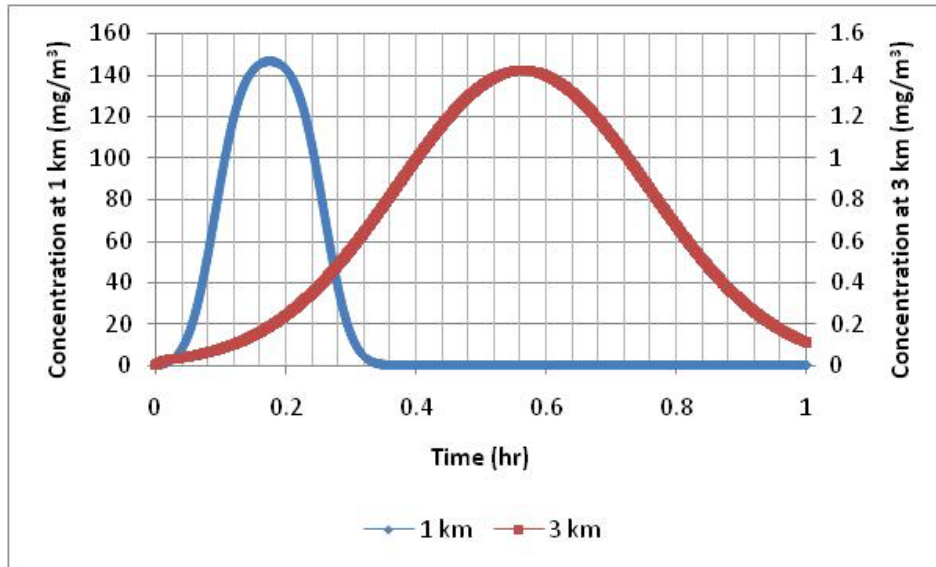
Figure 11-Distance Comparison

As seen in figure 11 above, the peak outdoor exposure decreases with increased

distance, however, the spread or the amount of time that the chlorine lingers at the

location increases.

Ideal Mixing

To illustrate the effect on the indoor concentration due to the assumption of good

mixing, the outdoor and indoor concentrations for a 10 minute release of a 1-ton chlorine

cylinder were predicted under a stability class F and wind speed of 3 mps at downwind

distance of 1 km with a mixing factor of 1 or perfect mixing and 0.4 or imperfect mixing.

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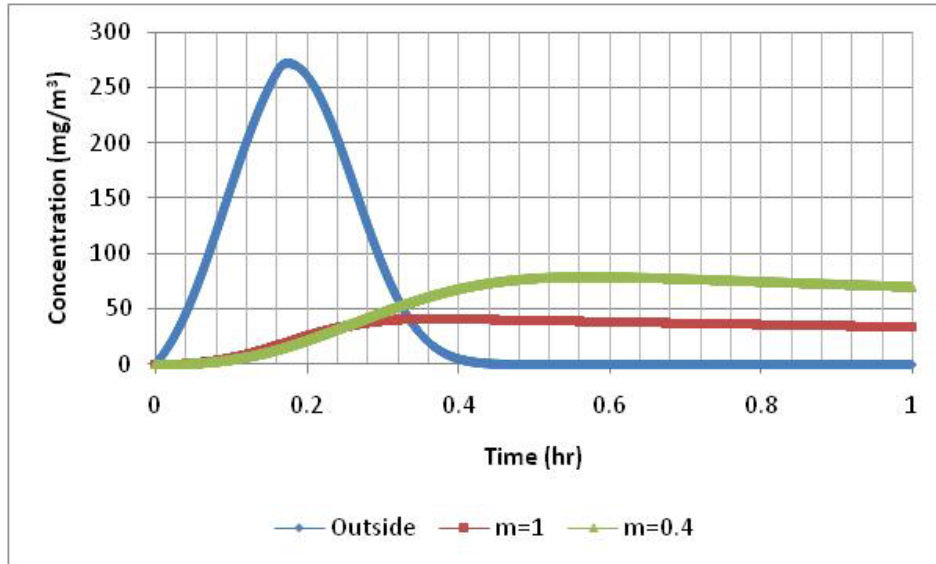
Figure 12-Well Mixing Comparison

As seen in figure 12 the peak indoor exposure increases with decreased mixing factor. This can be associated with concentration hotspots with poor mixing within a building, so the mixing factor acts as a safety factor to describe that uncertainty of overexposure.

SIP Strategies

To illustrate the consequences on delaying the process of sheltering, the outdoor and indoor concentrations for a 10 minute release of a 1-ton chlorine cylinder were predicted under a stability class F and wind speed of 3 mps at a downwind distance of 1 km with the exchange rate of 2 ACH and a 0.1 ACH infiltration rate.   The concentrations were then plotted below for a no HVAC shutdown (infinite time), 1 minute shutdown, and 30 minute shutdown against the exposure guidelines.

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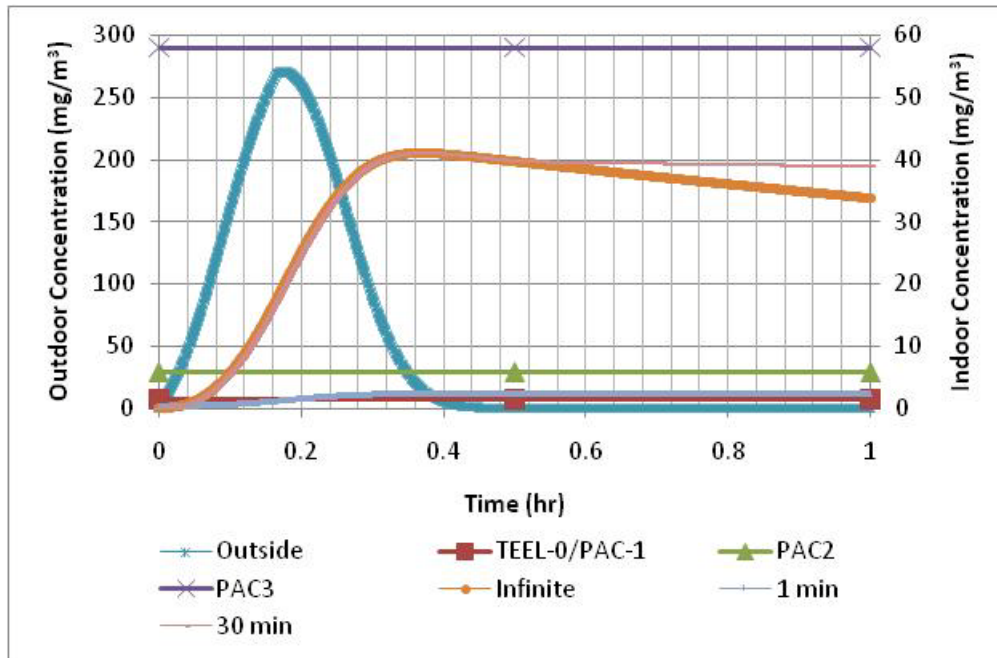
Figure 13-Short-Term Chlorine Release Strategy

The importance of immediate implementation is apparent here in that only then does the trial come close to the TEEL-0 value. That trial was the one minute shutdown of the HVAC system with a 60 minute time weighted average of 1.77 milligrams per cubic meter (mg/m^3). In this case it would be believed that nearly all individuals could be exposed without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor. It should also be noted that a late shutdown of 30 minutes has the negative effect of increasing the indoor exposure approximately 10 times greater than not shutting the HVAC system off at all (time of infinity).

To illustrate the consequences of delaying the process of sheltering on a virtually instantaneous release, the outdoor and indoor concentrations for a 1 minute release of a 150-lb sarin gas container was predicted under a stability class F and wind speed of 1.5

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mps at downwind distance of 1 km with the exchange rate of 2 ACH and a 0.1 ACH infiltration rate.   The concentrations were then plotted below for no HVAC shutdown, 1 minute shutdown, and 30 minute shutdown against the exposure guidelines.
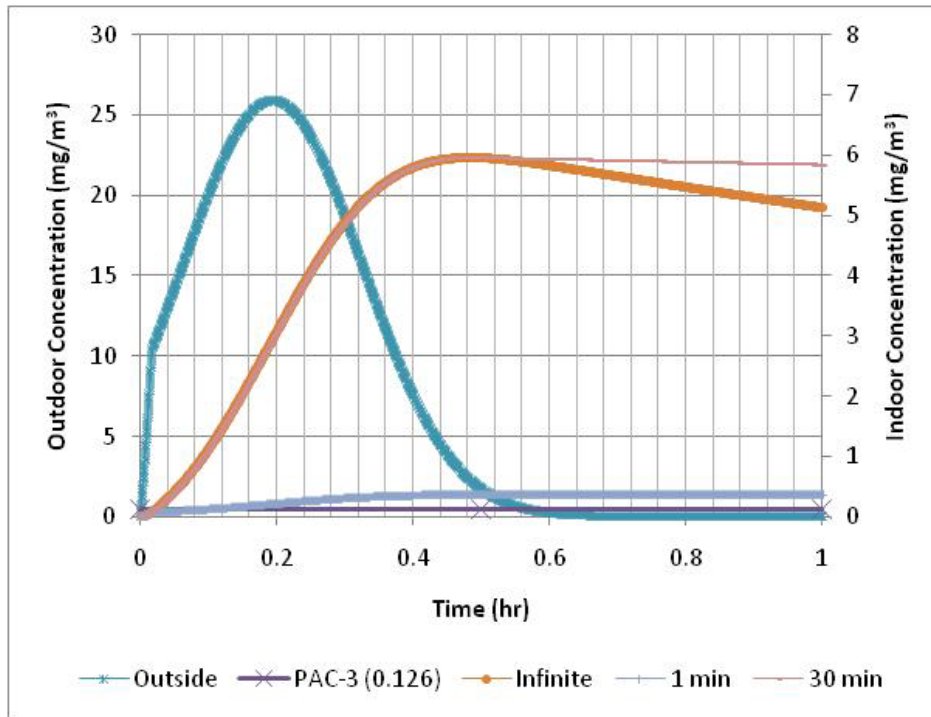
Figure 14-Short-Term Sarin Release Strategy

It is apparent in this case that the one minute shutdown of the HVAC system with a 60 minute time weighted average of 0.753 milligram per cubic meter (mg/m^3) is greater than the PAC-3 of 0.126 mg/m^3. In this case, it would be expected that a good proportion of individuals could experience or develop life-threatening health effects. It should also be noted that a late shutdown of 30 minutes has a negative effect of increasing the indoor exposure approximately 3 times greater than not shutting the HVAC system off.

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To illustrate the consequences of delaying the process of sheltering for a medium length release, the outdoor and indoor concentrations for a 30 minute release of a 17-ton chlorine cylinder were predicted under a stability class F and wind speed of 3 mps at downwind distance of 1 km with the exchange rate of 2 ACH and a 0.1 ACH infiltration rate. The concentrations were then plotted below for no HVAC shutdown (infinite time to SIP), 1 minute shutdown, and 30 minute shutdown against the exposure guidelines.
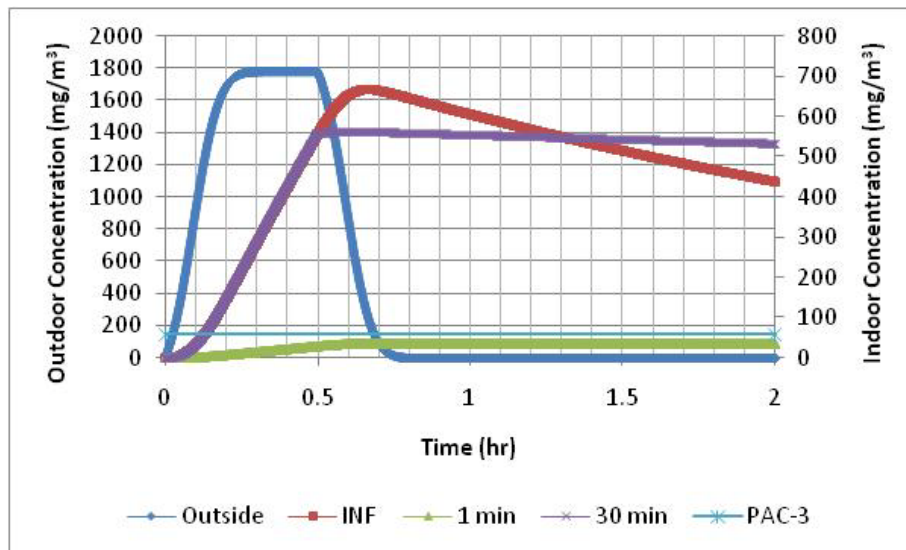
Figure 15-Medium-Term Chlorine Release Strategy

It is apparent in this case that the one minute shutdown of the HVAC system is the only strategy that is less than the PAC-3 of 58 mg/m^3. In this case, it would be expected that a good proportion of individuals could experience or develop life-threatening health effects if management was not able to shutdown the HVAC.

To illustrate the consequences on delaying the process of sheltering on an extended length release, the outdoor and indoor concentrations for a 60 minute release of a 17-ton chlorine cylinder were predicted under a stability class F and wind speed of 3 mps at a

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downwind distance of 1 km with the exchange rate of 2 ACH and a 0.1 ACH infiltration rate.   The concentrations were then plotted below for no HVAC shutdown (infinite time to SIP), 1 minute shutdown, and 30 minute shutdown against the exposure guidelines.
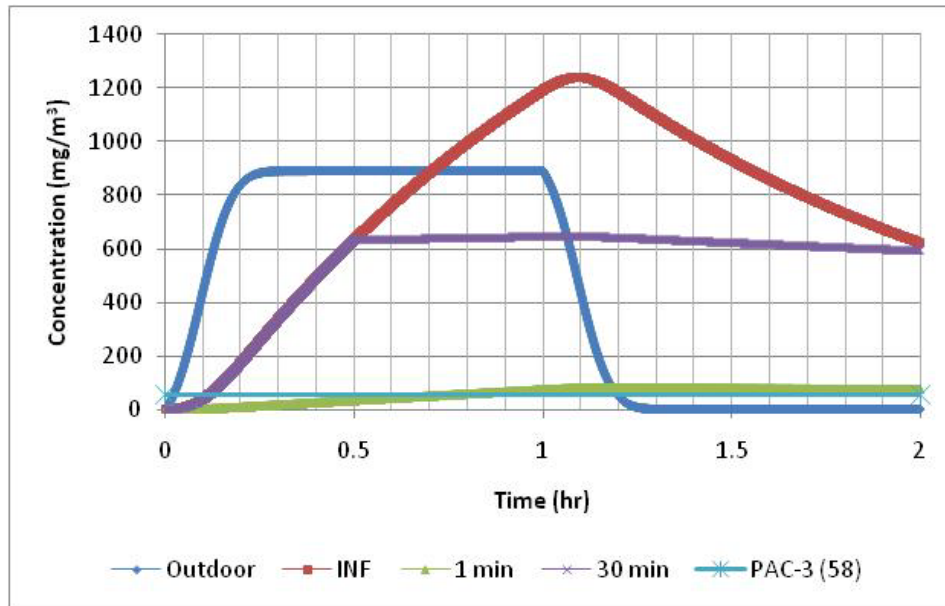
Figure 16-Extended Chlorine Release Strategy

It is apparent in this case that not one strategy results in a concentration below the PAC-3 exposure limit. However, this case also reveals that the failure to shut down the HVAC system would result in a peak indoor concentration almost 50% above the peak outdoor concentration.

It is important that the decision to shelter-in-place must be made immediately to reduce the exposure to those sheltered. Sheltering-in-place can provide adequate protection against hazardous material during short-term accidental and intentional releases. However, the level of protection provided by a SIP strategy depends on the

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level of filtration afforded by the building and HVAC system, the envelope airtightness, a quick decision by the incident commander, and the ability to shut down the system immediately. In other words, protection is a function of filtration, infiltration, and time to shutdown.

$$Protection = f(filtration, infiltration, time)$$

Given that the approximate time to construct a shelter within an existing structure ranges from 20 minutes to 60 minutes, with 35 minutes being the mean time, it is imperative that procedures to shutdown the HVAC system be enacted immediately.   This time does not include the amount to disseminate information to individuals that they are required to shelter.   During short-term CBRN releases, it would not be beneficial to construct the shelter, and time better served concentrating on shutdown of HVAC system. However, during long-term CBRN releases, constructing the shelters are still beneficial.

When in a deployed location, respiratory protection can be used in combination with SIP to significantly reduce the exposure to military personnel. As seen in Figure 17 below, when factoring in an assigned protection factor (APF) of 50 for a full-face air purifying respirator, all indoor exposures from the short-term sarin scenario reduced below the modified PAC-3 level of 6.3 mg/m^3. APFs are numbers assigned to a respirator by OSHA that indicate the level protection that a respirator or class of respirators is expected to provide to employees when used properly.
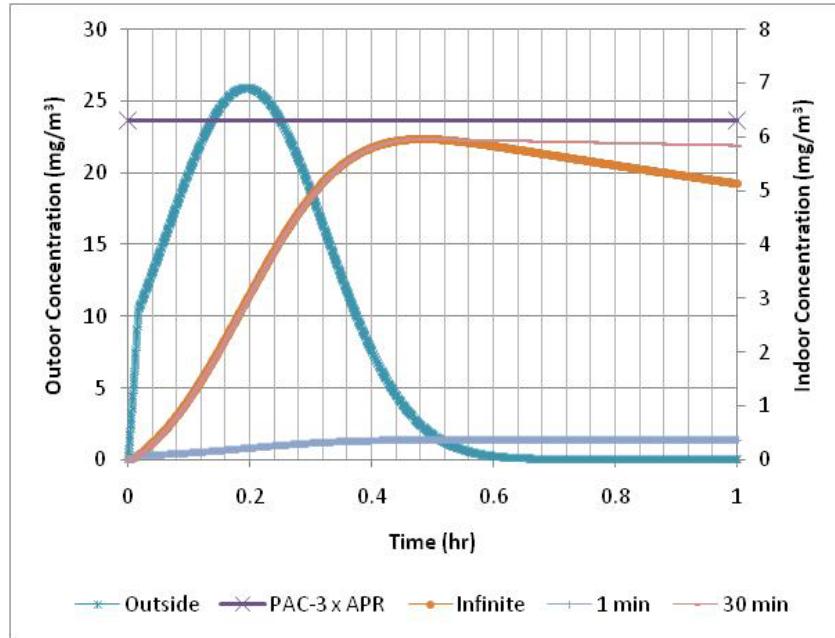
Figure 17-Short-Term Sarin Release plus RP

Beyond the ability of these simple models to estimate evacuation times, they can also help exercise planners with developing realistic CBRN exercises that are capable of linking exposures to casualties. The models can allow medical personnel to link post release signs and symptoms with likely dose received. They also can be used to predict casualty loads on the local hospitals during vulnerability assessments and drive changes to plans to be able to handle those casualties.

Model Performance

Since one goal was to provide a tool to base level BE personnel, an Excel® 2007 spreadsheet was used to numerically solve the developed transport equations and to evaluate the effectiveness of the SIP decisions. This thesis has shown that Excel® 2007 was capable of handling the calculations and challenge decision tree, but performance

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was degraded. Excel worksheet memory management caused a 20 to 30-sec delay in completing the calculations and occasionally caused Excel® to crash.   Additional conditional calculations had to be performed to overcome the limitations of Excel functions. Excel only calculates error functions for positive numbers.

For the purpose of this thesis, the source emission rate was assumed to be constant and the total mass is averaged over the duration of release and follows the form in the equation below. However, in an emergency response scenario, emission rates may not be constant. Such a case might be a release through a large pool of liquid like toluene, where the source emission rate is dependent on properties such as vapor pressure and diffusion.

Equation 24-Constant Source Generation

$$q\ (mg/sec) = \frac{Source\ mass\ emitted\ into\ air\ in\ release\ (mg)}{Time\ of\ Release\ (sec)}$$

In the long-term, coding the models into a different and more robust programming language would allow for quicker and more reliable decision making. Consideration must be given to what types of software packages are available to the base level planners.

Any long-term modeling efforts need to be checked against the current efforts of the Joint Chemical, Biological, Radiological and Nuclear (JCBRN) Defense Program and their efforts under the Joint Operation Effects Federation (JOEF) Project. JOEF is a modeling and simulation tool to determine effects and assess the impact and risks associated with CBRN releases on military personnel and operations. [49] As urban

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transport models such as MESO and RUSTIC are used to describe the contaminant flow around buildings and multizonal models to describe the transport within buildings, the more that resources in pre-planning will be required to take advantage of the models.

SIP Recommendations

Given that SIP can provide adequate protection against hazardous materials during short-term accidental and intentional releases, the following recommendations are given to help improve the decision making of whether to evacuate or shelter:

- Emergency planners (Civil Engineering Readiness, Fire Department, Bioenvironmental Engineering, Medical Readiness, Antiterrorism Officer, etc.) need to pre-plan the installation SIP protocol for likely scenarios identified during the various vulnerability surveys conducted for both on- and off-installation.

- Planners at a minimum should identify high value targets and shutdown the HVAC systems until the initial assessment of release has been conducted. The results above have shown that under most scenarios, a HVAC shutdown after 30 minutes is too late. In all likelihood after the initial assessment is completed, the ventilation system can be restarted, building flushed, and normal facility operations resumed.

- A suite of point source detection meters for concerned CBRN agents could be used in conjunction with SIP procedures to shutdown high value facility HVAC systems immediately upon release of hazardous materials.

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- At the installation level, a multizonal indoor air quality software package should be used to optimize the shelter location within a facility to maximize the protection against a particular CBRN threat. Ideally, this step should be conducted during the planning phase of a new facility or during an upgrade to a current facility's HVAC system.

Rules of Thumb

The following general rules of thumb than can be used to speed the process of making a decision and are listed in the table below. It should be noted that these are not specific to any one location or scenarios. These generalizations were developed by keeping the other variables constant and changing only the individual variable.

Table 8-Table of General Rules of Transport

Variable	Response
Double Wind Speed	Half the Peak Concentration Half the Appearance Time
Half the Mixing Factor	Double the Peak Concentration
Unstable to Stable Atmospheric Conditions	Increase Peak Concentration by factor of 4
Double the Distance Downwind	Decrease Peak Concentration by factor of 3
Half the ACH Rate	Decrease Peak Concentration by factor of 1.5

In the event that a building has been evacuated and determining to determine the amount of time required before personnel are permitted to return to that building is desired, the equation below can be used to determine the number of air changes required:

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Equation 25-Required Number of Air Changes

$$N \cong -\ln\left(\frac{C_L}{C_0}\right)$$

Where

$$N = Number\ of\ Air\ Changes$$

$$C_L = Required\ Concentration\ L$$

$$C_0 = Initial\ Concentration$$

When the air change rate for a particular building is unknown, assume the rate to be between 0.1 to 0.5 ACH. The values are low but within the ranges identified in the literature review, and will be more conservative in that they require longer dilution times. This assumption helps compensate for the fact that due to mixing of the air within the building, 100% of that volume of air will not be refreshed during that timeframe. A residential home will take about six hours to exchange 95% of the inside air with outside air with a 0.5 ACH. [50]

Assuming perfect mixing, the generalized indoor concentration represented as the percentage of the peak outdoor concentration related to SIP strategy is listed below. The values are calculated using stability class F, wind speed of 1.5 mps, ventilation rate of 2.0 ACH, and 1-km downwind. These generalizations may change for different conditions.

Table 9- Table of General Rules of SIP Strategies

Maximum Indoor Concentration (% Outdoor Peak Concentration)			
	SIP Strategy		
Release Condition	No HVAC Shutoff	1-min Delay	30-min Delay
Short-term (<1-min)	≈ 50	≈ 4	≈ 50
Short-term (<10-min)	≈ 54	≈ 3	≈ 54
Medium-term (<30-min)	≈ 78	≈ 5	≈ 55
Long-term (<60-min)	≈ 134	≈ 9	≈ 57

Future Projects

The consequences to the indoor exposure assessments associated with the delay of enacting SIP strategies and re-instituting full HVAC operations to normal as quickly as possible to further reduce exposures needs to be studied. The delay of restarting the HVAC not only has implications on health, but also has a cost or degradation to the mission. What part of the service do those individuals provide and what does it cost the Air Force in not being able to provide?

The consequences to the indoor exposure assessments associated with the delay of enacting SIP strategies with aerosol transport needs to be studied to provide guidance to the BE career field. Aerosol transport can be highly dependent on environmental conditions, and is not very well understood at installation level. A review of dispersion modeling and application to dispersion of particles has been conducted. [15].

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Conclusion

Combining outdoor dispersion models with indoor exposure models is an excellent way to evaluate the effectiveness of SIP on an Air Force installation by estimating indoor airborne exposures to test the consequences associated with the delay of implementation of SIP procedures.

It is important that the decision to shelter-in-place be made immediately in order to reduce the exposure. Given that it takes on average 35 minutes to construct a shelter, the results in this thesis have indicated that a delay greater than one minute can significantly increase the exposure resulting in additional casualties presenting at the local medical treatment facility.

It is imperative that emergency planners pre-plan the installation SIP protocol for likely scenarios identified during the various vulnerability surveys conducted for both on- and off-installation.

The tools used in this thesis can allow the base level BE personnel to numerically solve and evaluate the effectiveness of their SIP decisions in support of health hazard assessments.

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Appendix A. Commercial Indoor Exposure Model Derivation

This appendix describes the complete derivation of the simple box model representing the building and heating, ventilation, and air conditioning (HVAC) system of a commercial building.

Mass Balance on Commercial Building

$Accumulation$
$$= Generation + (Supply + Infiltration) - (Return + Exfiltration) - Nonventilatory\ Loss$$

Mass Differential on Building

$$V_B \frac{dC_B}{dt} = 0 + [(Q_s)(m)(C_s) + (Q_N)(m)(C_{out})] - [(Q_R)(m)(C_R) + (Q_X)(m)(C_B)] - \mathcal{k}(C_B)$$

where

$$C_S = Concentration\ supplied\ to\ the\ building\ by\ HVAC\ (mg/m^3)$$

$$C_R = Concentration\ returned\ to\ HVAC\ from\ building\ (mg/m^3)$$

$$C_B = Concentration\ within\ the\ building\ (mg/m^3)$$

$$Q_S = Volumetric\ Flow\ rate\ of\ Supplied\ Air\ (m^3/sec)$$

$$Q_R = Volumetric\ Flow\ rate\ of\ Return\ Air\ (m^3/sec)$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration(m^3/sec)$$

$$\mathcal{k} = Non-ventilatory\ loss\ rate(m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

$$t = time\ (min)$$

$$m = mixing\ factor$$

Mass Balance on Supply Air
$$Q_S C_S = Q_I C_{out} + Q_C C_C$$

Mass Balance on Return Air
$$Q_R C_B = Q_E C_E + Q_C C_C$$

where

$$C_{out} = Concentration\ from\ outdoors\ (mg/m^3)$$

$$C_E = Concentration\ exhausted\ to\ outdoors\ (mg/m^3)$$

$$C_C = Concentration\ of\ recycled\ (mg/m^3)$$

$$Q_I = Volumetric\ Flow\ rate\ of\ Intake\ Air\ (m^3/sec)$$

$$Q_E = Volumetric\ Flow\ rate\ of\ Exhaust\ Air\ (m^3/sec)$$

$$Q_C = Volumetric\ Flow\ rate\ of\ Recycled\ Air\ (m^3/sec)$$

Complete Differential Mass Balance on Building
$$V_B \frac{dC_B}{dt} = 0 + [m[(Q_I)(C_{out}) + (Q_C)(C_C)] + (Q_N)(m)(C_{out})]$$

$$- [m[(Q_E)(C_B) + (Q_C)(C_C)] + (Q_X)(m)(C_B)] - k(C_B)$$

The differential equation is rearranged in the form below to resemble the general

form of partial differential equations.

$$\frac{dC_B}{dt} = \left(\frac{m(Q_I + Q_N)}{V_B}\right) C_{out} - \left(\frac{m(Q_E + Q_X) + \hbar}{V_B}\right) C_B$$

$$\frac{dC_B}{dt} + \left(\frac{m(Q_E + Q_X) + \hbar}{V_B}\right) C_B = \left(\frac{m(Q_I + Q_N)}{V_B}\right) C_{out}$$

General form and solution for a partial differential is listed below:

General Form and Solution for Partial Differential Equation

$$\frac{dC}{dt} + P(t)C = R(t)$$

$$Ce^{\int P(t)dt} = \int R(t)e^{\int P(t)dt}dt + Constant$$

Applying the general solution for a partial differential equation takes the form shown below.

$$C_B e^{\int\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)dt} = \int \left(\frac{m(Q_I + Q_N)}{V_B}\right) C_{out} e^{\int\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)dt}dt + Constant$$

$$C_B e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t} = \left(\frac{m(Q_I + Q_N)}{V_B}\right) C_{out} \int e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t}dt + Constant$$

$$C_B e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t} = \left(\frac{m(Q_I + Q_N)}{V_B}\right) C_{out} \left(\frac{V_B}{m(Q_E + Q_X) + \hbar}\right) e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t} + Constant$$

$$C_B e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t} = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + \hbar}\right) e^{\left(\frac{m(Q_E+Q_X)+\hbar}{V_B}\right)t} + Constant$$

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$$C_B = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right) + Constant\, x\, e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)t}$$

Plugging the Boundary Conditions (at t=0, $C_B(t) = C_o$) to the above solution, the constant can be solved for.

$$C_o = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right) + Constant\, x\, e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)(0)}$$

$$C_o - \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right) = Constant$$

General Solution to Building Concentration

$$C_B = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right) + \left(C_o - \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right)\right) e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)t}$$

WMR Model for Building Concentration

$$C_B = \left(\frac{m(Q_I + Q_N)C_{out}}{m(Q_E + Q_X) + k}\right)\left(1 - e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)t}\right) + C_o\, e^{-\left(\frac{m(Q_E+Q_X)+k}{V_B}\right)t}$$

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Appendix B. Residential Indoor Exposure Model Derivation

This appendix describes the complete derivation of the simple box model representing the building of a residential building.

Mass Balance on Residential Building

$Accumulation$
$$= Generation + Infiltration - Exfiltration - Nonventilatory\ Loss$$

Mass Differential on Residential Building

$$V_B \frac{dC_B}{dt} = 0 + (Q_N)(m)(C_{out}) - (Q_X)(m)(C_B) - \hbar(C_B)$$

where

$$C_B = Concentration\ within\ the\ building\ \ mg/m^3$$

$$Q_N = Volumetric\ Flow\ rate\ of\ Infiltration\ (m^3/sec)$$

$$Q_X = Volumetric\ Flow\ rate\ of\ Exfiltration (m^3/sec)$$

$$\hbar = \ Non - ventilatory\ loss\ rate (m^3/sec)$$

$$V_B = Voume\ of\ the\ building\ (m^3)$$

$$t = time\ (min)$$

$$m = mixing\ factor$$

The mass balances for infiltration and exfiltration then substituted into a derived mass balance for the building.

Mass Balance on Infiltration

$$Q_X = Q_N$$

The differential mass balance on the building then resembles the equation below.

Complete Differential Mass Balance on Building

$$V_B \frac{dC_B}{dt} = 0 + (Q_N)(m)(C_{out}) - (Q_N)(m)(C_B) - k(C_B)$$

The differential equation is rearranged in the form below to resemble the general

form of partial differential equations.

$$\frac{dC_B}{dt} = \left(\frac{m(Q_N)}{V_B}\right)C_{out} - \left(\frac{m(Q_N) + k}{V_B}\right)C_B$$

$$\frac{dC_B}{dt} + \left(\frac{m(Q_N) + k}{V_B}\right)C_B = \left(\frac{m(Q_N)}{V_B}\right)C_{out}$$

General form and solution for a partial differential is listed below:

$$\frac{dC}{dt} + P(t)C = R(t)$$

$$Ce^{\int P(t)dt} = \int R(t)e^{\int P(t)dt}dt + Constant$$

Applying the general solution for a partial differential equation takes the form shown
below.

$$C_B e^{\int \left(\frac{m(Q_N) + k}{V_B}\right)dt} = \int \left(\frac{m(Q_N)}{V_B}\right)C_{out}e^{\int \left(\frac{m(Q_N) + k}{V_B}\right)dt}dt + Constant$$

$$C_B e^{\left(\frac{m(Q_N) + k}{V_B}\right)t} = \left(\frac{m(Q_N)}{V_B}\right)C_{out}\int e^{\left(\frac{m(Q_N) + k}{V_B}\right)t}dt + Constant$$

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$$C_B e^{\left(\frac{m(Q_N)+k}{V_B}\right)t} = \left(\frac{m(Q_N)}{V_B}\right) C_{out} \left(\frac{V_B}{m(Q_N)+k}\right) e^{\left(\frac{m(Q_N)+k}{V_B}\right)t} + Constant$$

$$C_B e^{\left(\frac{m(Q_N)+k}{V_B}\right)t} = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right) e^{\left(\frac{m(Q_N)+k}{V_B}\right)t} + Constant$$

$$C_B = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right) + Constant\, x\, e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}$$

Plugging the Boundary Conditions (at t=0, $C_B(t) = C_o$) to the above solution, the constant can be solved for.

$$C_o = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right) + Constant\, x\, e^{-\left(\frac{m(Q_N)+k}{V_B}\right)(0)}$$

$$C_o - \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right) = Constant$$

General Solution to Building Concentration

$$C_B = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right) + \left(C_o - \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right)\right) e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}$$

WMR Model for Building Concentration

$$C_B = \left(\frac{m(Q_N)C_{out}}{m(Q_N)+k}\right)\left(1 - e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}\right) + C_o\, e^{-\left(\frac{m(Q_N)+k}{V_B}\right)t}$$

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Appendix C. Gaussian Plume Models

There are three types of interactions between the diffusing agent and the surface:

1) Total reflection, 2) Total absorption, and 3) Partial absorption. [11]

For total reflection at z=0, the earth does not absorb the agent, but rather reflects

it. Chlorine gas would be an example where the surface would not absorb the agent.

Equation 26-Gaussian puff formula (Total Reflection)

$$c(x,y,z,t) = \frac{S}{(2\pi)^{2/3}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{\left(x-x^{'}-\overline{u}(t-t^{'})\right)^2}{2\sigma_x{}^2}-\frac{(y-y')^2}{2\sigma_y{}^2}\right] \text{x} \left[exp\left(-\frac{(z-z')^2}{2\sigma_z{}^2}\right)+exp\left(-\frac{(z+z')^2}{2\sigma_2{}^2}\right)\right]$$

Equation 27-Gaussian puff formula (Total Absorption)

$$c(x,y,z,t) = \frac{S}{(2\pi)^{2/3}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{\left(x-x^{'}-\overline{u}(t-t^{'})\right)^2}{2\sigma_x{}^2}-\frac{(y-y')^2}{2\sigma_y{}^2}\right] \text{x} \left[exp\left(-\frac{(z-z')^2}{2\sigma_z{}^2}\right)-exp\left(-\frac{(z+z')^2}{2\sigma_2{}^2}\right)\right]$$

Equation 28-Gaussian plume formula (Total Reflection)

$$C(x,y,z) = \frac{q}{2\pi\overline{u}\sigma_y\sigma_z}exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left[exp\left(-\frac{(z-h)^2}{2\sigma_z{}^2}\right)+exp\left(-\frac{(z+h)^2}{2\sigma_z{}^2}\right)\right]$$

Equation 29-Gaussian plume formula (Total Absorption)

$$C(x,y,z) = \frac{q}{2\pi\overline{u}\sigma_y\sigma_z}exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left[exp\left(-\frac{(z-h)^2}{2\sigma_z{}^2}\right)-exp\left(-\frac{(z+h)^2}{2\sigma_z{}^2}\right)\right]$$

Appendix D. ALOHA Chlorine Incident Results

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (sheltered double storied)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 3 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: D
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 1179 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 2.3 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 4.6 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 567 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1.1 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 2.5 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
   Concentration Estimates at the point:
   Downwind: 1000 meters   Off Centerline: 0 meters
   Max Concentration:
     Outdoor: 23 ppm
     Indoor: 1.19 ppm

Figure 18-ALOHA Chlorine Concentration at Point (#1, 1km, 0.32 ACH)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2.0 (sheltered double storied)
  Time: February 23, 2009 0800 hours EST (user specified)

 CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

 ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 3 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: D
  No Inversion Height   Relative Humidity: 50%

 SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 1179 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 2.3 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 4.6 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 567 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1.1 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 2.5 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1000 meters   Off Centerline: 0 meters
  Max Concentration:
    Outdoor: 23 ppm
    Indoor: 6.29 ppm

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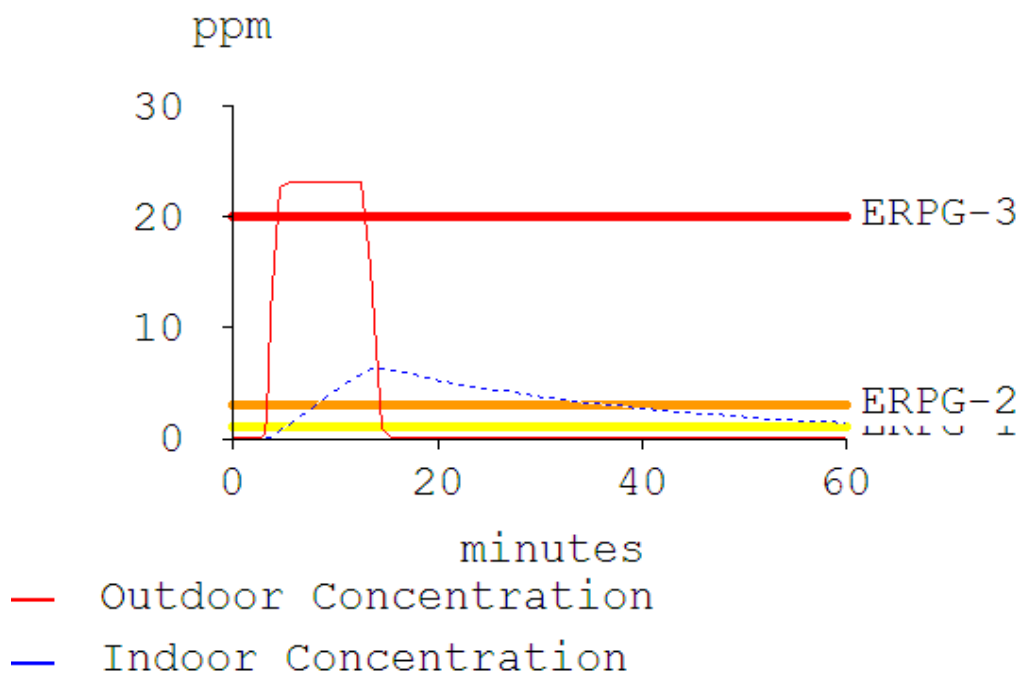
Figure 19-ALOHA Chlorine Concentration at Point (#1, 1km,, 2 ACH)

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -34.6° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/sec   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 5,440 kilograms/min
  Total Amount Released: 54,431 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 7.2 kilometers --- (20 ppm = AEGL-3(60 min))
  Orange: greater than 10 kilometers --- (2 ppm = AEGL-2(60 min))
  Yellow: greater than 10 kilometers --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 715 ppm
    Indoor: 36.6 ppm

Figure 20- ALOHA Chlorine Concentration at Point (#2, 1km, 0.32 ACH)

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm
  AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -34.6° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/sec   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 5,440 kilograms/min
  Total Amount Released: 54,431 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 7.2 kilometers --- (20 ppm = AEGL-3(60 min))
  Orange: greater than 10 kilometers --- (2 ppm = AEGL-2(60 min))
  Yellow: greater than 10 kilometers --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 715 ppm
    Indoor: 196 ppm

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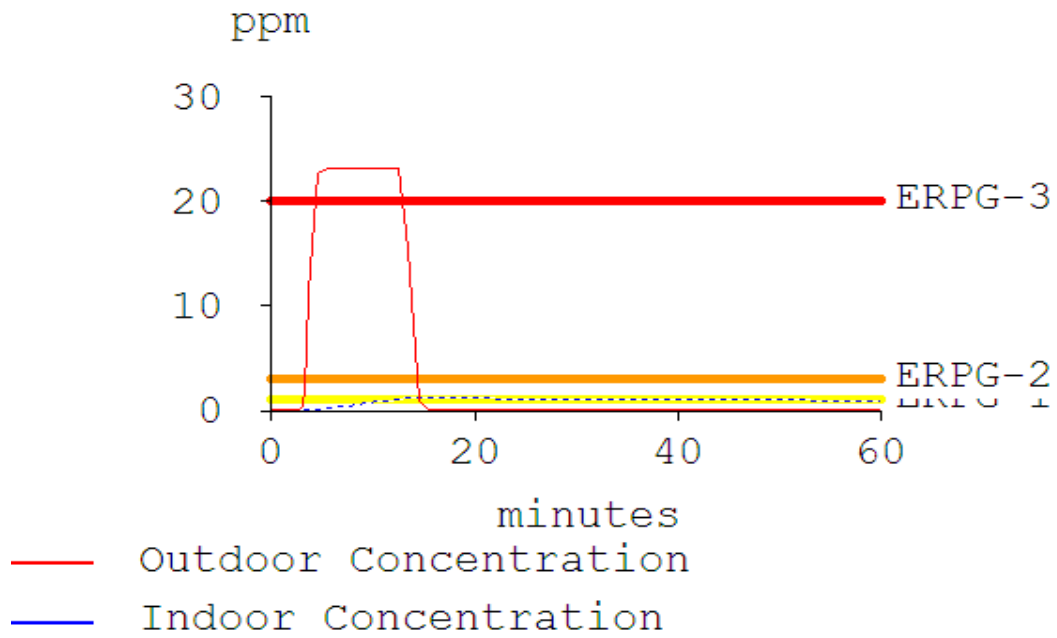**Figure 21- ALOHA Chlorine Concentration at Point (#2, 1km, 2 ACH)**

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 502 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1626 yards --- (2 ppm = AEGL-2(60 min))
  Yellow: 1.8 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 4.33 ppm
    Indoor: 0.223 ppm

Figure 22- ALOHA Chlorine Concentration at Point (#3, 1km, 0.32 ACH)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 502 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1626 yards --- (2 ppm = AEGL-2(60 min))
  Yellow: 1.8 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
   Outdoor: 4.33 ppm
    Indoor: 1.18 ppm

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Figure 23- ALOHA Chlorine Concentration at Point (#3, 1km, 2 ACH)
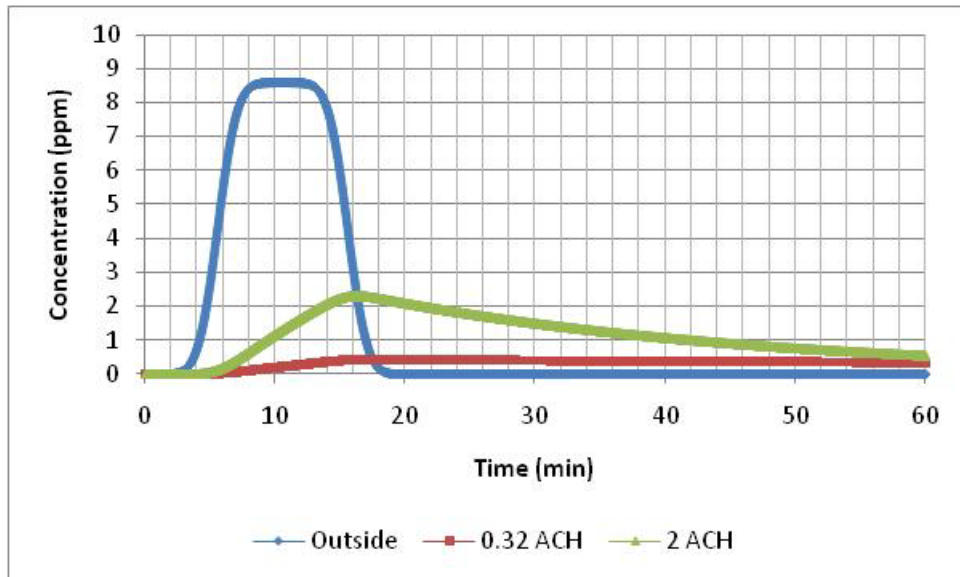
Figure 24-Model Chlorine Concentration at Point (#3, 1 km)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 1109 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 2.1 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 4.1 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
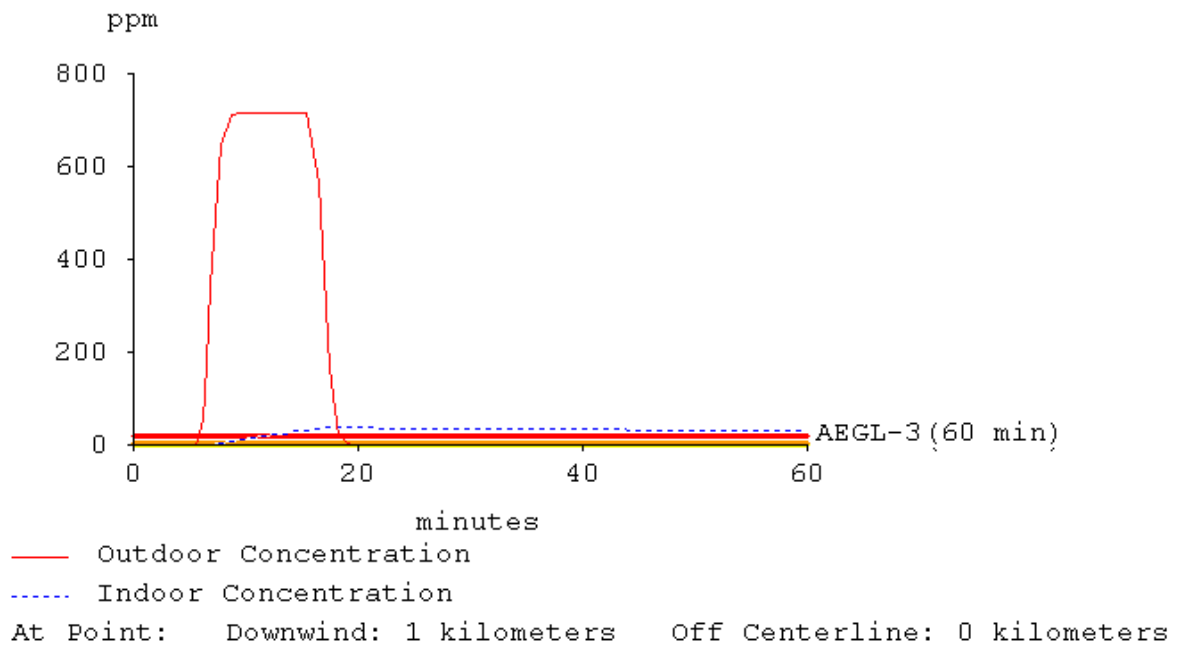   Outdoor: 20.6 ppm
    Indoor: 5.64 ppm

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Figure 25- ALOHA Chlorine Concentration at Point (#4, 1km, 2 ACH)

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Model Run: Heavy Gas
  Red   : 1109 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 2.1 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 4.1 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 20.6 ppm
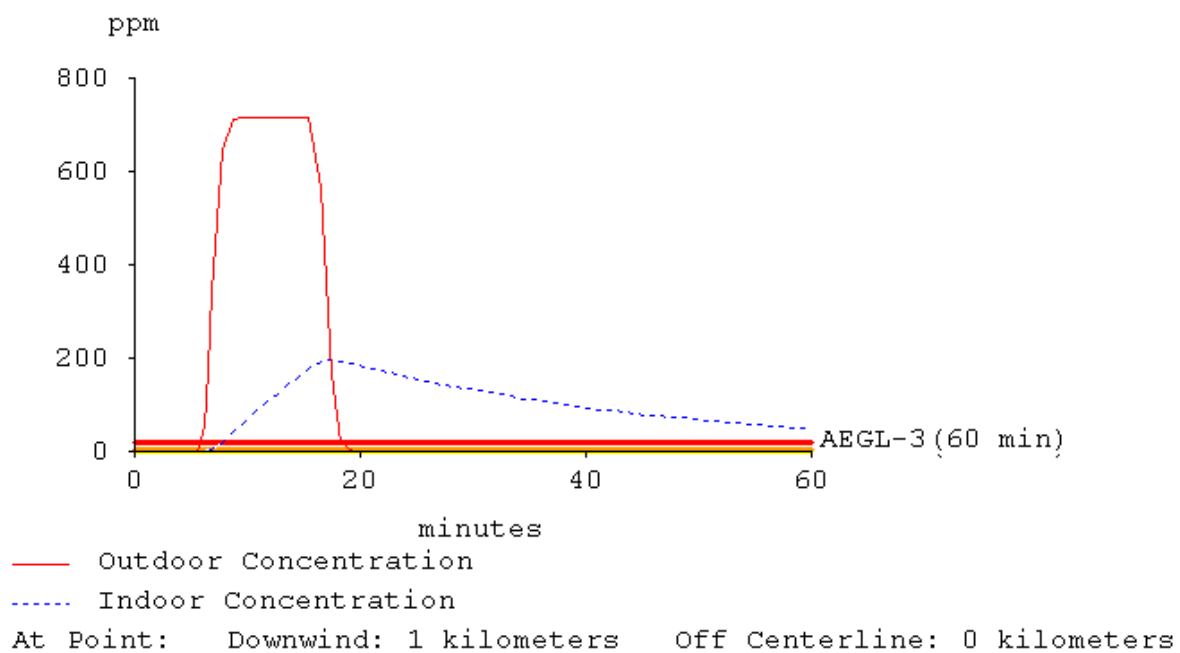   Indoor: 1.05 ppm

Figure 26- ALOHA Chlorine Concentration at Point (#4, 1km, 0.32 ACH)

SITE DATA:

  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: .32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 20 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 20 pounds/min
  Total Amount Released: 200 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red : 158 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 502 yards --- (2 ppm = AEGL-2(60 min))
  Yellow: 1016 yards --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
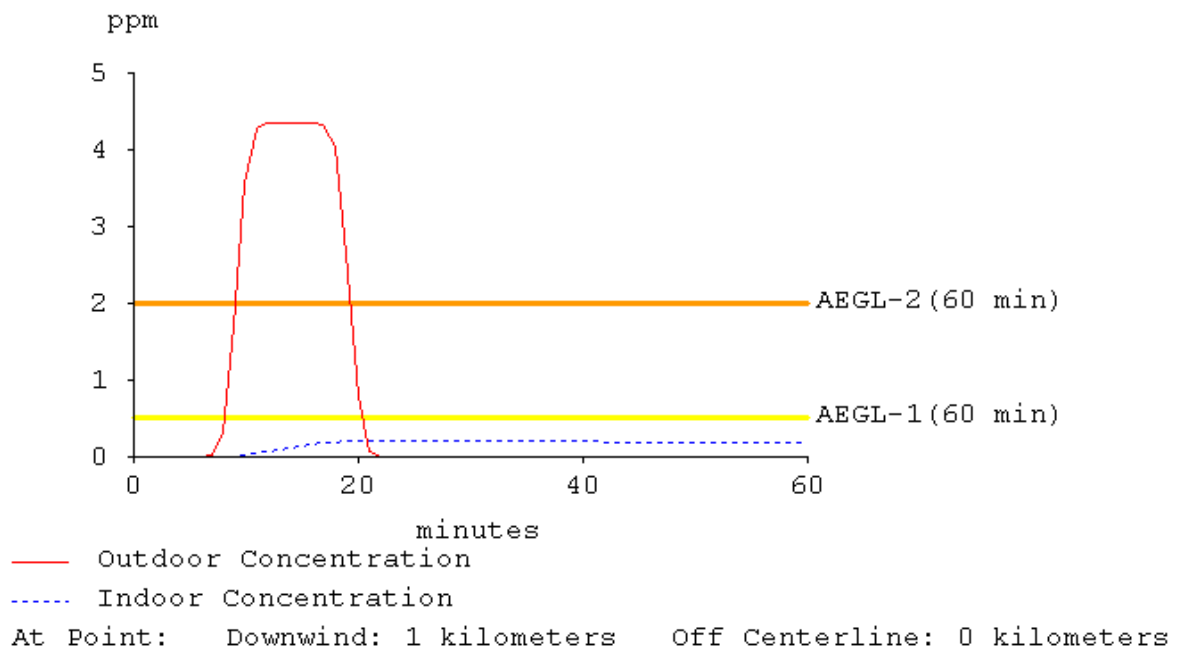 Max Concentration:
    Outdoor: 0.433 ppm
    Indoor: 0.0223 ppm

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SITE DATA:
 Location: DAYTON, OHIO
 Building Air Exchanges Per Hour: .32 (user specified)
 Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
 Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
 AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
 IDLH: 10 ppm
 Carcinogenic risk - see CAMEO
 Ambient Boiling Point: -30.3° F
 Vapor Pressure at Ambient Temperature: greater than 1 atm
 Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
 Wind: 3 meters/second from 180° true at 10 meters
 Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
 Air Temperature: 70° F   Stability Class: C
 No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
 Direct Source: 100 pounds/min   Source Height: 0
 Release Duration: 10 minutes
 Release Rate: 100 pounds/min
 Total Amount Released: 1,000 pounds
 Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
 Model Run: Gaussian
 Red   : 354 yards --- (20 ppm = AEGL-3(60 min))
 Orange: 1139 yards --- (2 ppm = AEGL-2(60 min))
 Yellow: 1.3 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
 Concentration Estimates at the point:
 Downwind: 1 kilometers   Off Centerline: 0 kilometers
 Max Concentration:
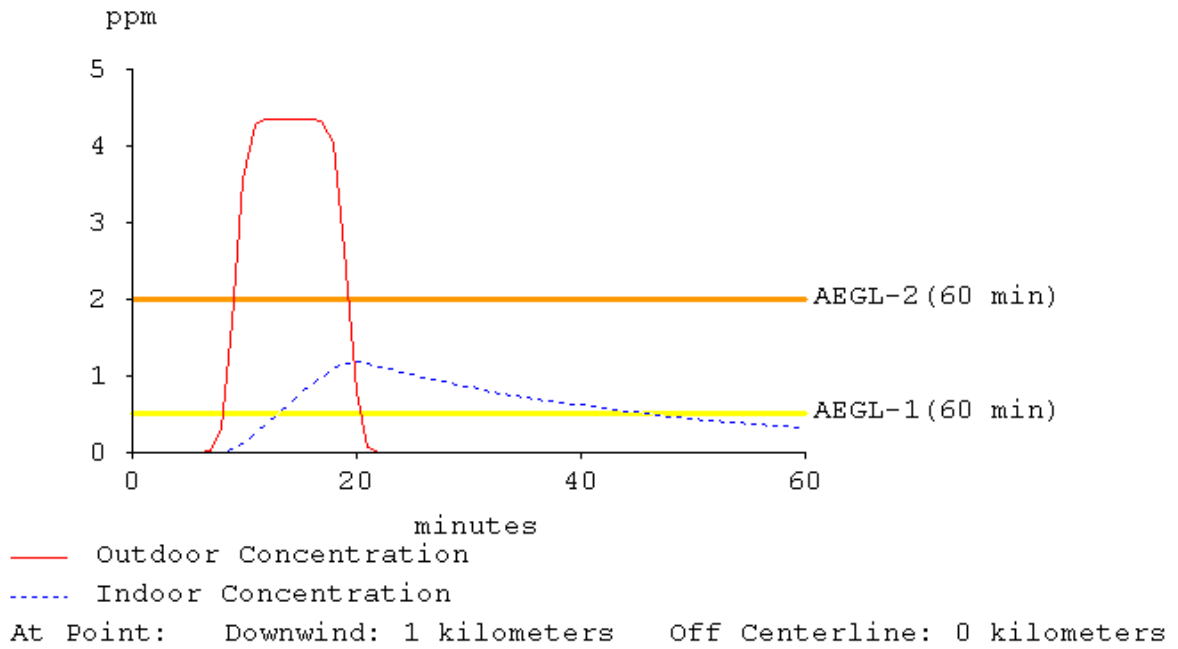   Outdoor: 2.17 ppm
   Indoor: 0.111 ppm

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: .32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

 CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

 ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 200 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 200 pounds/min
  Total Amount Released: 2,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 502 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1626 yards --- (2 ppm = AEGL-2(60 min))
  Yellow: 1.8 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
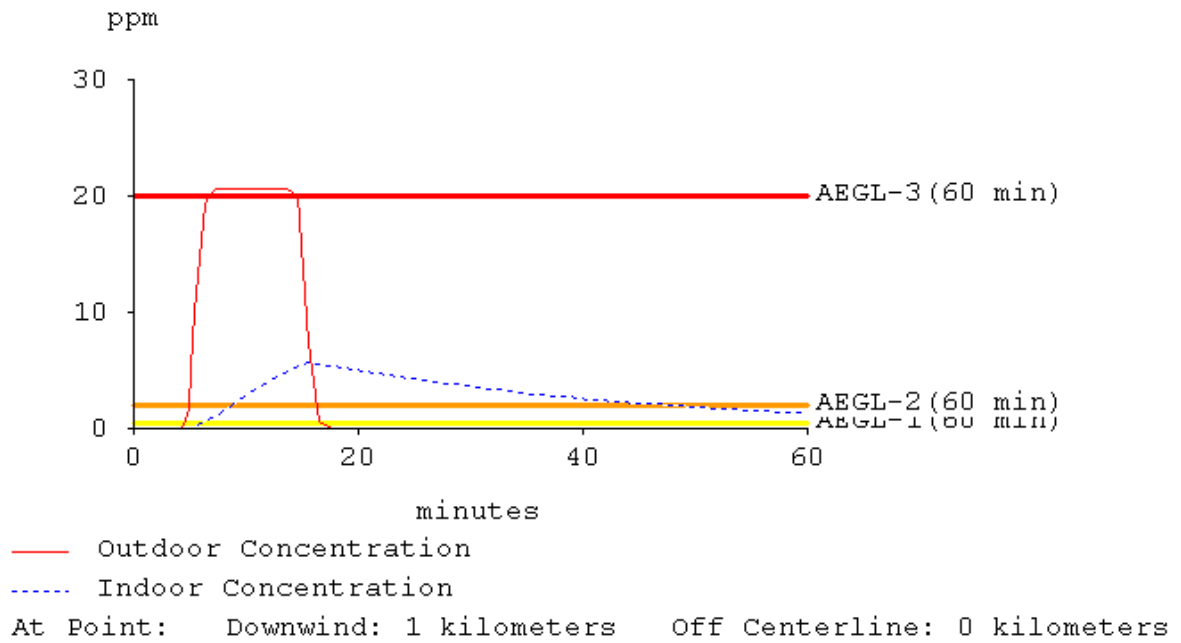 Max Concentration:
    Outdoor: 4.33 ppm
    Indoor: 0.223 ppm

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: .32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 300 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 300 pounds/min
  Total Amount Released: 3,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 617 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1.1 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 2.1 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
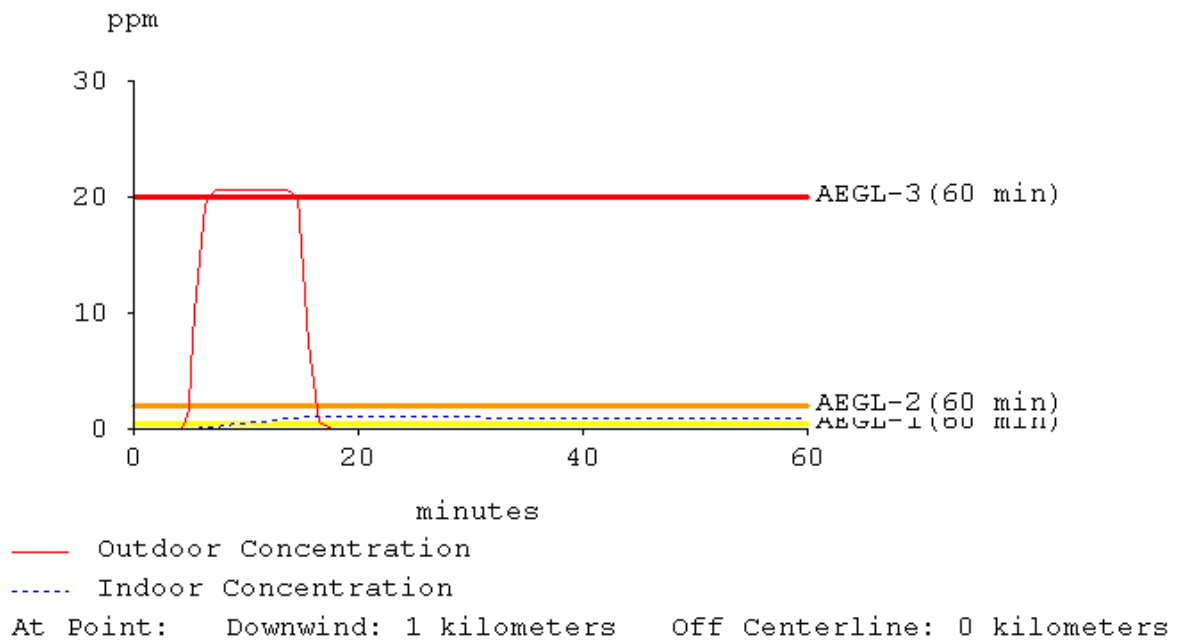   Outdoor: 6.5 ppm
    Indoor: 0.334 ppm

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: .32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: CHLORINE   Molecular Weight: 70.91 g/mol
  AEGL-1(60 min): 0.5 ppm   AEGL-2(60 min): 2 ppm   AEGL-3(60 min): 20 ppm
  IDLH: 10 ppm
  Carcinogenic risk - see CAMEO
  Ambient Boiling Point: -30.3° F
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 400 pounds/min   Source Height: 0
  Release Duration: 10 minutes
  Release Rate: 400 pounds/min
  Total Amount Released: 4,000 pounds
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 714 yards --- (20 ppm = AEGL-3(60 min))
  Orange: 1.3 miles --- (2 ppm = AEGL-2(60 min))
  Yellow: 2.4 miles --- (0.5 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 8.66 ppm
    Indoor: 0.445 ppm

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Appendix E. ALOHA Sarin Incident Results

SITE DATA:
   Location: DAYTON, OHIO
   Building Air Exchanges Per Hour: 0.32 (sheltered double storied)
   Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
   Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
   AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
   AEGL-3(60 min): 0.022 ppm
   Normal Boiling Point: 147.2° C
   Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
   Wind: 3 meters/second from 180° true at 3 meters
   Ground Roughness: urban or forest   Cloud Cover: 5 tenths
   Air Temperature: 70° F   Stability Class: D
   No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
   Direct Source: 1000 pounds   Source Height: 0
   Release Duration: 1 minute
   Release Rate: 7.56 kilograms/sec
   Total Amount Released: 454 kilograms

THREAT ZONE:
   Model Run: Gaussian
   Red   : 9.1 kilometers --- (0.022 ppm = AEGL-3(60 min))
   Orange: greater than 10 km --- (0.006 ppm = AEGL-2(60 min))
   Yellow: greater than 10 km --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
   Concentration Estimates at the point:
   Downwind: 1000 meters   Off Centerline: 0 meters
   Max Concentration:
      Outdoor: 8.97 ppm
      Indoor: 0.0789 ppm

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Figure 27-ALOHA Sarin Concentration at Point (#1, 1 km, 0.32 ACH)

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2.0 (sheltered double storied)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 147.2° C
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 3 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: D
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1000 pounds   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 7.56 kilograms/sec
  Total Amount Released: 454 kilograms

THREAT ZONE:
  Model Run: Gaussian
  Red   : 9.1 kilometers --- (0.022 ppm = AEGL-3(60 min))
  Orange: greater than 10 km --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 10 km --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT: (2 ACH)
  Concentration Estimates at the point:
  Downwind: 1000 meters   Off Centerline: 0 meters
  Max Concentration:
    Outdoor: 8.97 ppm
    Indoor: 0.459 ppm

Figure 28-ALOHA Sarin Concentration at Point (#1, 1 km, 2 ACH)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1000 pounds/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 16.7 pounds/sec
  Total Amount Released: 1,000 pounds

THREAT ZONE:
  Model Run: Gaussian
  Red   : 3.6 miles --- (0.022 ppm = AEGL-3(60 min))
  Orange: 5.5 miles --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 4.89 ppm
    Indoor: 0.0575 ppm

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Figure 29- ALOHA Sarin Concentration at Point (#2, 1 km, 0.32 ACH)

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: urban or forest   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1000 pounds/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 16.7 pounds/sec
  Total Amount Released: 1,000 pounds

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 4.89 ppm
    Indoor: 0.334 ppm

Figure 30- ALOHA Sarin Concentration at Point (#2, 1 km, 2.0 ACH)
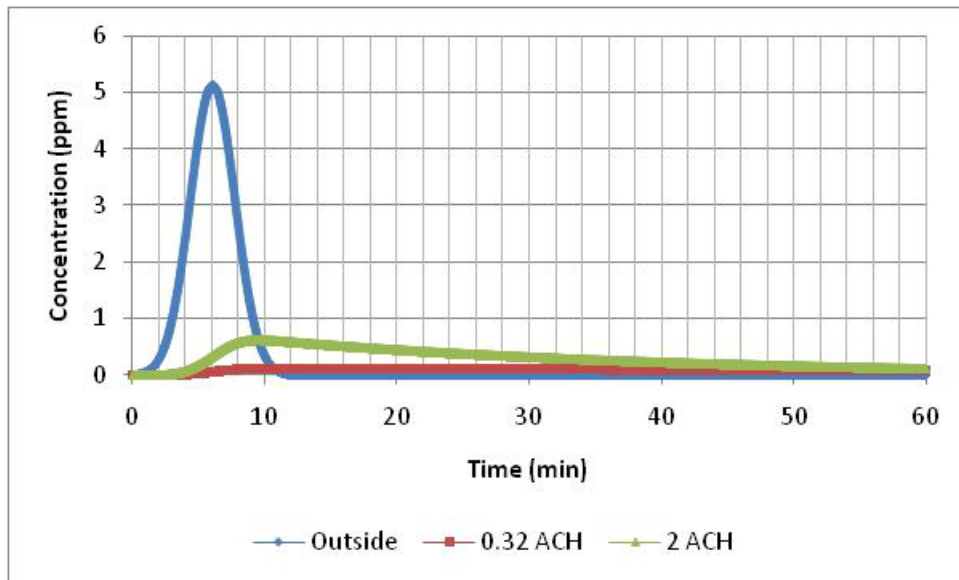
Figure 31- Model Sarin Concentration at Point (#2, 1 km)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 0.32 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1000 pounds/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 16.7 pounds/sec
  Total Amount Released: 1,000 pounds

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
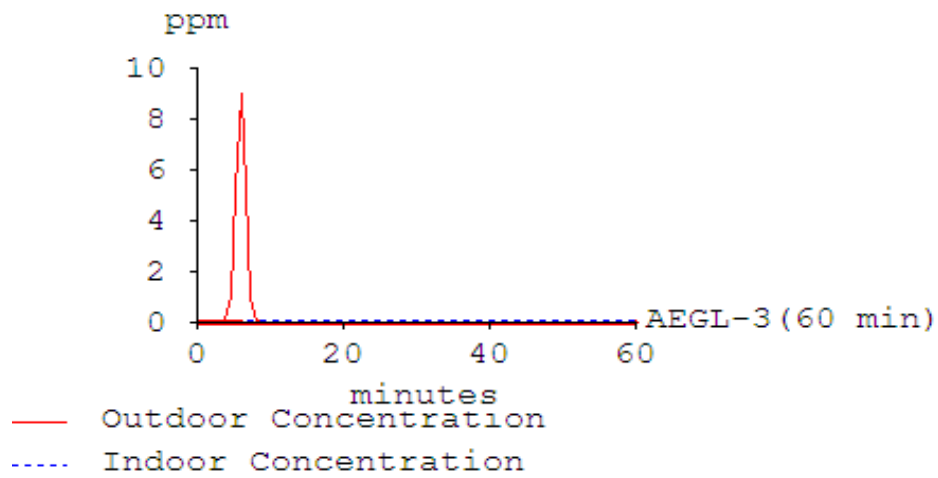   Outdoor: 4.89 ppm
    Indoor: 0.0575 ppm

Figure 32- ALOHA Sarin Concentration at Point (#3, 1 km, 0.32 ACH)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

 CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm   AEGL-3(60 min):
0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

 ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

 SOURCE STRENGTH:
  Direct Source: 1000 pounds/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 16.7 pounds/sec
  Total Amount Released: 1,000 pounds

 THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometer   Off Centerline: 0 kilometers
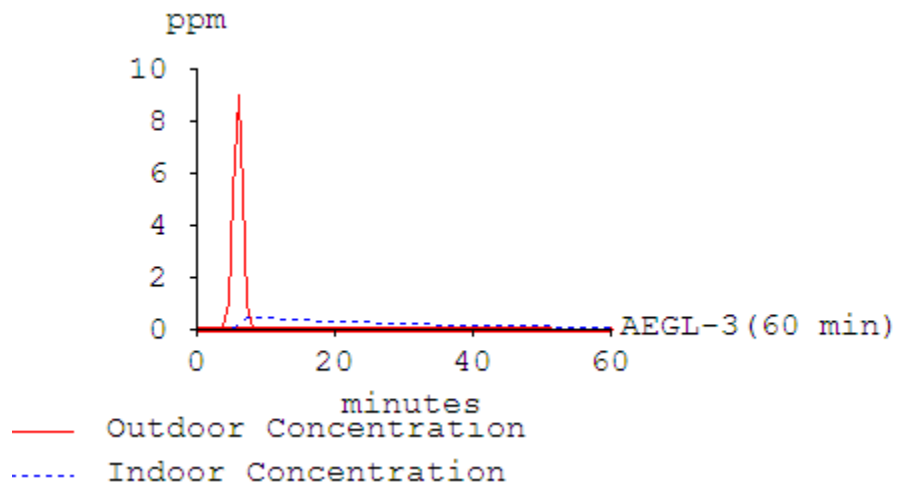 Max Concentration:
    Outdoor: 4.89 ppm
    Indoor: 0.334 ppm

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Figure 33- ALOHA Sarin Concentration at Point (#3, 1 km, 2 ACH)
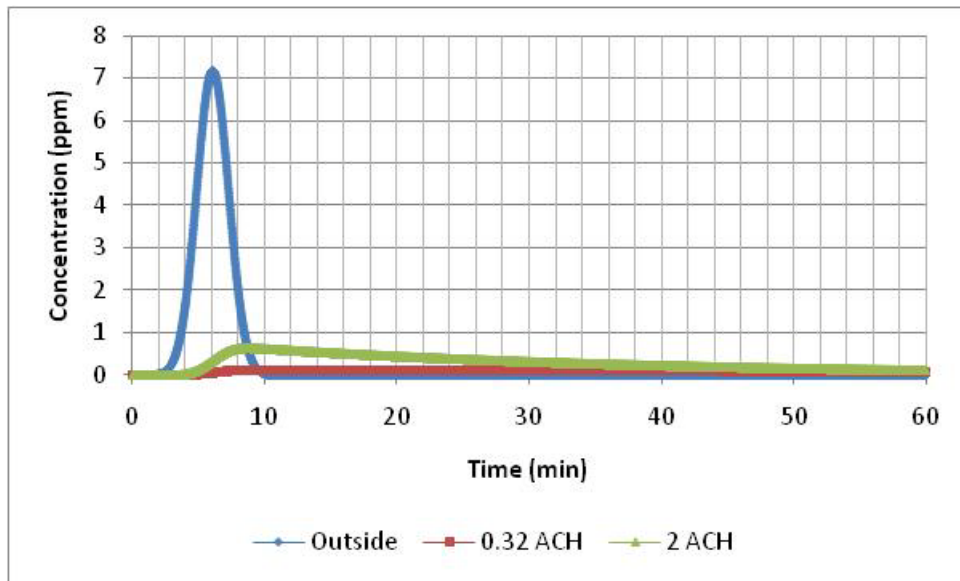
Figure 34- Model Sarin Concentration at Point (#3, 1 km)

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: .1 tons/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 3.33 pounds/sec
  Total Amount Released: 200 pounds

THREAT ZONE: (GAUSSIAN SELECTED)
  Model Run: Gaussian
  Red   : 2.1 miles --- (0.022 ppm = AEGL-3(60 min))
  Orange: 3.2 miles --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
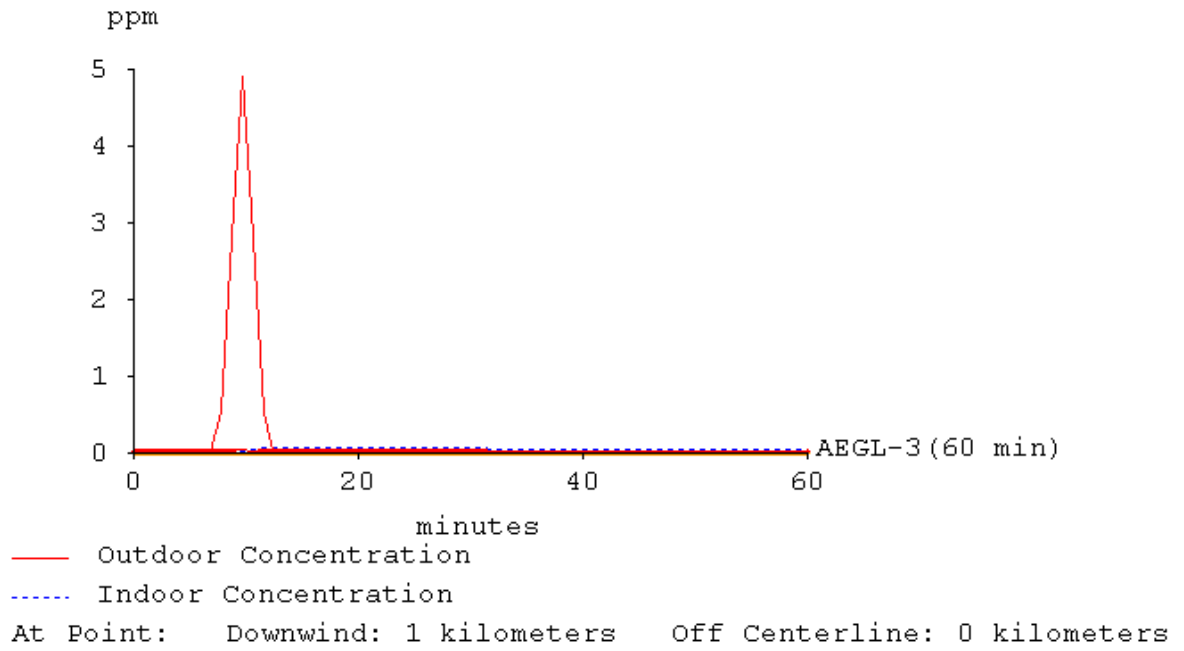   Outdoor: 0.978 ppm
    Indoor: 0.0115 ppm

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SITE DATA:
   Location: DAYTON, OHIO
   Building Air Exchanges Per Hour: 2 (user specified)
   Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
   Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
   AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
   AEGL-3(60 min): 0.022 ppm
   Normal Boiling Point: 297.0° F
   Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
   Wind: 3 meters/second from 180° true at 10 meters
   Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
   Air Temperature: 70° F   Stability Class: C
   No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
   Direct Source: .5 tons/min   Source Height: 0
   Release Duration: 1 minute
   Release Rate: 16.7 pounds/sec
   Total Amount Released: 1,000 pounds

THREAT ZONE:
   Model Run: Gaussian
   Red   : 3.6 miles --- (0.022 ppm = AEGL-3(60 min))
   Orange: 5.5 miles --- (0.006 ppm = AEGL-2(60 min))
   Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
   Concentration Estimates at the point:
   Downwind: 1 kilometers   Off Centerline: 0 kilometers
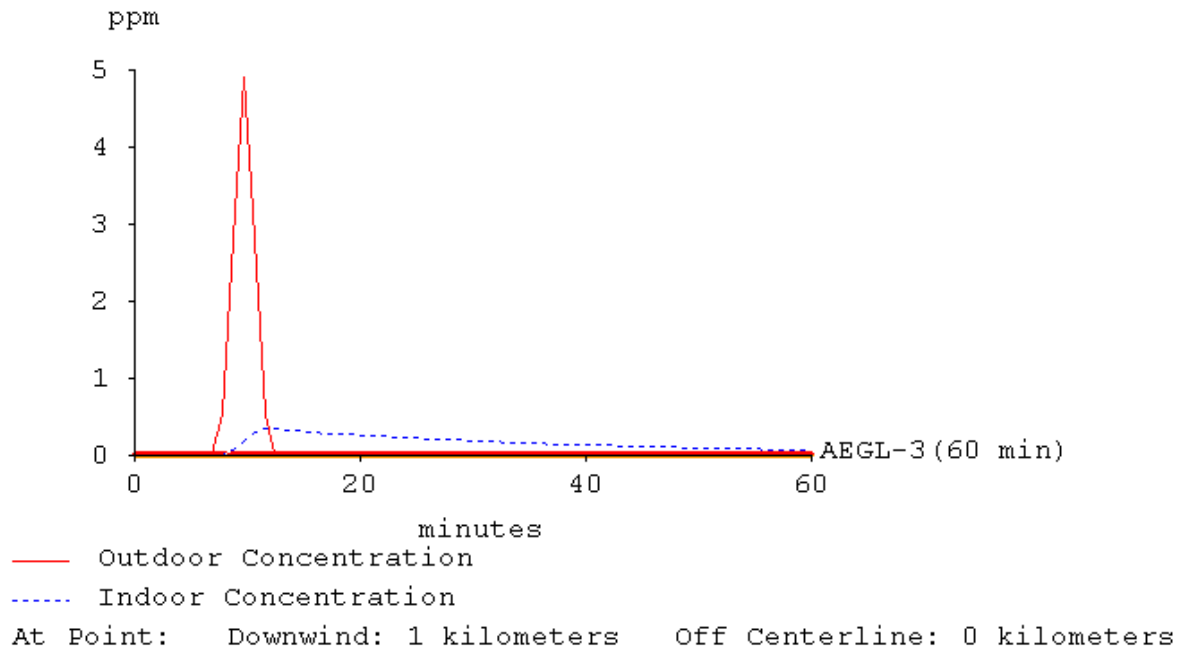   Max Concentration:
     Outdoor: 4.89 ppm
     Indoor: 0.0575 ppm

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1 tons/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 33.3 pounds/sec
  Total Amount Released: 2,000 pounds

THREAT ZONE:
  Model Run: Gaussian
  Red   : 4.5 miles --- (0.022 ppm = AEGL-3(60 min))
  Orange: greater than 6 miles --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
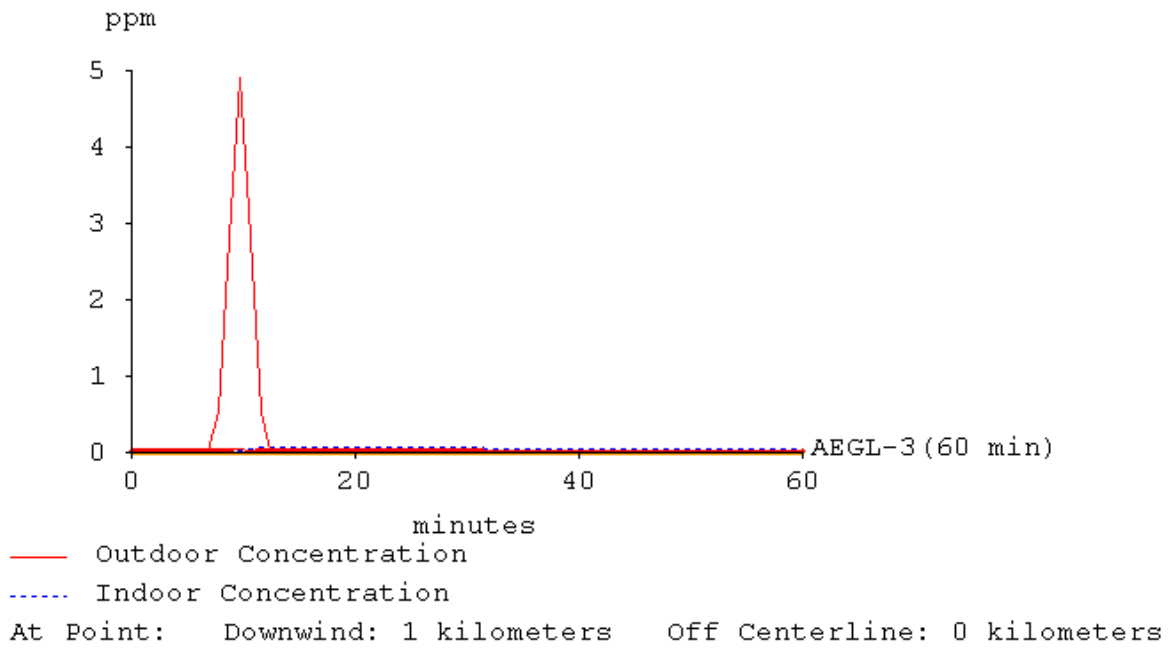 Max Concentration:
    Outdoor: 9.78 ppm
    Indoor: 0.115 ppm

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SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 1.5 tons/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 50 pounds/sec
  Total Amount Released: 3,000 pounds

THREAT ZONE:
  Model Run: Gaussian
  Red   : 5.2 miles --- (0.022 ppm = AEGL-3(60 min))
  Orange: greater than 6 miles --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
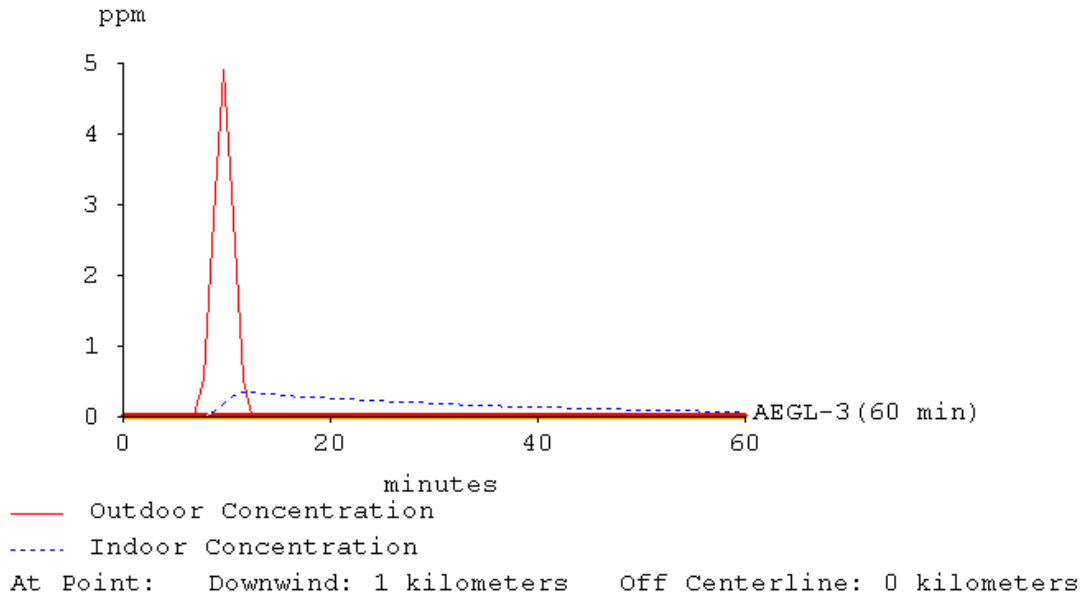 Max Concentration:
    Outdoor: 14.7 ppm
    Indoor: 0.172 ppm

109

SITE DATA:
  Location: DAYTON, OHIO
  Building Air Exchanges Per Hour: 2 (user specified)
  Time: February 23, 2009 0800 hours EST (user specified)

CHEMICAL DATA:
  Chemical Name: SARIN   Molecular Weight: 140.11 g/mol
  AEGL-1(60 min): 4.8e-04 ppm   AEGL-2(60 min): 0.006 ppm
  AEGL-3(60 min): 0.022 ppm
  Normal Boiling Point: 297.0° F
  Note: Not enough chemical data to use Heavy Gas option

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from 180° true at 10 meters
  Ground Roughness: 100 centimeters   Cloud Cover: 5 tenths
  Air Temperature: 70° F   Stability Class: C
  No Inversion Height   Relative Humidity: 50%

SOURCE STRENGTH:
  Direct Source: 2 tons/min   Source Height: 0
  Release Duration: 1 minute
  Release Rate: 66.7 pounds/sec
  Total Amount Released: 4,000 pounds

THREAT ZONE:
  Model Run: Gaussian
  Red   : 5.7 miles --- (0.022 ppm = AEGL-3(60 min))
  Orange: greater than 6 miles --- (0.006 ppm = AEGL-2(60 min))
  Yellow: greater than 6 miles --- (4.8e-04 ppm = AEGL-1(60 min))

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 1 kilometers   Off Centerline: 0 kilometers
  Max Concentration:
    Outdoor: 19.6 ppm
    Indoor: 0.23 ppm

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31	Chlorine	F	1	3	0	1000	0	2	17	30	2	0.1	1	inf	1778	18	81.9	34.8	930
32	Chlorine	F	1	3	0	1000	0	2	17	30	2	0.1	1	1	1778	18	4.89	36	56.9
33	Chlorine	F	1	3	0	1000	0	2	17	30	2	0.1	1	30	1778	18	71	33.6	894.5
34	Chlorine	F	1	3	0	1000	0	2	90	240	2	0.1	1	inf	1176	28.2	249	240	794
35	Chlorine	F	1	3	0	1000	0	2	90	240	2	0.1	1	1	1176	28.2	32.8	247	47
36	Chlorine	F	1	3	0	1000	0	2	90	240	2	0.1	1	30	1176	28.2	79.72	244.4	601.3
37	Chlorine	F	1	3	0	1000	0	2	90	240	2	0.1	1	60	1176	28.2	133.9	60	794.3
38	Chlorine	F	1	3	0	1000	0	2	1	10	2	0.1	0.4	inf	271.3	10.5	15.14	22	31.4
39	Sarin	A	1	1.5	0	100	0	2	0.075	1	0.5	0.1	1	inf	514.15	1.6	0.5	3	2.39
40	Sarin	A	1	1.5	0	100	0	2	0.075	1	2	0.1	1	inf	514.15	1.6	1.75	3	7.58
41	Sarin	A	1	1.5	0	1000	0	2	0.075	1	0.5	0.1	1	inf	0.0956	11.6	9.1	39.85	0.00658
42	Sarin	A	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	0.0956	11.6	29.31	35.4	0.0213
43	Sarin	A	1	1.5	0	3000	0	2	0.075	1	0.5	0.1	1	inf	2.19E-04	33.8	59.46	270	2.48E-05
44	Sarin	A	1	1.5	0	3000	0	2	0.075	1	2	0.1	1	inf	2.19E-04	33.8	138.2	199	8.00E-05
45	Sarin	B	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	1.71	11.6	10.99	19.8	0.14
46	Sarin	C	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	6.39	11.6	7.99	17.7	0.37
47	Sarin	D	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	18.02	11.6	8.64	18.1	1.15
48	Sarin	E	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	22.7	11.6	12.88	21	2.19
49	Sarin	F	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	inf	25.9	11.6	22.97	28.7	4.56
50	Chlorine	F	1	3	0	1000	0	2	1	10	2	0.1	1	30	271.3	10.5	34.9	30	71.9
51	Sarin	F	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	1	25.9	11.6	3.55	25.8	0.753
52	Sarin	F	1	1.5	0	1000	0	2	0.075	1	2	0.1	1	30	25.9	11.6	51	20.4	10.5
53	Chlorine	F	1	3	0	1000	0	2	17	60	2	0.1	1	inf	889.04	27	139	62	600
54	Chlorine	F	1	3	0	1000	0	2	17	60	2	0.1	1	1	889.04	27	9.48	65.4	35.5
55	Chlorine	F	1	3	0	1000	0	2	17	60	2	0.1	1	30	889.04	27	72.65	62	454.3
56	Chlorine	C	1	3	0	1000	0	2	0.1	10	0	0.32	1	inf	2.52	7.8	5.24	16.2	0.098
57	Chlorine	C	1	3	0	1000	0	2	0.5	10	0	0.32	1	inf	12.6	7.8	5.24	16.2	0.488
58	Chlorine	C	1	3	0	1000	0	2	1	10	0	0.32	1	inf	25.3	7.8	5.22	16.2	0.976
59	Chlorine	C	1	3	0	1000	0	2	1.5	10	0	0.32	1	inf	37.89	7.8	5.12	16.2	1.47
60	Chlorine	C	1	3	0	1000	0	2	2	10	0	0.32	1	inf	50.5	7.8	5.23	16.2	1.95
61	Sarin	C	1	3	0	1000	0	2	0.1	1	0	0.32	1	inf	8.33	5.88	1.58	8.4	0.105
62	Sarin	C	1	3	0	1000	0	2	0.5	1	0	0.32	1	inf	41.68	5.88	1.58	8.4	0.527
63	Sarin	C	1	3	0	1000	0	2	1	1	0	0.32	1	inf	83.4	5.88	1.58	8.4	1.05
64	Sarin	C	1	3	0	1000	0	2	1.5	1	0	0.32	1	inf	125.1	5.88	1.58	8.4	1.58
65	Sarin	C	1	3	0	1000	0	2	2	1	0	0.32	1	inf	161.8	5.88	1.58	8.4	2.11

Appendix F. Summary of Results

Trial	Chemical	Stability	Roughness	Wind Velocity	H	x (m)	y (m)	z (m)	Quantity (ton)	Tr (min)	ACH (h-1)	Infiltration (ACH)	Mixing	Implementation Delay (min)	Peak Outside Concentration (mg/m3)	Time (min)	% peak of Outside Peak	Time (min)	60 min TWA
1	Chlorine	A	1	1.5	0	100	0	2	0.075	10	0.5	0.1	1	inf	74.85	4	9.73	12	5.93
2	Chlorine	A	1	1.5	0	100	0	2	0.075	10	1	0.1	1	inf	74.85	4	17.54	11.75	10.09
3	Chlorine	A	1	1.5	0	100	0	2	0.075	10	2	0.1	1	inf	74.85	4	32.42	11.5	16.89
4	Chlorine	A	1	1.5	0	100	0	2	0.075	10	0.5	0.1	1	1	74.85	4	1.71	12.3	1.11
5	Chlorine	A	1	1.5	0	100	0	2	0.075	10	1	0.1	1	1	74.85	4	1.77	12.2	1.15
6	Chlorine	A	1	1.5	0	100	0	2	0.075	10	2	0.1	1	1	74.85	4	1.9	12.2	1.24
7	Chlorine	A	1	1.5	0	100	0	2	0.075	10	0.5	0.1	1	30	74.85	4	9.73	12.1	6.07
8	Chlorine	A	1	1.5	0	100	0	2	0.075	10	1	0.1	1	30	74.85	4	17.54	12	10.55
9	Chlorine	A	1	1.5	0	100	0	2	0.075	10	2	0.1	1	30	74.85	4	32.42	11.8	18.14
10	Chlorine	A	1	3	0	100	0	2	0.075	10	0.5	0.1	1	inf	32.43	1.5	9.75	10.7	2.6
11	Chlorine	A	1	3	0	100	0	2	0.075	10	1	0.1	1	inf	32.43	1.5	17.61	10.7	4.22
12	Chlorine	A	1	3	0	100	0	2	0.075	10	2	0.1	1	inf	32.43	1.5	32.6	10.7	7.29
13	Chlorine	A	1	3	0	100	0	2	0.075	10	0.5	0.1	1	1	32.43	4	2.02	10.7	0.584
14	Chlorine	A	1	3	0	100	0	2	0.075	10	1	0.1	1	1	32.43	4	2.39	10.9	0.698
15	Chlorine	A	1	3	0	100	0	2	0.075	10	2	0.1	1	1	32.43	4	3.13	10.9	0.927
16	Chlorine	D	1	1.5	0	100	0	2	0.075	10	0.5	0.1	1	inf	566.4	2.7	9.75	11.6	45.05
17	Chlorine	D	1	1.5	0	100	0	2	0.075	10	2	0.1	1	inf	566.4	2.7	32.55	11.4	126.6
18	Chlorine	D	1	3	0	100	0	2	0.075	10	2	0.1	1	inf	283.21	1.35	32.65	10.7	63.73
19	Chlorine	D	1	3	0	100	0	2	0.075	10	2	0.1	1	1	283.21	1.35	3.13	10.9	8.1
20	Chlorine	D	1	1.5	0	1000	0	2	0.075	10	0.5	0.1	1	inf	11	16.1	10.03	25.8	0.7663
21	Chlorine	D	1	1.5	0	1000	0	2	0.075	10	2	0.1	1	inf	11	16.1	32.55	24.1	2.235
22	Chlorine	D	1	3	0	1000	0	2	0.075	10	2	0.1	1	inf	5.78	10.5	31.84	17	1.2182
23	Chlorine	D	1	3	0	1000	0	2	1	10	2	0.1	1	inf	77.16	10.5	31.84	17	16.24
24	Chlorine	D	1	3	0	1000	0	2	1	10	2	0.1	1	1	77.16	10.5	1.64	18	1.018
25	Chlorine	E	1	3	0	1000	0	2	1	10	0.5	0.1	1	inf	149.5	10.5	9.67	18.7	10.87
26	Chlorine	E	1	3	0	1000	0	2	1	10	2	0.1	1	inf	149.5	10.5	31.62	17.8	31.08
27	Chlorine	E	1	3	0	1000	0	2	1	10	2	0.1	1	1	149.5	10.5	1.66	19.7	1.96
28	Chlorine	E	1	3	0	3000	0	2	1	10	0.5	0.1	1	inf	16.8	21.7	15.03	36.6	1.6
29	Chlorine	F	1	3	0	1000	0	2	1	10	2	0.1	1	inf	271.3	10.5	34.9	29.4	65.39
30	Chlorine	F	1	3	0	1000	0	2	1	10	2	0.1	1	1	271.3	10.5	1.97	23.3	1.77

Appendix G. Excel Screen Shots

Since the goal was to provide a tool to base level BE personnel, a Microsoft Office Excel® 2007 spreadsheet was used to evaluate the SIP decisions. The Excel® spreadsheet requires information to be entered into the area of atmospheric information, building information, and shelter-in-place strategy. Information required to calculate the outdoor concentration includes the stability class, roughness, mean wind velocity, mixing height, mass of release, time of release, downwind coordinates.   The required information is marked in yellow in Figure 35 below. The vertical, horizontal, and along axis dispersion coefficients will calculate automatically based on imputed information.

Atmospheric Information

Stability	C	
Roughness	1	m

$\bar{u}$ = 3 m/s   Z = 10 m   p = 0.2

h =	0	
M =	2	ton 1814369480 mg
q =	30239491.33	mg/sec
tr =	1	min
	60	sec

x (m)
1000 m
σx	211.1844329	m
σy	103.800	m
σz	61.140	m
zr	30.57	m
zc	10.3938	m
y=	0	m
z =	2	m
Cg (mg/m3) =	505.2987281	

Figure 35-Atmospheric Input

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When inputting building information, users must first decide where or not the
building is residential or commercial and how calculate the air exchange rates. The air
exchange rates can be calculated by the design flow rates or specify the air exchange rates.
The user must then choose to calculate the infiltration rates or specify by air exchange
rates. The required information is marked in yellow in Figure 36 below.

Building Information

Type of Building	R				
How to Calculate Flows	A				

A	2500 ft2		ACH =	2	
$V_{building}$	25000 ft3	707.9212 m3			

	Design Criteria		ACH		Used Values
Q_{Intake}	0.18 cfm/ft2				
	450 cfm	0.212376 m3/sec	cfm	m3/sec	0 m3/sec
Q_{intake}/Q_{Supply}	0.19				
Q_{Supply}	2368.421053 cfm	1.11777 m3/sec	cfm	m3/sec	0 m3/sec
Q_{supply}/Q_{return}	1.14				
Q_{return}	2077.562327 cfm	0.9805 m3/sec	cfm	m3/sec	0 m3/sec
$Q_{Exhaust}$	159.1412742 cfm	0.075106 m3/sec	cfm	m3/sec	0 m3/sec

How to Calculate Infiltration	A		ACH =	0.32
Driving Force?	W			

	Design Criteria		ACH		Used Values
ELA	0.01 in2/ft2				
Free Area	25 in2	0.173611 ft2			
Cv	0.55				
v	9.84252 ft/sec				
Toutside	60 oF	520.67 R			
Tinside	70 oF	530.67 R			
T	70 oF	530.67 R			
C_D	0.425				
ΔH_{NPL}	3 ft				
Qinfiltration	82.70450833 cfm	0.039032 m3/sec	133.3333 cfm	0.062926 m3/sec	0.062926 m3/sec
Qexfiltration	82.70450833 cfm	0.039032 m3/sec	133.3333 cfm	0.062926 m3/sec	0.062926 m3/sec

m	1		
k	0 m3/h	0 m3/sec	
Co	0		

Figure 36-Building Information Input

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The final section of input involves choosing the shelter-in-place strategy, which involves inputting the delay time in shutting down the HVAC system. The required information is marked in yellow in Figure 37 below. The Excel® spreadsheet will calculate and plot both the indoor and outdoor concentrations for assessment.

Shelter-In-Place Strategy

Taking Action of SIP?	Y
HVAC Shutoff?	N
HVAC Termination Delay	30 min
	1800 sec

Figure 37-SIP Strategy Input

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14. ABSTRACT

The goal of Shelter-In-Place (SIP) is to reduce human exposure to chemical, biological, radiological, and nuclear (CBRN) agents in the event of an accidental or intentional airborne release into the outdoor environment. The Air Force Bioenvironmental Engineering (BE) career field is responsible for providing sampling, identification, and quantification input to hazard prediction models and supporting evacuation plan development to provide risk-based control recommendations to the Incident Commander. This also includes providing exposure and contamination control recommendations for sheltered populations. A Gaussian plume model combined with indoor box model was used to test the consequences associated with the delay of implementing SIP procedures. It is imperative that emergency planners pre-plan the installation SIP protocol for likely scenarios identified during the various vulnerability surveys. The decision to shelter-in-place must be made immediately in order to reduce the exposure and thereby decreasing any additional casualties presenting at the local medical treatment facility.

15. SUBJECT TERMS

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